MINISTRY OF RAILWAYS

TREATISE

ON

ELECTRIC TRACTION DISTRIBUTION

VOLUME - I

INDIAN RAILWAYS INSTITUTE OF ELECTRICAL ENGINEERING
NASIK ROAD
FOREWORD

“Old order changes yielding place to new”, thus goes a saying. Railway is no exception to this rule. Core strength of Indian Railways has been continuous technological upgradation to keep a balance on rising costs and economic viability of train operation. Thus, the motive power technology got upgraded from steam locos to diesel locos to electric locos. Initially till late seventies the pace of 25 KV electric traction was slow and the designers had to depend upon various articles published in RE journals, literature of SNCF etc. There was no source of authentic available information at one place. Having worked as head of OHE design cell in 1981, when there was a boost to pace of electrification, I felt the need of comprehensive knowledge base for OHE & Power Supply design. I hope with this book this gap will be bridged.

The original ACTM was a single volume and since then, it has expanded to four volumes and contained the design parameters, calculations and system designs contributed by OHE design engineers of 80s. The ACTM should be a manual used by the staff who have been trained in Traction Technology and not a text book to teach them. I, therefore, think that subject covered in these two volumes should also be delinked from ACTM. The bulky volumes of ACTM, will get reduced to a required size. IRIEEN was thus entrusted with the job of bringing out the books with the help of RDSO & CORE.

I am delighted to note that IRIEEN has put in lot of efforts in bringing out the two volumes “Treatise on Electric Traction Distribution” in the present form. I am sure that these books will serve the needs of Traction Engineers.

NEW Delhi
14.6.2007

RAMESH CHANDRA
Member Electrical
PREFACE

Railway Board vide their letter No.2005/RE/170/1 dated 02.09.2005, assigned the work of Preparation and issue of "Treatise on Electric Traction Distribution". At the beginning, the entrusted work appeared to be simple but as the time passed by, the complexity of the task became known. Newton said that by standing on the shoulders of his seniors, he could see far. These two volumes are based on the pioneering work done by many of the seniors. Acknowledgement of their contribution is, therefore, my foremost duty.

The manuals had to be typed with the help of tiny staff available at IRIEEN. IRIEEN acknowledges the efforts put in by CORE in supplying the drawings and RDSO for verifying the draft. The outdated part like locations of water columns have been omitted from these volumes. The setting distances revised recently by RDSO have been included. Some practical layouts and worked examples have been added to make the book useful. Attempts have been made to simplify the language of the text to the extent possible though lot needs to be done in this area.

Before presenting the book, I would like to place my thanks on record to Member Electrical, Shri Ramesh Chandra without whose guidance and help, these volumes would not have come out and Additional Member Electrical Shri U C D Shreni, in helping to bring out the books early. S/Shri W W Kamble, Bukane, Nitin Deshpande Chauhan, and Balapure, have done a tremendous work of typing these books. My thanks are to my present and Ex Faculty Members, Sr Professors, Sh R K Mehta, Pravin Pradhan, Yogesh Asthana, Sanjay Deep, A.A.Phadke, Professors, S K Srivastava, R Bhargava, Ravi Agarwal, and H R Khandekar for their untiring support. Thanks are also due to Shri Arvind Kishore, COS C Rly for bringing out these volumes in short time.

This Treatise is intended for the guidance only and is not to supersede RDSO's instructions or standards available on this subject. In case there is any disagreement between the stipulations made in this Publication and RDSO's latest guidelines on the subject, RDSO's guidelines shall prevail.

Suggestions for improvement are always welcome and may be sent to The Director, IRIEEN.

NASIK ROAD.
08-06-2007

S. P. KHADE
DIRECTOR, IRIEEN NKRD.
PART- 1

RAILWAY ELECTRIFICATION SURVEYS
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CHAPTER - I

INTRODUCTION

1.1.1 Purpose of Railway Electrification

Electric Power Contact lines are provided as overhead conductors over running Railway lines to provide energy to electrically driven Railway locomotives or the train sets. As compared to diesel locomotives, whose power is limited to the permissible axle load and the moving dimensions for accommodation of the diesel engine, the contact lines permit almost unlimited power at the disposal of the electrically driven vehicle. Higher power permits heavier trains to achieve higher speeds. Electric Multiple Units provide fast commuter services with quick reversal at terminals, ensuring high frequency of service. On routes where the commuter services share tracks with main line trains, the Electric Multiple Units offer least interference to the latter due to the EMU's high acceleration rates. The major advantages of electric traction are, economy in operation and maintenance, saving in consumption of scarce diesel oil and increased throughput of traffic. In addition it is eco-friendly. The capital cost for provision of fixed installation required for electric traction is found adequately remunerative for routes having high levels of traffic.

1.1.2 Railway Electrification Works

1.1.2.1 Main Works

These consist of:

- Provision of most economical & reliable electric contact system to continuously supply power to the moving electric rolling stock.

- Power Supply Arrangements

- Provision of switches to regulate the flow of power along with the electric protective gear.

- Monitoring and remote control of power supply.

- Immunisation of signalling and the trackside telecommunication circuits & equipments against electromagnetic and electrostatic effects of 25 kV, 50 Hz, single phase traction power supply.

- Modernization of signalling and telecommunications.
- Provision of maintenance & operation facilities for electric traction.

1.1.2.2 Disciplinewise division of Works.

Different Engineering disciplines take up their portion of the work which form components of Electrification works. These are given below :-

a) Electrical :
   iii) Remote Control of the Power supply Equipment
   iv) Electric Locomotive Maintenance facilities.
   v) Ancillary Works of modification to the existing power supply arrangements on the route to immunize the system against induced voltages due to the traction currents and provision of power supply at new points.
   vi) Liaison with Electricity Authorities to modify their power line crossings to suit 25 kV ac traction and to avail high tension input power supply for TSS.
   vii) Consequential electrical works like electrification and air-conditioning of service buildings and staff quarters.

b) Signal and Telecommunications :
   i) Provision of colour light signals and immunization of the signaling installation against induction effects of 25 kV ac traction power supply system.
   ii) Provision of underground cables for the Railway’s telecommunication lines and provision of additional traction control circuits.
   iii) Liaisoning with the Department of Telecommunications for modification of their circuits to immunize them against induced voltages due to traction current.

c) Civil Engineering:
i) Yard remodelling, slewing of tracks, sidings and all track works.

ii) Construction of loco sheds, service buildings, and staff quarters.

iii) Modification to over line structures such as over bridges, flyovers, through girder bridges etc as well as to tunnels, platform shelters and water columns to suit 25 kV ac clearances.

1.1.2.3 Choice of System of Power Supply.

Before designing the Power Supply arrangements and the type of Overhead equipment for a section; a choice is required to be made whether conventional 25 kV a.c. system is to be adopted or 2 x 25 kV a.c. Auto transformer system is to be adopted. This choice depends upon a number of factors viz. the sections to be provided with booster transformers and return conductor as demanded by the Department of Telecommunications, the demand of power for the volume and type of the traffic and suitable locations available for traction substation.

1.1.2.4 Coordination of Works

Railway Electrification, being a multi-disciplinary project work, needs close coordination amongst electrical, signalling & telecommunications and civil engineering disciplines. Further coordination with outside agencies such as Power Supply Authorities, the Department of telecommunications, the Revenue officials as well as with Open Line organization on whose section the work is to be taken up is also required. Accordingly the organisation for Railway Electrification coordinates works of all the disciplines and the agencies from inception to completion including support services to the open line in early stages of electric traction over the section.

1.1.3 Selection of Route for Electrification

1.1.3.1 Main Consideration

Railway Electrification, being in the nature of major improvement to the infrastructure of a section is taken up basically on routes having high density of traffic. Short spurs or those lines which interconnect the electrified lines and expected to improve the mobility of the rolling stock are also taken up for electrification.

1.1.3.2 Financial Evaluation

As Railway Electrification entails capital expenditure, the sanction to the project is subject to Cost Benefit Analysis (CBA) through Discounted Cash Flow (DCF)
technique. Two scenarios are considered: one, under diesel traction, and the other under electric traction; for the given volume of traffic forecast on the section for a long enough period of time such as 30 years after the energisation of the section on electric traction. The cash outflows under the two scenarios are discounted at the approved rate (14% and 12% thereafter) over the life of the project (taken as 35 years, about 5 years for construction and 30 years thereafter, of operation). If the total of the stream of the annual discounted cash flow for electric traction is found to be lower than that for diesel traction, the project is considered as remunerative and desirable for approval. Sometimes an Economic analysis is also called for such as when funding by an international aid agency viz the World Bank of Asian Development Bank is proposed. Although the Economic analysis is also carried out on the same DCF technique, the inputs and the outputs reflect the Social costs and benefits, and the discount factors chosen may also be different, being dependent upon funds available for investment for future benefit against those required for immediate consumption and as decided by, say, the Planning Commission. The investment in electric traction is found remunerative on account of:

i. Lower fuel costs

ii. Less number of locomotives,

iii. Lower operating costs and

iv. Lower locomotive maintenance costs as compared to diesel traction on given value of traffic.

The traffic level in Gross Million tonne per route kilometer per annum at which the minimum acceptable rate of return is obtained is called the “Break Even Level” of traffic density. This is covered in detail in Chapter 6.

1.1.3.3 Past policy on Electrification.

a) Early Years

At the end of the 19th century electricity was in widespread use for running trams in North America and Europe, since more economical than haulage by horses. By 1930s the electric traction was in use in different parts of the world over short high density main line or suburban sections. The system of supply was usually 1500 V dc although some sections at 600 V dc or 750 V dc with third rail system were also adopted. The copper catenary was heavy and complex, rectifier substations were required to be located at close intervals. The cost of electrification was high. In India, also, by 1930 the suburban sections of Mumbai and Chenai were electrified.
at 1500 V dc. There were only two main line sections on electric traction e.g. Mumbai to Pune and from Kalyan to Igatpuri. The electrification drastically increased the throughput of traffic over these sections, both having 1 in 37 gradient over the Western Ghats. The steam traction required reversing stations to negotiate, such steep inclines. There being no adequate generating capacity in the country, the entire power for these electrified sections was generated and transmitted by the then Great Indian Peninsular Railway to its traction substations.

b) Post World War II Scenario

After India’s independence, electrification of Howrah- Burdwan section on 3000 V dc was taken up and was completed in 1958. In the meanwhile in 1955 the French National Railway (SNCF) who had perfected the system of Electrification on 25 kV ac, demonstrated its advantages at the international conference of the International Union of Railways (UIC) at Lille in France. The major advantages of 25 kV ac 50 Hz single phase system was a light Overhead Equipment, simple traction substations located afar feeding power to rectifier locomotives having tap changer control giving greatly improved adhesion characteristics. But the adjacent signalling and telecommunications circuits needed immunisation from the electro-magnetically induced voltages due to traction currents. This called for modification to these circuits and to their terminal equipment, but in the process gave an opportunity to improve and upgrade these equipment. This system was more reliable and on the whole cheaper to construct and to maintain; the ac locomotive could haul heavier loads and gave better acceleration than dc locomotives. However, such a system was dependent upon power supply from Extra High Voltage grid system having adequate short circuit capacity required for supplying the extent of single phase traction loads. Weighing the advantages of this system and the fact that such grid system was also in the process of being set up in the country, Indian Railways in the year 1957 decided to adopt 25 kV ac 50 Hz single phase system for all future Railway Electrification schemes, as well as to convert the system of 3000 V dc traction recently established in Burdwan - Howrah section of Eastern Railway and the one existing at 1500 V dc on the suburban meter gauge section of Chennai on Southern Railway, to this system for uniformity. For the initial stages the technical collaboration of SNCF was taken. Choice of 25 kV ac single phase system at industrial frequency (50 Hz) gave a large drive towards main line electrification of Indian Railway. During the second and third Five Year Plans, electrification of the coal and iron ore routes serving the steel plants located on the Eastern and South Eastern Railways was carried out. To cater for the suburban commuter traffic of Sealdah Division of Eastern Railway so far on steam traction, these routes on the Division were electrified. Electrification of Igatpuri-Bhusaval section of Central Railway and Tambaram-Villupuram (Meter Gauge) section of Southern Railway was also taken up.
c) Corporate Plan of Indian Railways.

Indian Railways, in their first Corporate Plan for the period 1974-89, identified the Broad Gauge trunk routes inter-connecting the four major metropolitan cities viz. Kolkata, Chennai, Mumbai and Delhi were identified and ultimately electrified. These lines had high potential for growth of traffic along with other high density coal and ore carrying routes.

d) Accelerated Pace of Electrification

The Arab-Israel wars of the 1970s highlighted the strategic nature of Petroleum and their scarcity value. Further the sharp increase in the cost of oil in the period from 1973 to 1980 and increasing outflow of India’s foreign exchange for importing petroleum and its products spurred the Government of India in 1980, to take a policy decision to accelerate the pace of Railway electrification. The target was to achieve electrification of 1000 route kilometer per year. Though this was not achieved, a rate of hitherto 150 to 200 km of energisation was increased to a rate of 500 to 600 km per year from 1985 onwards. Electrification of complete route rather than section has been, thereafter, planned. By 1992, Electrification of Delhi-Kolkata, Kolkata-Mumbai, Delhi-Secunderabad and Bangalore were completed and connected to the electrified network. The Overhead Equipment and the Power Supply on some of the electrified routes are being strengthened to cater to goods train with the loads of 9000 tonne. The major milestone has been achieved in Oct. 2005, when the electrification of HWH-Chennai route was completed.

1.1.3.4. Present Policy On Electrification

The successive Corporate Plans of Indian Railways generally identify the routes most suitable for electrification. Following considerations dictate the priority for electrification of a route:

a) High traffic density.

b) Extension of an electrified route on short spur or interconnection of two electrified routes to improve rolling stock mobility, and

c) Passenger commuter sections.

Availability of requisite power supply at reasonable rates is a basic condition combined with availability of adequate short circuit power at the point of tap for the single phase traction power needs. The zonal Railways and the Railway Board maintain section wise traffic density figures as a part of their statistics. With this as the
base and the anticipations of future traffic the highest traffic density routes which are not electrified are short listed, after making a list of such routes and short listing them in order of their operating benefits, priorities for electrification are finalized by the Ministry of Railways in consultation with the Planning Commission.

1.1.4 Survey for Electrification

1.1.4.1 General

After having narrowed down the choice of routes which may be considered for electrification, it is essential to further examine the chosen route in detail for its suitability for electrification in following aspects:

a) The feasibility and availability of reliable power supply, suitability of the terrain and of the overline structure (or their amenability to modifications) to suit the electrical clearances, and of terminal yards to be able to provide lines for change of traction.

b) A realistic assessment of the cost of the project.

c) The financial viability of the investment.

To ascertain the above details a route is surveyed for Railway Electrification. The survey may either be a “Reconnaissance Survey” or a detailed foot-by-foot “Cost-cum-Feasibility Survey” as the circumstances call for.

1.1.4.2 Reconnaissance Survey

This is a rapid survey examining the salient and vital points, leaving the details to be worked out in the extensive foot by foot Survey. The survey covers the following items.

a) Assessment of existing traffic and realistic forecast of projected traffic, both for goods and passenger, including special requirements such as plans for running superfast passenger trains or/and of heavy haul goods trains.

b) Availability of Electric Power.

c) Details of the section covering the terrain, the terminal yards, the signal and telecommunication installation and the volume of work involved in modification to overline structures and the over bridges to suit ac traction. This is normally done by a joint inspection team of the officers
of the concerned disciplines viz. electrical, civil engineering, and signal and telecommunications using motor trolley or an OHE inspection car.

d) An idea of the lengths of the route to be equipped with booster transformers and return conductor, involving a preliminary discussion with Department of Telecommunications.

e) The information collected by this rapid survey yields a fairly accurate idea of the volume of Electrification work content. For obtaining an estimate within 10 to 20% of it’s cost, Unit costs derived from a recently completed project on cost per unit of work, or per route or track km, as most applicable, are applied to the quantities of the component works estimated, and the project cost is worked out. Based on the latest cost of inputs: of fuel- electric energy, specific fuel or energy consumption and other operating and maintenance norms derived from statistical data a rate of return is worked out.

The feasibility for electrification, its cost and its remunerative-ness so worked out gives adequate information based on which the project can be sanctioned. However, if the competent authority desires to examine the project more closely, then a detailed Cost-cum-Feasibility Survey has to be taken up. This survey has to be included in the programme for Surveys and sanctioned in the Annual Works Programme by the Railway Board and a separate organization set up to conduct it. Such a situation may arise, for example, when the cost of inputs has altered radically and the traffic density forecast on the route is not very much above the 'break even' level.

1.1.4.3 Cost – cum – Feasibility Survey

A multidisciplinary Survey Team is formed expressly for carrying out the detailed survey. This survey organisation finalises the wiring plan, conducts foot by foot survey for the route and prepares the survey plans followed by the pre-pegging and pegging plan. The team examines the clearances on the route to suit 25kV ac 50 Hz single phase system and suggests modifications wherever required. By liaising with the power supply authorities and the Department of Telecommunications, it also examines in detail the availability of power and the quantum of protection required by the Department of Telecommunications respectively. These studies give a sufficient idea regarding the amount of work involved and the cost implications to be worked out. Based on these the financial viability of the work is examined. Finally all these details are incorporated in the Project Report and the Abstract Estimate is prepared which is placed before the competent authority for sanction of the Railway.
Electrification project. On sanction of the project the drawings are prepared and the estimates made are used for calling of tenders and finalisation of schedule of quantities. Accurate foot-by-foot survey, and carefully finalized designs prepared by a survey organisation is the cornerstone of a successful Electrification Project.
CHAPTER 2
THE SURVEY TEAM AND ITS WORK

1.1.1 The Survey Team

Having narrowed the field to a few routes which can be beneficially electrified, an accurate estimate of the costs and benefits likely to accrue are required to assist in taking the decision to invest in electrification of a particular route. To obtain these, a cost cum feasibility survey is sanctioned by the Railway Board. The survey team consists of officers and subordinates of Electrical, Signal, Telecommunication and Civil Engineering disciplines along with those of Operating and Finance. The team being multidisciplinary, individual members work in close coordination, finalizing their portion of survey and design work thoroughly. The officer belonging to electrical discipline generally coordinates all the activities. Individual members, discipline-wise responsibilities are itemized in the following paragraphs

1.2.2 Electrical Engineering

1.2.2.1 Item of Survey/Data Collection

| Remarks |
|------------------|------------------|
| a) Traction Power supply: |
| Availability of power at reasonable tariff. Based on discussions and finalization of details with the concerned Power supply authorities |
| Suitable locations of points of power supply |
| Cost and time schedule to obtain supply |
| b) Foot by Foot Survey of the Route Close coordination of Civil Engineer (Survey) essential |
| c) Route survey of Railway’s transmission line from supply Authority’s grid sub-station -do- |

1.2.2.2 Items of works and drawings to be finalized

| Remarks |
|------------------|------------------|
| a) The ‘Wiring Plan’ indicating Finalized with open- |
b) The Sectioning Diagram for Traction Overhead Equipment

The tracks to be wired line; the Operating Officer (Survey) --do--

c) The General Supply Diagram Indicating location of Power Control Points

Finalized in consultation with the open Supply and line

d) The pegging Plans for Traction Over Head Equipment

Prepared as a result of foot by foot survey

e) The plans for modification of power distribution lines at stations and yards to immunize them against Electro-Magnetic induction effects of traction power supply.

Finalised in consultation with Open Line

f) Modifications to Power Line Crossings of Electricity Supply Authorities to suit Electric Traction

Finalised in consultation with Electricity Supply Authorities

g) The location of Electric locoshed and Trip inspection sheds.

Finalised in consultation with Open line

h) Locations of OHE & PSI maintenance depots; their staff strength, tools & plant road and rail vehicles.

--do--

i) Cost Estimates for items of work including payments to the Power Supply Authorities for Traction Power Supply

By Electrical Member after taking details from supply authorities

j) Overall coordination of survey, preparation of Project Report and Abstract Estimate and Financial

Norms required for Financial appraisal to be collected from Open Line & verified
appraisal of the project

1.2.3 Operating

Items of Survey and their finalisation

a) Traffic density, existing and forecast, both goods and passenger; train loads and speeds. Assessment based on data obtained from the Open Line & Railway Board; forecasts should be accepted by them.

b) Location of Remote Control Centre Finalised in consultation with open line in coordination with Electrical officer of the Survey.

c) Remodeling & wiring to be done in Yards & at change of traction points.

d) Movement of Over dimensional consignments

e) Assessment of locomotives required

f) Location of Electric loco shed and trip inspection shed (see also para 1.22.g above)

1.2.4 Signal & Telecommunications

1.2.4.1 Survey

a) Existing signalling installations Data collection during field survey

b) Existing telecommunication Installations -do-

c) Department of Telecommunication's overhead track crossings. -do-
And a general idea of their installations along the route.

1.2.4.2 Items of designs and drawings to be finalized

a) Design of colour light signals at large and way side stations
   In accordance with approved policies of the Railway Board

b) Design of Telecommunication system incorporating the additional circuits required for electric traction
   -do-

c) Tapping Diagram for
   i) Remote control
   ii) Traction Power Control
   iii) Traction Loco Control
   In coordination with Electrical officer of Survey team and with approval of Open Line

d) Telecommunication facilities with Remote Control Centers and Supply Authorities’ load dispatch centers
   -do-

e) The sections on the route where Booster transformers and return conductor are to be provided
   To be finalised with DOT

f) Cost estimates of signaling & telecommunications works and of payments to DOT for taking up protection works against induction from traction currents
   -do-

1.2.5 Civil Engineering

1.2.5.1 Survey

a) For preparation of Roll Diagram To update the existing
Roll Diagram incorporating the existing ground conditions and doubling works in hand and in imminent future.

b) Of over-line structures:
   i) Through Girder bridges
   ii) Long deck type bridges
   iii) Flyovers & Road Over-Bridges
   iv) Tunnels

Drawings of Open Line to be verified and updated during the detailed survey

c) Re-modeling and track works in hand and under progress

During field survey

d) Soil conditions over the route

During survey

1.2.5.2 Finalisation of Designs

a) Plans for Modification to overline structures to suit ac traction clearances.

With the approval of Open Line

b) Designs of supports for OHE on bridge and in tunnels

With the approval of Open Line

c) Details of Plans to alter the track geometry through realignment, re-sleepering or remodeling etc.

Details are required to be incorporated in the survey sheets.

d) Site Plans for Service Buildings, loco sheds, staff quarters & Remote Control Center.

With the approval of Open Line

e) Land Acquisition Plans

To be coordinated with Civil District Revenue Official

f) Right of way including Land acquisition for Railway’s transmission line

-do-
g) Estimate of costs for civil Engineering works.

1.2.6 Finance

The finance office examines the cost estimates, the financial appraisal for the Project Report and all other financial details, essential to finalize the Project Report and the Abstract Estimate.

1.2.7 Approval of Drawings

To ensure the validity of the drawings and the designs finalised, these are required to be accepted by the Heads of the Departments of the Open Line organization. Accordingly, they should bear the signature of the concerned authorities, being given in token of approval. On the Open Line, generally, the Chief Electrical Engineer functions as the coordinating officer. However, for technical matters, the officers of the concerned disciplines of the survey team discuss and finalise the details with the Heads of the Departments of the open line.

1.2.8 Inclusion of Ancillary Works

Quiet often, works for infrastructure improvements such as Yard Re-modeling, Route Relay interlocking of other works not directly linked with Railway Electrification are required to be taken up concurrently by the Electrification team, being a suitable agency to execute such a work. It is essential that the survey team clearly identifies such work to ensure their allocation to the appropriate Head of Account, isolating them from the cost for Electrification works. This will ensure that the financial viability of the Electrification Project remains factual and the cost estimates remain within their legitimate Plan Heads.
CHAPTER 3
PRINCIPLES FOR WIRING PLANS, SECTIONING DIAGRAMS AND
GENERAL SUPPLY DIAGRAMS

1.3.1 General

OHE and Power Supply installations form a major portion of the cost of Railway Electrification. To estimate the accurate cost, route survey, finalized Pegging Plans and the General Power Supply Diagrams are required. This entails following steps of survey and drawing work:

a) Finalization of the Wiring Plan showing the tracks required to be wired.

b) Finalization of the Sectioning Diagram, which indicates the electrical sections in which the OHE is to be divided.

c) Finalization of the General Power Supply Diagram which gives schematic arrangement of equipments and remote controlled Circuit Breakers at the locations of the traction substations, Feeding Posts (F.P’s), sub-sectioning and Paralleling Posts (SSPs), and the Sectioning and Paralleling Posts (S.P’s) (which are all covered under the general term - Supply Control Posts).

d) Preparation of the Survey Plans based on the field survey.

e) Preparation of the Pre-pegging plan on the survey sheet, based on the information contained in items (b) and (c) above.

f) Preparation of the final pegging plan after site verification.

The first step in the above sequence of the plans is to obtain and update the Roll Diagram, finalize the wiring Plan in advance of the field survey so that the tracks proposed to be wired are surveyed in detail. The General Supply Diagram and the Sectioning Diagram may be finalized concurrently with the field survey, but prior to commencement of work on the OHE Pre-pegging Plans.

* For definition of different electrical sections of OHE denoted by elementary section, sub-sector and sector, see “Principles for Layout Plans and Sectioning Diagrams for 25 kV AC Traction, document No.ETI/OHE/53 issued by RDSO.”
The sections over the route where booster transformers and return conductor are required to be provided have to be finalized prior to the preparation of the General Supply Diagram. Also if it is decided to provide the 2x25 kV AT system, a prior decision on this account is called for.

1.3.2 The Roll Diagram

The roll Diagram forms the basis of the wiring plan. This is schematic diagram, which indicates the tracks existing on the ground i.e. on the open route, at stations and in yards. The basic plan is obtained from the Open Line and is updated by incorporating therein all the remodeling works taken up thereafter. The take off points of private siding (which may need to be wired) and those, which run alongside the tracks to be wired are also shown. It is also vital to indicate under a suitable legend the Remodeling and Doubling works in progress or in hand on this plan. Such works affect the design of traction overhead equipment. Those works, which have to be taken into account for the designs, have to be accurately and formally finalized with the Open Line officials. A specimen of Roll Diagram is shown in Fig. 1.3.1

![Specimen Roll Diagram](image-url)
1.3.3 The Wiring Plan

The wiring plan indicates the tracks, which are to be provided with traction overhead equipment for movement of electric stock. Yard lines such as sorting, classification, humping as well as sidings, should also be wired, so that the electric locomotives could be used for shunting and humping duties. Since optimizing the cost of electrification is the primary responsibility of the survey team, it is of great importance to the officers of the survey team to critically study yard movements so as to finalize the most economic yard wiring plans with the open line officials.

Generally, in the yards, reception lines receiving electrically hauled trains are wired in full, but only the top ends of the departure lines are wired (depending upon how placement is to be done on the departure lines).

Medical van sidings and loops are wired fully so that the van can be moved by first available electric locomotive in either direction. In some yards crossovers may exist between two wired lines but for shunting movement by non-electric engines only. These should be invariably wired to prevent OHE and locomotive pantograph damage, in the event an electric engine is routed over it inadvertently.

Generally the private sidings are required to be wired in accordance with current policy off the Indian Railways, the cost sharing being dependent upon the Agreement with the siding owner. In addition to achieving economy, there is need to optimize on the reliability and cost of repairs and maintenance of the OHE.

Yard derailments, might damage the OHE resulting in power having to be switched off not only of the damaged portion, but also the adjacent track for crane working. Sectioning/switching arrangement shall be made such that minimum section can be switched off. A specimen of a Wiring Plan for a yard is shown in 1.3.2
1.3.4 The Sectioning Diagram

1.3.4.1 Once the wiring plan is finalized, the next step is to make the sectioning diagram which indicates the electrical division of the OHE, in convenient parts so as to limit the portion, which can be isolated and taken out of service for either maintenance or due to breakdown, to a minimum portion permitting the rest for movement of electric stock and thus minimizing the dislocation to the train movement. However sectioning of OHE should be kept to the minimum in number, commensurate with traffic movement requirements such that it gives best possible reliability and availability of the OHE.
1.3.4.2 Main Principles of Sectioning

a) Main running lines and loops should be electrically separate from secondary lines and yard lines.

b) On double track section, OHEs of Up and Down tracks should be electrically separate. Unless it is inevitable the OHEs of Up and Down lines should be supported on separate structures.

c) Lines for different activities should be electrically separate. In yards, reception, dispatch, common exit and entry lines, engine run around lines, loco shed lines and sidings should be separated from each other.

d) Electric locomotive lines used for locomotive pit lines, and sidings where open wagons are loaded or unloaded, should be specially isolated at both ends through short neutral sections and shall be provided with earthing arrangement for the dead section at both ends, for the safety of personnel working close to OHE.

e) Opposite to feeding post either an insulated overlap or a PTFE section insulator or a PTFE type neutral section is inserted in the OHE.

f) At Sectioning Posts a neutral section is provided in the OHE (preferably PTFE type).

g) On main running line every block section should be separate from the adjacent block section.

h) Running lines immediately in rear of normal crossovers should be electrically separate, to enable use of crossover to divert a train, in case OHE in the rear of the crossover is not available for train movement.

i) On main running lines the sectioning should be such that the electrical insulated overlap is protected by a stop signal. This will permit direct reception of the train up to the stop signal even when there is a power block ahead of the stop signal.

j) At a wayside station, if a loop line has separate structures for OHE (Normally as it should be), having mechanical independence, the electrical isolation of the loop and the main line be staggered by having the loop section insulator located behind the loop starter and the insulated overlap for the main just beyond the turnout well in advance of the main line starter This will have the flexibility of
receiving a train on the loop if there is a power block on the main line section in rear of the starter signal, and of being able to dispatch a train from the main line when there is a power block in the traffic block section in advance of the station.

k) Sectioning in yards in addition to the provisions contained in section 1.3.4.2 (c) above, the reception and dispatch lines may also be segregated in groups of 3 or 4 lines to form separate electrical section, so gathering lines, locomotive run around lines, common entry and exit lines have special importance, hence power supply to these lines should be either from alternate feed arrangements or from a gantry with bus-bar arrangements to ensure their greater availability.

1.3.4.3 Reliability of Sectioning Arrangements

Excessive sectioning, resulting in having a large number of isolating switches, feeder wires and section insulators can reduce reliability while increasing the need for maintenance. It should be appreciated that any equipment installed needs maintenance and is also liable to fail. Section insulators, overlaps, and isolating switches need regular maintenance, which requires power blocks on both sides of such equipments. Power block taken on one side of a section insulator which has not been cleaned of soot is likely to fail at the very moment the power block is taken, leading to an unwarranted failure. Minimum sectioning, therefore, should be the aim while preparing the Sectioning diagram. Examples of sectioning are shown in Fig. 1.3.3.
FIG. 1.3.3
PRINCIPLES OF SECTIONING

SINGLE LINE WAY SIDE STATION

NOTE: LOCATE SSP SUCH THAT 25 KV FEEDER LENGTH IS SHORT.

DOUBLE LINE WITH COMMON LOOP ARRANGEMENT

SECTIONING FOR TRAILING CROSSOVER

BEST LOCATION FOR INSULATED OVERLAP PROTECTED BY STOP SIGNAL

LEGEND:
- ADVANCE STARTER TRACK WITH OHE
- UNWIRED LINE
- REMOTE CONTROLLED INTERRUPTOR
- SECTION INSULATOR
- INSULATED OVERLAP
- COLOUR LIGHT SIGNAL

MANUALLY OPERATED ISOLATOR
MANUALLY OPERATED ISOLATOR WITH EARTHING HEEL
SHORT NEUTRAL SECTION ASSEMBLY
NEUTRAL SECTION (OVERLAP TYPE)
SHORT NEUTRAL SECTION (WITH SECTION INSULATOR)

PURPOSE OF SECTIONING: TO DIVIDE O.H.E. IN SMALL ELECTRICAL PORTIONS WHICH CAN BE CONVENIENTLY ISOLATED FOR MAINTENANCE.
1.3.4.4 Remote Control

Having decided upon the sectioning of the OHE it is to be decided which section should have remote controlled circuit breakers and which should be provided with locally operated manual isolating switches. The sectioning diagram is now combined with the general supply diagram which shows the locations of the remote controlled switches at the Feeding, Sectioning and Paralleling, and the Sub-sectioning and Paralleling Posts. The physical location of these Posts as shown in the pre-pegging plans is finalised after site inspection. The final pegging plan contains the actual location of the overlap, the section insulator as well as the location selected for the supply control post.
1.3.5 The General Supply Diagram

1.3.5.1 The general supply diagram fixes the locations of the traction substations and supply control posts. Remote control and Tele-signalling of the status of the switches is effected at the Remote Control Centre on the console of the TPC. Other Remote control switches such as yard and loco shed circuit breakers & interrupters are also incorporated in the General Supply diagram. This diagram also forms the basis of RC equipment for the center and the control post.

1.3.5.2 Locations of Traction Substations or Feeding Posts (FP)

The basic consideration in locating the traction substations is to ensure satisfactory voltage condition on the OHE. While the maximum voltage at the substation should not normally exceed 27.5 kV, the voltage of the farthest end, based on the traction load conditions taking into account the traffic density, the loads and speeds of the trains and the terrain, with one substation taken out of commission, should not fall below 19 kV. The distance between traction substations decrease if the section has booster transformers and return conductor due to increase in impedance offered by them, if however the system chosen is 2 x 25 kV system, the distance between substations increases considerably, while designing the system, the spacing between substations is calculated for different scenarios of traction loads and system of supply and optimized. The method, of calculation is obtained in volume II. The location of the traction substation is also dependent upon the proximity of Supply authority’s substations. As a first approximation the distance between adjacent traction substations may be tentatively taken as under, how ever requirements of increase of traffic in future shall be taken care of:

System Distance (km)

25 kV with Booster Transformers and return conductors 40 – 50 Km
25 kV Without Booster Transformers 50 – 80 Km
2 x 25 kV AT system 80 – 100 Km

In arriving at the location of traction substations, apart from the above considerations, the practical need is to have them approachable by all weather roads, as well as to have minimum length of Railway’s EHV transmission line from the Supply Authority’s substation and site shall be decided considering these aspects as well. Also the site selected for the substation should be free from danger of flooding and water logging, be level, and need minimum amount of acquisition of land. The locations selected with these considerations will be the most suitable compromise and
economical as well.

It may in future be necessary to add more traction substations due to the increase in traffic and load. When such situation arises, the sectioning posts between the traction substations will need to be converted to feeding posts. This aspect shall be considered in advance and exercise shall be done to see how feeding arrangements will be done in such case. It may be noted that the interval between substations being dependent upon the sections to be provided with booster transformers and return conductor, finalization of this detail is a prerequisite to preparation of General Supply Diagram.

1.3.5.3 The Sectioning Posts (SP)

The conventional neutral section in the OHE at the Sectioning and Paralleling post is 41 m long and overlap type. The electric locomotive coasts through this dead section in case it comes to a halt under this portion of OHE, there being no power in the OHE, the electric locomotive becomes immobile. In such a situation it needs to be pushed or pulled by another locomotive to bring it under a live OHE. The site for location of the neutral section, therefore, needs to be selected with care, so that the terrain assists the train in negotiating it. Accordingly the neutral section for the Sectioning Post should be located on a straight track at sufficient distance from a stop signal either behind or ahead of it. In undulating terrain the neutral section should be located in a valley. Locating it on a rising gradient or on crest of hill is not desirable. In case a satisfactory location cannot be found, PTFE type short neutral section may be provided. Since such a neutral section requires more inspection and maintenance and still needs to be imported, its unrestricted use is not recommended.

Chief Electrical Engineers of Open Line often desire location of a neutral section at the territorial limits of their Railway. The Survey team should carefully examine this request. If it is established that by acceding to this desire there is no need to increase the total number of traction substations and suitable arrangements for extended power supply between the two Railways are possible, this may be agreed to. Accounting for cost of supply of power to the section on the adjoining Railway can be reckoned simply through calculating the average cost of energy used during the accounting period for the gross tonne km moved over the section fed by the substation.

1.3.5.4. The Sub-sectioning and Paralleling Post (SSP)

Between the Feeding post and the Sectioning post a number of intermediate Sub-sectioning and Paralleling posts are inserted in the OHE, to provide remote controlled switches for facilitating isolation of faulty sections of OHE. Stations having
large yards need to have an individual SSP so that the yards, loco sheds and other running lines are fed through individual remote controlled interrupters or circuit breakers. The block sections in between the SSP’s are isolated through manually operated isolating switches. Figure 1.3.4 shows a specimen of General Supply diagram.

1.3.5 The final Sectioning Diagram.

The final sectioning diagram indicates the entire sectioning, showing also the remote controlled switches as shown in the General Supply Diagram. It also shows the structure-number of the OHE structures on both the sides of the insulated overlap, the neutral section or the section insulator, across which the switches are located. These details are taken from the finalized pegging plan.
CHAPTER 4
FOOT-BY-FOOT SURVEY

1.4.1 General

In order to prepare the designs of Overhead Equipment Layout, forming the basis of the Project construction work, a detailed foot by foot survey of the route proposed for Electrification is taken up. This survey forms the basis of Survey Sheets. These sheets are prepared to scale, the longitudinal scale being 1: 1000 in open route and 1: 500 within station limits and in yards. The sub-scale chosen for cross sections is 1: 200. On these sheets the OHE structures and anchor foundations are marked according to the Principles for OHE Layout Plans and Sectioning Diagrams for 25 kV ac traction - Document No. ETI/OHE/53 with A&C Slip No.1 to 4 issued by RDSO. These plans, called pre-pegging plans are then verified at site and modified to site conditions and finalised. The final plan thus issued is called the Pegging Plan and forms the basis for estimation of quantities, the cost estimates and for schedule of quantities to tenders for OHE construction Contracts. Bonding and earthing plans and plans for modification of power distribution line at stations and yards are also prepared based on these survey plans. Preparation of accurate detailed survey plan, therefore, cannot be overemphasized.

1.4.2 Field Book

A Surveyor’s field book is required to be maintained in which all the details obtained during the survey should be entered. These details are transferred to field sketches. Such sketches are then sent to the Drawing Office to enable preparation of Survey plans. The entries in the field book should be dated and progress recorded in accordance with increasing chainage. Details entered should include important features along the track and their offset from the center line of the nearest track. The chainage of location where embankment changes to level ground or level ground to cutting or vice versa should be recorded as these are needed to finalise the foundations for OHE structures. Continuous features, such as, Track centers, width of ccess, offsets to continuous running drains, fences or pipes, cables; either on surface or buried underground, should be recorded at every 50 m intervals on open route and at every 25 m intervals in yards and within stations limits. Cross section of the route at intervals of 250 m should also be measured and recorded.

1.4.3 Important Features to be noted.

These are:

a) Track centers between all tracks.
b) Track structure i.e. type of sleeper, depth of ballast, width of cess, embankment, level or cutting. The programme of track works such as re-sleepering with prestressed concrete sleepers, deep screening of ballast or rail renewal works, which affect the track levels and/or alignment, should also be ascertained and noted.

c) Details of cross section every 250 m.

d) Type and condition of soil every 250 m and at geologic discontinuities.

e) Buried water mains, and cables and their runs alongside and across tracks.

f) Signal and location boxes, signal wires, point rods, cranks and signal cables.

g) Signals: Main, Routing, Shunt; their type and track for which meant, distance from the center line of track.

h) Buildings, huts, platforms, other structures such as columns for over-bridges, abutments of road over-bridges.

i) Platform shelters, their profile across tracks, height and distance of columns, and edges of shelters from adjacent track.

j) Turnouts, crossovers, and diamond crossings, their deviation numbers viz. 1 in 8.5, 1 in 12 or 1 in 16; chainage of the fouling boards/marks; track centers at toes of turnouts and at the fouling boards/marks.

k) Water columns, ash pits and steam blow-down pits

l) Fuelling points for Diesel locomotives

m) Metallic circuits (electric, low or high tension; signal; or telecommunications) running parallel to tracks and their distance from adjacent track centers.

n) Fencing: Metallic or otherwise, running along tracks, chainages of their beginning and end, and their distance to adjacent track at regular intervals; their type of construction.

o) Overhead wire crossings of tracks: Telecommunications (Railway or belonging to Department of Telecommunications); signaling; and power (including their ownership), their voltage and clearances from each track crossed; if the voltage
of the power line is 33 kV or above the angle of crossing and also the location of two adjacent supports on either side of the tracks.

p) Overline structures such as Road over-bridges, Flyovers, foot over-bridges and signal gantries: their vertical clearances from each track spanned, and horizontal distances of their support columns or abutments from the adjacent tracks; if the overline structure has smoke baffle plates, the clearance to the lowest member of the structure should be recorded. A sketch of the cross – section across the tracks giving the leading dimensions is required to be prepared.

q) Curves: Whether right hand or left hand as seen in the direction of increasing chainage; the degree of curvature, and the chainage of tangent points both at the beginning of transition and of main curves; versines in mm are taken every 50 mm with nylon cord for the entire curve. The super-elevation as found at site should be recorded as per Table 4.1 (at the end of the text) giving the value of versines of uniform circular curves over spans of 25 m and 50 m for BG track. Actual versines measured at the site may be different depending upon the disturbance the track has suffered since its last realignment.

r) Level Crossings: their chainages, and location of gate lodges, whether manned or unmanned and location of gate signals, if any. Special note should be made of level crossings on important roads or those giving access to main roads (this is useful during construction and subsequently for maintenance). It is prudent to get the Information about the nearby airports if any from civil aviation.

s) Locations of gradient posts and signal location marker posts.

t) Culverts and bridges: Chainage of their abutments, peers, trolley Trolley and man refuges; whether culverts or long bridges, if so whether deck type or through girder type. For through girder type the head room at entry portals. Sketch showing plan and elevation of the piers and the entry portals are also required. Location of alignment of water mains, cables and open wires running on the bridge structures should also be noted.

u) Tunnels: their chainages and profile, whether lined or unlined, location of trolley and main refuges, areas with extensive water seepage, arrangements of water drainage, and location of drains.

v) Identification and extent of exposed Locations: Areas where full wind effects are likely to be encountered by OHE structures and termed ‘Exposed locations’ should be noted down. These are generally encountered on approach
embankments to long bridges and on them, high bare grounds and in valleys subject to funnel effect of wind.

w) Identification of polluted Locations: Areas adjacent to factories and power stations having high ambient pollution particles should be identified and recorded.

1.4.4 Field Survey

To ensure accuracy only steel tape or fiber glass/plastic coated tape should be used for measurements. Yellow point or crayon marks should be marked on the web of the rail along which measurements have been made every 25 m. On curves the chainage should be taken along the outer rail of the middle track when there are odd numbers of tracks. If there are even numbers of tracks the chainage should be taken along the inner rail of the first track outside the center line of the group of tracks. At the point of start ‘Zero’ chainage is taken. While proceeding along the tracks the features detailed in paragraphs 1.4.2 and 1.4.3 are recorded indicating their chainages and offset distances. When the next kilometer post is recorded, Chainage distance with respect to the new km post is commenced afresh. Thus chainages are taken from one km post to the next.

1.4.5 Overline Structures

The headroom available under on overline structure is an important parameter, the design of OHE under it being governed by this parameter, it is necessary to mark the track level on the adjacent support column with yellow paint and use this reference mark to measure the headroom. This reference point is essential to be made permanent subsequent to survey else it may lead to great confusion later on while providing the electrical clearance to OHE and may radically affect the solutions to provide adequate electrical clearance which are found after a detailed study subsequent to field survey. Accordingly, all locations under overline structures having restricted clearance need careful watch.

1.4.6 Soil Characteristics

The survey of soil characteristics every 250 m should also include its type and bearing pressure capacity. Samples of the soil should be collected and sent to a soil mechanics test laboratory to obtain the type of soil and its bearing pressure. This information is required to be recorded on the survey sheet.

1.4.7 Curve Realignment
While measuring versines on curves if it is found that the figures are not uniform as should be found for a circular curve of that degree. It may be necessary to have the track examined by the open line permanent way engineers and get the curves realigned prior to finalization of designs of OHE. Similarly, the super-elevations may also be adjusted to the designed values. This will ensure that the OHE designs have been appropriately made for the designed track layout minimizing subsequent adjustments during operation of the service.

1.4.8 Proposal to alter the track geometry

During the survey it is essential to obtain from the line details of such works which may alter the track geometry and which may be taken up earlier than the anticipated programme of electrification such as:

- Provision of pre-stressed concrete sleepers, resulting in rising of track level.
- Realignment of curves for higher speeds, needing longer transition curves and higher super-elevation.
- Easing of gradients.
- Re-modeling of yards, and doubling works.
- Replacement of lower speed turn-outs to higher speed turn-outs.

1.4.9 Programme of improvement to track structure

As OHE is erected to suit the track, if any subsequent alteration to the erected OHE has to be done it is difficult and expensive. It is, therefore advantageous to advise the open line to complete the works prior to taking up the OHE work. The survey Plans should, indicate the existing track layout as well as the altered location with respect to the existing track after improvement. Details of such improvements should be invariably obtained through joint dispatch with open line officials during foot by foot survey.

1.4.10 Field Sketches

The data recorded in the field books by the surveyor should be promptly transferred to field sketches as the survey proceeds. This will ensure the missing details which can readily be collected by another visit to the site which may be either in progress or likely to commence soon. Each vertical line denotes distance of 50 m on open route and 25 m in yards and station limits. The horizontal lines represent center lines of tracks.
Major yards having more than five to six lines may need special sketches to be made as required to suit the geographical conditions. Each sheet may contain details for 250 m of track and have at least one cross-section of the route. All details should be carefully recorded, as this forms the basic document for preparation of the survey sheets. All distances should be in meters and the versines in milli-meters.

1.4.11 Survey Sheets

The preparation of survey sheets is done in the drawing office sequentially on receipt of the field sketches.

1.4.12 Table of Versines on Broad Gauge.

Table 1.4.1 with values of versines on spans for 50 m and 25 m on curves, along with the formula obtaining these values is given below:

Table 1.4.1: Versine in mm on spans or 25 m & 50 m on curves

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Degree of Curve (m)</th>
<th>Radius of Curve (m)</th>
<th>Versine (mm) for a span</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>25 m</td>
</tr>
<tr>
<td>(1)</td>
<td>10</td>
<td>175</td>
<td>447</td>
</tr>
<tr>
<td>(2)</td>
<td>6</td>
<td>292</td>
<td>268</td>
</tr>
<tr>
<td>(3)</td>
<td>5</td>
<td>350</td>
<td>224</td>
</tr>
<tr>
<td>(4)</td>
<td>4</td>
<td>438</td>
<td>179</td>
</tr>
<tr>
<td>(5)</td>
<td>3</td>
<td>583</td>
<td>134</td>
</tr>
<tr>
<td>(6)</td>
<td>2</td>
<td>875</td>
<td>89</td>
</tr>
<tr>
<td>(7)</td>
<td>1 ½</td>
<td>1164</td>
<td>67</td>
</tr>
<tr>
<td>(8)</td>
<td>1</td>
<td>1747</td>
<td>45</td>
</tr>
<tr>
<td>(9)</td>
<td>¾</td>
<td>2328</td>
<td>33</td>
</tr>
<tr>
<td>(10)</td>
<td>½</td>
<td>3492</td>
<td>22</td>
</tr>
</tbody>
</table>

Note 1: These figures apply to uniform curves. The versines of transition curves at the two ends of the curves are lower.

Note 2: $1^\circ$ curve is defined as that when in 100 ft (30.48 m) turns through $1/360^{th}$ of a complete circle.
Annexure 1.4.1

Standards for Drawings for OHE Layout Plans

1. Scope:

All drawings of OHE Surveys, Pre-pegging, Pegging and OHE lay out plans, as well as Sectioning Diagrams shall comply with the standards laid down in this specification.

2. Size of Drawings

The standard size shall be A4 i.e. 210 x 297 mm or any integral multiple of this size either in length or height or both, such as:

<table>
<thead>
<tr>
<th>Trimmed size of Print</th>
<th>Corresponding size of Tracing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td></td>
</tr>
<tr>
<td>210,420,630,840</td>
<td>240, 450,660,870</td>
</tr>
<tr>
<td>or 1050</td>
<td>or 1080</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>330,630 or 930</td>
</tr>
<tr>
<td>297,594 or 891</td>
<td></td>
</tr>
</tbody>
</table>

A border line should be provided within the trimmed print 15 mm below the edge of the drawing.

3. Folds in the Drawing:

All drawings shall be prepared and trimmed such that they can be neatly folded differently up and down and finally presented in 210 m x 297mm size without any parts of the folds being short or overlapping and ensuring that the title of the drawing is exposed in the top fold so that it is identified without opening the folds. Short fold marks may be made on the border line of appropriate intervals so as to facilitate their folding accurately and neatly.

4. Orientation of the Drawings:

All plans of tracks shall be prepared in such a manner that the distance from the reference terminal increases from left to right.

5. Scale:

Following scale shall be adopted for the survey plans:
Along the tracks  
Across the tracks.

| Open route | 1:1000 | 1:500 |
| Stations & yards | 1:500 | 1:250 |

The scale adopted shall be clearly indicated on the top sheet at the appropriate place on the title sheet.

6. Lettering:

Standard square upright lettering of the following dimensions shall be used as necessary

Min titles : 5, 8, 10, or 12 mm

Sub titles : 4 or 6 mm

Notes, legends or dimensions : 2 or 3 mm

7. Layout of the legends Panel and Title Sheet:

An uniform standard panel shall be adopted. A specimen is at Fig. 1.4.1A.1

8. Symbols:

The symbols adopted for different items shall be uniform and in accordance with the drawing in Fig. 1.4.1A.2.
CHAPTER 5
PREPEGGING, PEGGING AND LAYOUT PLANS

1.5.1 General

Prepegging plans are prepared based on the survey sheets in accordance with the “Principles for OHE Layout Plans and Sectioning Diagrams for 25 kV a.c. traction” issued by RDSO. The aim is to provide the most economical support arrangement for the catenary system, being technically sound for the maximum traction current expected and the maximum number of pantographs expected in a span. The prepegging plan is superimposed in soft pencil on print of the survey sheet. After a number trials, the best plan providing for least number of structures, called the ‘Prepegging plan’, is got ready for check at site for its feasibility. This plan is sent to site for marking out the location of structures and anchors on the adjacent rail. A joint inspection of the site is then conducted, by Electrical (OHE designs), Civil, and Signal & telecommunications engineers. During the inspection the plan is verified, and if required, modified to suit the field conditions. At this time the Civil and the Signal and Telecommunications engineers also make out their plans for track slewing, shifting of drains, pipes, or signal point rods, cranks etc, to create space for the foundations for the OHE structures and their anchors. The site verified plan is then finalized as ‘Pegging Plan’ and is available for use for tendering for the contract for field work and for estimation of quantities. On award of the contract for field work, the pegging plan is once again verified by the contractor jointly with project electrical (OHE) Engineer prior to taking up the field work. The plan actually followed for field work, incorporating further details of type of structures used, the style of the cantilevers used, the stagger of the OHE conductors, the run of wires, portal spans as well as the setting distances of the structure legs becomes the ‘OHE layout plan’. This plan is a record to be kept for proper maintenance of the equipment after commissioning. The prepegging and the pegging plans are finalized in series in increasing chainages without leaving any gap in between. There may be exceptions where yard remodeling, doubling or any other work involving insertion of turnouts and crossovers are contemplated but not taken up or not marked at site. The field party of the survey organization takes up the site marking and assists in the verification of the plan.

1.5.2 Particular Specification

Prior to commencement of work on prepegging plan, the site conditions and the specific design of the equipment to be adopted needs to be finalized. Based on those parameters, known as particular specifications, the various details of the designs are adopted.
1.5.2.1 Meteorological conditions

a) The maximum, the minimum and the mean ambient temperatures:

The mean temperature adopted over the entire Indian subcontinent is $35^0\text{C}$ with a range of $15^0\text{C}$ to $65^0\text{C}$ as the minimum and the maximum is followed for India for the northern plains. With colder winters, this range is $4^0$ to $65^0\text{C}$. For unregulated OHE a contact wire height at supports of 5.65 m for the former range and of 5.75 m for the latter range of temperatures. The contact wire height of regulated OHE is uniformly kept as 5.60 m at supports. The wide variations the limit the length of the OHE between the anticreep central mast to the balance weight anchor mast. The movement of the balance weights on the masts due to thermal expansion and contraction of conductors being limited as also to limit the swing of the bracket assemblies nearer the balance weights. For both the temperature ranges a maximum length of 750 m from anticreep to the balance weight anchor mast is prescribed. Inside the long tunnels the temperature ranges are much lower and, therefore advantage may be taken of this fact for specially designing the passage of OHE through them by minimizing the number of anticreep and balance weight anchors.

b) Wind speed zone

It is to be ascertained from IS: 875-1987 as to in which wind zone area the section to be electrified falls. This will decide the maximum permissible span and the relevant employment schedule for the design of structures and foundations.

c) Identification of “Exposed Locations”

As ascertained during foot by foot survey [refer paragraph 1.4.3 (v)] the exposed location which are likely to have maximum severity of wind velocity should have the maximum permissible span reduced by 4.5 m in line with item (b) above.

1.5.2.2 Design Parameters

The design parameters and the type of equipment to be adopted are required to be specified in regard to the following:

a) Choice of Portals or individual masts at stations and on multi-track (more than two tracks) sections: whether portals spanning all the wired tracks are to be provided or
individual masts should be provided, if the track centers permit. Whether head spans are to be used for yard lines, and if so, where?

b) Sections of open route and yard lines where regulated/unregulated OHE is to be used.

c) Choice of the type of OHE for:

i) Main lines: Choice between copper conductors and Aluminum conductors or any other

ii) Sidings and yards: Choice between conventional OHE with catenary and contact wire or tramway type of equipment. For tramway type whether the equipment is to be regulated.

a) Choice between the use of portals and independent masts on the open route, stations and yards.
b) Use of head spans.
c) Choice between regulated and unregulated equipment on open route and in yards.

d) Booster transformers and return conductors: The decision jointly arrived at with the Department of Telecommunications, of the sections over which these are to be provided.

e) Decision to use 2 x 25 kV AT system: A decision jointly arrived at with the open line Railway whether this system is to be adopted: If the Department of Telecommunication require Booster transformers and return conductor over the concerned section, their consent to the use of this system in lieu of the provision of booster transformers and return conductors is also necessary.

f) Finalization of track slewing plans for yard or secondary lines to locate OHE structures in the identified lanes.

1.5.2.3 Movement of Over Dimensional Consignments (ODCs)

The minimum height of the contact wire under heavy overline structures is normally kept such that class “C” ODCs of height 4.80 m can be moved at unrestricted speed with electric locomotives. At heavy overline structures such as through girder bridges, road-over bridges or tunnels having low clearances, and where modifications may not be feasible or the cost excessive, a decision may have to be taken in regard to their passage such as:
a) Whether adequate clearance may be provided to move with electric locomotive of restricted speed.

b) Whether the ODC can be diverted through, another line not spanned by the overline structure.

c) Whether only one line on a multitrack section under the overline structure can be nominated to move the ODC with electric locomotive.

d) Whether the ODC can be moved with 'power off' on OHE by a non electric engine, ensuring only adequate physical clearance.

e) Or whether the ODC should not be permitted under the over-line structure, nominating on alternative route through which the ODCs should be diverted.

1.5.3 Principles of Pegging Plans

It is essential to be conversant with “Principles for layout Plans and Sectioning Diagrams for 25 kV ac Traction”, documents No.ETI/OHE/53 with A&C Slip no.1 to 4 issued by RDSO before attempting preparation of prepegging plan. Some important principles, however, are brought out in the following paragraphs for ready reference.

1.5.3.1 Span Lengths

Span lengths are chosen in multiples of 4.5 m the shortest span adopted is 27 m and the longest is 72m. The longest span is a function of wind pressure of area and type of equipment etc. The difference between two consecutive spans should not exceed 18 m. Non standard span lengths are permitted only if special conditions do not permit choice of standard span sizes, such as on bridge piers, or on a bridge structure. The maximum span lengths should be aimed at on tangent track. On curves, turnouts and cross-overs, the span lengths are less governed by the maximum permissible stagger of the contact wire at the structure and in the middle of the span; this limitation is guided by the pantograph, its sway and blow-off of OHE conductors due to wind. As a general rule, the maximum stagger at a structure should not exceed 300 mm on curves and 200 mm on tangent track. Mid span staggers should also not exceed the figures prescribed by RDSO.

1.5.3.2 The setting Distance (Implantation) of structure

The Setting distance to be provided are:
a) For individual masts carrying one OHE:

i) ON tangent track

<table>
<thead>
<tr>
<th></th>
<th>Existing work</th>
<th>New electrification work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>2.50 m</td>
<td>2.80 m</td>
</tr>
<tr>
<td>Minimum *</td>
<td>2.36 m</td>
<td>2.80 m</td>
</tr>
</tbody>
</table>

(Note: * In special circumstances with prior approval of the Chief Electrical Engineer of the Railway)

iii) On curves

<table>
<thead>
<tr>
<th>Degree of curve</th>
<th>Radius of Curve in m</th>
<th>Setting Distance in m</th>
<th>Existing work</th>
<th>New work</th>
</tr>
</thead>
<tbody>
<tr>
<td>In side curve</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero to ½</td>
<td>0 to 3500</td>
<td>2.90</td>
<td>3.20</td>
<td></td>
</tr>
<tr>
<td>½ to ¾</td>
<td>3500 to 2350</td>
<td>3.05</td>
<td>3.35</td>
<td></td>
</tr>
<tr>
<td>¾ to 1 ½</td>
<td>2351 to 1150</td>
<td>3.25</td>
<td>3.55</td>
<td></td>
</tr>
<tr>
<td>½ to 6</td>
<td>1151 to 300</td>
<td>3.30</td>
<td>3.60</td>
<td></td>
</tr>
<tr>
<td>Outside Curve</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero to 2</td>
<td>0 to 875</td>
<td>2.50</td>
<td>2.80</td>
<td></td>
</tr>
<tr>
<td>Above 2</td>
<td>less than 875</td>
<td>2.65</td>
<td>2.95</td>
<td></td>
</tr>
</tbody>
</table>

b) For a Portal upright or a head span leg or a mast carrying more than one OHE the setting distance adopted should not be lesser than 3.00m and 3.30m for new works.

c) Lower setting distances permissible on curves:

If the stipulated standard setting distances mentioned in subparagraphs (a) and (b) above cannot be obtained, lower setting distances up to a minimum setting distance as permitted in the schedule of fixed structure as provided in the “Schedule of Dimensions 1676 mm Gauge” a slewing allowance of 150 mm should be added; to this a curve allowance for the degree of curve should be added. The curve allowance for different degree of curves and for different speed potentials are given in the “Schedule of Dimension 1676 m Gauge” and in tables I, II and of RDSO’s document No.ETI/ OHE/53 (6/88) with A&C Slip no.1 to 4. Principles for layout plans and sectioning Diagrams for 25 kV ac Traction. Table 1.5.1 gives the curve allowances for different speed potentials.
by combining in one table, the tables I and III of the RDSO’s Document No. ETI/OHE/53 with latest amendments.

Table 1.5.1 Curve Allowance for Broad Gauge

Extra clearances to be provided to OHE structures

<table>
<thead>
<tr>
<th>Degree Of curve</th>
<th>Maximum speed Permitted Km/h</th>
<th>Super Elevation (mm)</th>
<th>Extra Clearance mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>In side curve</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>½</td>
<td>200</td>
<td>71</td>
<td>191</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>40</td>
<td>89</td>
</tr>
<tr>
<td>¾</td>
<td>200</td>
<td>133</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>60</td>
<td>159</td>
</tr>
<tr>
<td>1</td>
<td>190</td>
<td>185</td>
<td>575</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>100</td>
<td>295</td>
</tr>
<tr>
<td></td>
<td>105</td>
<td>50</td>
<td>130</td>
</tr>
<tr>
<td>1½</td>
<td>155</td>
<td>185</td>
<td>585</td>
</tr>
<tr>
<td></td>
<td>105</td>
<td>75</td>
<td>220</td>
</tr>
<tr>
<td>2</td>
<td>135</td>
<td>185</td>
<td>590</td>
</tr>
<tr>
<td></td>
<td>105</td>
<td>100</td>
<td>310</td>
</tr>
<tr>
<td>3</td>
<td>110</td>
<td>185</td>
<td>605</td>
</tr>
<tr>
<td></td>
<td>96</td>
<td>120</td>
<td>390</td>
</tr>
<tr>
<td>4</td>
<td>95</td>
<td>185</td>
<td>620</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>125</td>
<td>420</td>
</tr>
<tr>
<td>5</td>
<td>85</td>
<td>185</td>
<td>640</td>
</tr>
<tr>
<td></td>
<td>72</td>
<td>120</td>
<td>420</td>
</tr>
<tr>
<td>6</td>
<td>80</td>
<td>185</td>
<td>655</td>
</tr>
<tr>
<td>7</td>
<td>56</td>
<td>125</td>
<td>470</td>
</tr>
<tr>
<td>8</td>
<td>48</td>
<td>140</td>
<td>540</td>
</tr>
<tr>
<td>9</td>
<td>48</td>
<td>140</td>
<td>550</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
<td>120</td>
<td>500</td>
</tr>
</tbody>
</table>

1.5.3.3 Location of obligatory structure

There are certain point on the track, within a few metre of which an OHE structure must be provided. These are, for example, at turnouts and crossovers or adjacent to overline structures. These OHE structures are called ‘Obligatory Structures’. While commencing a pegging plan it is convenient to commence from an obligatory structure
at a turnout or a crossover. An OHE structure should be located within 2 m of the theoretical center of a turnout. If this is found not feasible as an exception the structure may be located farther away. The maximum distance from a center of a turnout that where a structure can be located is indicated in Table 1.5.2. In all cases the contact wire stagger at structures and at mid spans should be verified during site verification of the pegging plan. During the site survey the location of the section insulator, if required to be provided should also be fixed. The span under the overline structure should not exceed 54 m to limit the amount of push up of catenary by the upward thrust of the pantograph; also the structures supporting the OHE should be more or less equidistant from the center line of the overline structure to ensure maximum clearance. Passage of OHE under overline structures having restricted clearance has to be designed specially through a “Profile Study”. Such a study fixes the location of OHE structures, the span lengths to be adopted under and adjacent to the overline structure, along with the contact wire gradient and the encumbrances at the supports.

<table>
<thead>
<tr>
<th>No. of Turn-out</th>
<th>Distance from center of turnout − out to:</th>
<th>Maximum, distance permissible from center of turnout to the OHE Structure, towards</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Toe (m)</td>
<td>Nose (m)</td>
</tr>
<tr>
<td>1 in 8 ½</td>
<td>11.15</td>
<td>14.30</td>
</tr>
<tr>
<td>1 in 12</td>
<td>15.15</td>
<td>20.15</td>
</tr>
<tr>
<td>1 in 16</td>
<td>20.10</td>
<td>26.85</td>
</tr>
<tr>
<td>1 in 20</td>
<td>23.75</td>
<td>33.50</td>
</tr>
</tbody>
</table>

This is based on the fact that on a turn out, although the contact wire for the main track is appropriately placed for the pantograph of a locomotive running at full speed, the contact wire of the turn out should also be within stagger (± 300mm at support and the appropriate mid span stagger for the turn out span) as given in Para 1.3.3.1. The curvature on the turn out requires stagger of 300 mm in all cases the main track. Further there should be a horizontal separation, between the two contact wires of minimum of 50 mm and a maximum of 200 mm at support to ensure non-interference between two OHEs and smooth changeover of contact wire for the pantograph of the locomotive negotiating the turn out.
This is possible, if the obligatory structure at a turn out is located at any point between the track separation of 150 mm and 700 mm, irrespective of the number of the turn out, as would be clear from the Figure 1.5.1.
PERMISSIBLE TRACK SEPARATION OF 700mm

Fig. 1.5.1(a)

 STRUCTURE LOCATION TOWARDS NOSE AT MAXIMUM
PERMISSIBLE TRACK SEPARATION OF 700mm

NOTE: ALL DIMNS. ARE IN mm.

Fig. 1.5.1(b)

 STRUCTURE LOCATION TOWARDS TOE AT MAXIMUM
PERMISSIBLE TRACK SEPARATION OF 150mm

NOTE: ALL DIMNS. ARE IN mm.
1.5.3.4 Location of OHE Structures in advance of a Signal

OHE Structure should not be located nearer than 10 m behind and 30 m in advance of a signal. For proper visibility of a signal, a larger setting distance is given to a few OHE structures in advance of a signal. For Semaphore signals a larger setting distance is required for 5-OHE structures, with the one immediately in advance having a minimum setting distance of 3.05 m, followed by the next one at 2.9 m and the next three consecutive structures having a minimum setting distance of 2.75 m. For colour-light signals, the minimum setting distances are regulated up to 600 m in advance of the stop signals and up to 300 m in advance of a signal with route indicators. The forbidden zones for location of OHE structures are diagrammatically shown in fig 1.5.2 as ready reference. On curved track, depending upon the topography and curvature, the structures, should be so located as to ensure the best continued visibility of signals. In such cases the setting distances and the lanes for location of OHE structures.
structures should be fixed by a joint field inspection of Electrical Engineer (OHE designs) engineer with the signal Engineer.

1.5.3.5 The location of overlaps

The insulated overlaps are located at the appropriate sites selected for the subsectioning and paralleling posts (Neutral sections are required to be provided at the sectioning and at feeding posts), the locations for the manually operated isolating switches, and for the booster transformers stations; all of these having been finalized in the sectioning diagram earlier. Having located the insulated overlaps the uninsulated overlaps are inserted ensuring longest tension lengths, the effort being to have minimum number of overlaps in the section. There is a limit of 750 m between the anti-creep central mast to the corresponding balance weight anchor mast at the overlap for regulated OHE. This restriction limits the tension length to minimum 1500 m. For unregulated OHE no anti-creeps are required and the maximum tension length of conductors is increased to 2000 m. In case the insulated overlap is on a curve having a radius of 5000 m or sharper (0.35 degree) a four span overlap becomes necessary for this a central overlap OHE structure is provided with two brackets at different elementary sections. To ensure satisfactory clearance between the two brackets, the distance from anti-creep to the center of the 4-span insulated overlap is limited to 600 m. Maintaining appropriate clearances at the conventional overlap central mast is difficult. Also there is a need to take power block on two elementary sections for maintenance of such overlaps, locations of insulated overlaps on curves should be therefore avoided as far as possible. The tension lengths of conventional overlap type of neutral section and at short neutral section are limited to 600 m. The overlaps should be so adjusted that their location at the station does not result in use of three bracket structures. If provision of the un-insulated overlaps between the predetermined location of insulated overlaps results in tension length of 750 m or lower (600 m if adjacent to 4 span insulated overlap or adjacent to a 41 m neutral section), a half tension length of OHE, having one end as fixed termination may be adopted, omitting the anti-creep.

1.5.3.6 Location of Section Insulator.

The total weight of the section insulator including the weight of the two insulators on the OHE and of the copper runners is 55 kg. To accommodate the two insulators for both the conductors and to permit the locomotive pantograph to glide over the two runners of the section insulators there is a requirement of a minimum dropper length 450 mm and a maximum permissible stagger of 100 mm at the location of the section insulator. Since the maximum encumbrance at the OHE structure is limited to 1.4 m, this imposes a limit to the sag and therefore, the distance of the section insulator from the nearest OHE support. This limit is given in Table 1.5.3 below. In view of the limit of
100 mm of stagger, this should be achieved by adjusting the staggers at the adjacent OHE structures during site verification of the prepegging plan.

Table 1.5.3

Maximum permissible distance of section insulator from nearest OHE structure, having 1.4 m encumbrances of the span, applicable for regulated OHE with 107 mm$^2$ contact wire and 65 mm$^2$ catenary at 1000 kgf tension in each,
Weight of section insulator = 55kg
All dimensions in m

<table>
<thead>
<tr>
<th>Span</th>
<th>72.0</th>
<th>67.5</th>
<th>63.0</th>
<th>58.5</th>
<th>54.0</th>
<th>49.5</th>
<th>45.0</th>
<th>&lt;45.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>7.7</td>
<td>8.1</td>
<td>9.4</td>
<td>12.3</td>
<td>13.5</td>
<td>15.0</td>
<td>18.2</td>
<td>no limit</td>
</tr>
</tbody>
</table>

At a turnout the section insulator assembly should be located beyond the Nose of Crossing with runners facing away from the center of turn out. It is a good Design practice to locate the OHE mast towards the Nose so as to make the Span over the turnout short permitting wider latitude in location of the section Insulator and having adequate latitude in the section of suitable staggers at the Structures in order to achieve the stagger of contact wire below 100mm under the section insulator.

1.5.3.7 OHE at a turnout

On main running lines the OHE of the turnout should have overlap type of equipment. On secondary lines this may be crossed type to reduce the cost. The turnout OHE taking off from the main line should be regulated and have both, the contact wire and the catenary. The OHE for a secondary line taking off from a loop line may be either unregulated or tramway type. Three Brackets assemblies at a turnout structure should be avoided, as adjustments to the OHE are difficult. As mentioned in paragraph 1.5.3.5 above overlap multi-cantilever OHE supports should be suitably located, away from turnout structures.

1.5.3.8 OHE at Special Locations

a) Adjacent to overline structures:

Prior to preparation of OHE prepegging plan in vicinity of a heavy overline structure the clearance study should be completed. In case of restricted clearances the profile drawing should be prepared in advance for incorporation in the OHE prepegging plan.
b) On long bridges:

The spans on long bridges are dictated by the location of the piers on which the OHE structures are located therefore these are usually non standard. On through girder bridges the OHE may have to be supported on specific members of the trusses, as such the design of OHE on such a bridge may be finalized subsequently, without delaying the finalization over the rest of route. However, the feasibility of location of the OHE support must be established in advance during the survey.

c) In tunnels:

The design of OHE in tunnels require careful study. The spans are required to be kept short as it becomes difficult to obtain adequate headroom for large encumbrances. Unless the tunnel is long, anticreep and overlaps should not be located inside the tunnel. For long tunnels one method to avoid the anti-creep is to erect unregulated OHE. Efforts should be made to avoid imposition of speed restriction on account of OHE inside the tunnel. A detailed examination of the local conditions inside a tunnel is required before finalizing the design of OHE.

1.5.4 Provision of Remodelling

Yard remodeling works or doubling works may also be in progress. If the electrification work is expected to be taken up either after the remodeling or has to take into account such remodeling, the design of OHE should take into account such works in the prepegging plan. Accordingly the proposed locations of toes of turnouts and the alignment of the new track should be jointly examined by the civil engineer in charge of the track construction plan and should be finalised.

1.5.5 Preparation of prepegging plans

The drawings should be of standard size and follow the standard orientation of the top sheet and the direction of progress. The exercise for preparation of the pre-pegging plan should commence in soft pencil on a print of the survey sheet. It may begin from an obligatory structure at a turnout on one main line and structures marked according to the guidelines. Adjusting the location of structures, to minimise their number, and those of the location of the overlaps, anti-creeps and anchors to the most suitable locations may need number of attempts. At locations where portals can not be used, main and loop line cantilevers may be located in an ‘umbrella’ fashion on a common mast,
provided they are on the same elementary section. Number of brackets on a mast, the anchors, return conductors, earth wires, and 25 kV feeders should be clearly marked. After the trials, when the plan is considered satisfactory, the structure numbers and their chainages are marked. This plan is now transferred to the inked tracing of the survey sheet in SOFT PENCIL, so as to erase and incorporate the changes, if required, after site verification of the plan. To confirm the feasibility of the plan during site verification the prepegging plan should include the following details:

a) Anchors – Balance weight, fixed termination, and anti-creep for OHE: 25 kV feeders, return conductors and earth wire.

b) Anti-creep central masts – indicating thereon the number of spans and distance in meter from the balance weight anchors.

c) Multiple cantilevers – for overlaps, turnouts and out of run wires.

d) Overlaps – insulated, un-insulated, or neutral section: the insulated overlaps being at the location selected for the supply control post, manually operated isolating switch or for booster transformer.

e) Conductors – OHE return conductors, 25 kV feeders and earth wires. The length of the OHE span is to be recorded in the middle of the span.

f) Section insulators – for sectioning or for neutral sections: the distance to the nearest mast should be recorded.

g) Signals - existing as well as those to be installed.

h) Auxiliary transformer (25/0.230 kV) locations – for stations, signal cabins, intermediate block signal huts and level crossings. At least two prints of the prepegging plan, thus made ready, are furnished to the site subordinate conducting the survey. Copies are also furnished to the survey civil and S&T engineers who are required to attend the site inspection for verification of the plan.

1.5.6.1 Marking at site

On receipt of the print of the prepegging plan of site, the field staff marks the locations of the structures and anchors in yellow print on the web of the rail adjacent to the shown location of the OHE structure or anchor 7.5 m away from the OHE structure alongside. Structure numbers and their chainages are also
marked. During marking out the locations on web of the rail, obstruction, if any, to the location of structures or anchors, found at site should be recorded on the print. Further at the location of structure the following measurements are recorded on the print for:

a) Track centers
b) width of the cess : if in a cutting, distance to the drain and its width and to the edge of the slope.
c) Turnouts : distance of the structure location from the toe of the switch, and track separation at the location.
d) drains, point rodding, underground pipeline or cables running along the route : distance from the adjacent track to be checked if located in the same lane in which the structure locations, are proposed.
e) versines in mm of span for the tracks on curves and at turnouts and crossovers.
f) Signals : distance to the nearest OHE structure location.
g) power line, signal or telecommunication crossings : distance along the track from the nearest structure location.
h) obstructions , if any, for location of structures as shown in the prepegging plan.

Marking out the prepegging plan at site gives one more opportunity to the survey team to verify ground conditions, and incorporate changes, if any, since the original survey. After marking out the locations structures on rails and incorporating other details as required, one copy of ‘as marked’ plan is returned to the OHE design office. One copy is retained by the field subordinate as his copy.
1.5.7 Joint Field Inspection

In the OHE design office the ‘as marked’ plan carefully examined and the plan is modified taking into consideration the ground conditions viz. obstruction or excessive versines on curves or at turnouts, or inadequate track centers for location of a structure. This revised prepegging plan is now ready for joint Field Inspection. Copies of this plan are distributed to the Civil and Signal and telecom engineers of the Survey Organization. A programme of joint inspection of the site is now made by the Electrical (OHE designs) engineer with the concerned civil and S&T engineers. The official must be of adequate level so as
to take decisions on the spot during the inspection in regard to modification, if any, required to be done to the civil engineering or S&T installations, at site. The S&T official should have with him the finalized plan for the proposed colour light signals. Modifications, such as, diversions of drains, pipe lines, trolley or man refuges, or slewing of tracks to obtain adequate track centers, or shifting of point rodding alignments or of cranks for locating OHE structures are recorded for their compliance. All overhead crossings of Signal and telecommunications circuits including those belonging to the DOT are specifically taken note of, so as to either divert them or cable them well before commencement of OHE construction work. Any power line crossing should conform to the Regulations for Power Line Crossings of Railway Track. If not, the owner of the crossing will have to be advised to modify the crossing to conform to the Regulations. Annexure 1.5.1 contains some of the important provisions of the Regulations for Power Line Crossings of Railway Tracks for ready reference. Based on the decisions token during the joint Inspection the OHE layout is finalized. This plan is now termed the ‘Pegging Plan’.

1.5.8 The Pegging Plan

The location of OHE structures and of anchors, being final, are now inked over in the tracing at the original Survey Sheet. Vital details at the location of structures, such as the track centers and measured cess widths; spans of portals; versines of spans on curves, at turn outs and at crossovers are recorded on the plan. This pegging plan forms the basis for estimation of quantities of work and of materials, based on which the tender schedules are finalized. A specimen pegging plan is giver in Fig 1.5.3.

1.5.9 The OHE Layout Plan

This pegging plan Is further completed in stages as the construction work proceeds. Finally, when the construction work is over, the final plan, called the OHE Layout Plan contains the details of run of conductors, showing both ‘In run’ and ‘out of run’ contact wires, the setting distance of each structure and type, the type of portal and span of its boom, the stagger of the contact wire and any other special features which may be required to be given such as reference to a profile drawing for passage of OHE below an overhead structure. There is usually a time gap between preparation of pegging plan, which indicates the milestone of conclusion of the survey, and the OHE layout plan, prepared during construction by the contractor, who commences the work after further verifying the pegging plan. On completion of the work the contractor finishes the OHE layout plan as ‘As completed’ plan for handing over to the maintenance organization.
1.5.10 Modifications to Railways electrical overhead distribution lines

The overhead distribution lines running on platforms or in yards need to be checked for the electro-magnetic and electrostatic induction due to traction currents. During the survey, drawings should also be made of the power distribution lines indicating their separation from the center line of the track to be electrified and the arrangements of feed, whether in the middle or at the end to ascertain the extent of parallelism. On receipt of the survey sheets in the electrical design office the voltage rise due to electromagnetic induction and the discharge current due to electrostatic Induction in the distribution lines are checked in accordance with the formula obtained from SNCF. If the induction effects are found beyond permissible limits, the distribution lines need to be modified to bring down the effect within the safe limits. Annexure 1.5.2. gives the formula and tables to enable calculation of electro- magnetically induced voltage rise and of electro-statically induced discharge current.

1.5.11 Bonding and Earthing plans

All metal work adjacent to electrified lines have electro-magnetically induced voltages in them which increase in proportion to their length, such metallic fences, platform shelter running parallel to tracks, other metal works open to public such as the foot over bridges and platform columns may also pick up hazardous voltages either induced or by accidental contact with the OHE. Rails of the track carry heavy traction currents in vicinity of feeding posts or at other locations where some rails are taken up for track circuits. These locations may pose hazard to the permanent way gang. Accordingly plans for suitably earthing and bonding of the metalwork adjacent to track, breaking the long fencing in smaller sections, are made. Safe passage of traction currents through rails by various longitudinal and transverse bonds for running rails are ensured. All OHE structures are bonded to the non track circuited rail through structure bonds. If such a rail is not available, an earth wire is run on the OHE structures. The earth wire is broken electrically in parts and each part individually earthed. Bonding and earthing plans are made for the entire route to be electrified. These are made in accordance with the Code for Bonding and Earthing, Document No, ETI/OHE/71 issued by RDSO. This plan, however, needs to be made only at the stage of construction activity.

1.5.12 Progress Chart
To monitor the progress of survey, preparation and finalisation of the plans, conducting soil tests and carryout the clearance studies under overline structures, a progress chart is essential. A suggested progress chart is given in Fig. 1.5.4.

### FIG. 1.5.4
RAILWAY ELECTRIFICATION SURVEY AND PEGGING PLAN

<table>
<thead>
<tr>
<th>SPECIMEN</th>
<th>PROGRESS REPORT CHART</th>
</tr>
</thead>
<tbody>
<tr>
<td>SECTION - SONENAGAR-PATRATU</td>
<td></td>
</tr>
</tbody>
</table>

#### STN 295

<table>
<thead>
<tr>
<th>S.NO.</th>
<th>PART</th>
<th>DESCRIPTION</th>
<th>WEIGHTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>A</td>
<td>SURVEY DETAILS RECEIVED</td>
<td>4.09 45</td>
</tr>
<tr>
<td>1.2</td>
<td>A</td>
<td>SURVEY PLANS READY</td>
<td>2.00 46</td>
</tr>
<tr>
<td>2.1</td>
<td>B</td>
<td>PREPEGGING PLANS READY</td>
<td>8.06 47</td>
</tr>
<tr>
<td>2.2</td>
<td>B</td>
<td>PREPEGGING SITE MARKED</td>
<td>9.55 48</td>
</tr>
<tr>
<td>2.3</td>
<td>C</td>
<td>SITE WALK OUT COMPLETED</td>
<td>4.09 49</td>
</tr>
<tr>
<td>3.1</td>
<td>D</td>
<td>F.O.B./R.O.B. DETAILS RECEIVED</td>
<td>4.09 50</td>
</tr>
<tr>
<td>3.2</td>
<td>D</td>
<td>POWER LINE X-ING DETAILS</td>
<td>8.06 51</td>
</tr>
<tr>
<td>3.3</td>
<td>D</td>
<td>LONG BRIDGE / TUNNEL DETAILS</td>
<td>9.55 52</td>
</tr>
<tr>
<td>3.4</td>
<td>D</td>
<td>CLEARANCE PROFILE DRAWING DETAILS</td>
<td>4.09 53</td>
</tr>
<tr>
<td>3.5</td>
<td>D</td>
<td>BRIDGE / TUNNEL DRAWING DETAILS</td>
<td>8.06 54</td>
</tr>
<tr>
<td>4.1</td>
<td>D</td>
<td>SOIL TEST DATA COLLECTED</td>
<td>9.55 55</td>
</tr>
<tr>
<td>4.2</td>
<td>D</td>
<td>SOIL TYPE CHARACTER FINALISED</td>
<td>4.09 56</td>
</tr>
<tr>
<td>5</td>
<td>D</td>
<td>BILL OF QUANTITIES READY</td>
<td>8.06 57</td>
</tr>
</tbody>
</table>

**Legend**

- A. SURVEY
- B. O.H.E. PEGGING PLAN
- C. CLEARANCE STUDIES
- D. SOIL TESTS
- E. ESTIMATION OF QUANTITIES

#### ANNEXURE

1.5.13 Practical examples in the form of Annexure as detailed below are enclosed:

- **Annexure 1.5.3 Survey and OHE Pegging Plan** (Fig. 1.5.5)
- **Annexure 1.5.4 OHE Layout Plan** (Fig. 1.5.6)
- **Annexure 1.5.5 CSD & SED Drawings** (Fig. 1.5.7)
Annexure 1.5.1


1. Power Line crossings up to and including 11 kV require to be cabled and crossed underground.

2. Power Line crossings up to and including 33 kV is recommended to be crossed through underground cables.

3. For overhead crossings of Power lines, the minimum height above rail level to the lowest conductor including the guard wire shall be as given below:

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Minimum height above Rail Level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 to 66</td>
<td>14.10</td>
</tr>
<tr>
<td>above 66 to 132</td>
<td>14.60</td>
</tr>
<tr>
<td>above 132 to 220</td>
<td>15.40</td>
</tr>
<tr>
<td>above 220 to 400</td>
<td>17.90</td>
</tr>
<tr>
<td>above 400 to 530</td>
<td>19.30</td>
</tr>
<tr>
<td>above 500 to 800</td>
<td>23.40</td>
</tr>
</tbody>
</table>

4. The angle of overhead crossing should be perpendicular to the tracks. In exceptional cases it may be permitted with a skew, the angle of deviation not exceeding 30 degrees. In case it is likely to be more than this value the case should be referred to the Electric inspector to the Government (Chief Electrical Engineer of the Open Line Railway).

5. In view of high cost of modifications to Power Line Crossings and also difficulty in getting shut down of important transmission line crossings of tracks contemplated to be electrified, Electrical inspectors to Government may approve crossings with lower heights provided the clearance between lowest conductor of the power line to the highest traction conductor under most adverse ambient temperature conditions is as indicated below:

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Minimum clearance (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 to 66</td>
<td>4.44</td>
</tr>
<tr>
<td>above 66 to 110</td>
<td>4.75</td>
</tr>
<tr>
<td>above 110 to 132</td>
<td>5.05</td>
</tr>
</tbody>
</table>
If the power line crossing has a guard wire, a minimum clearance from the guard wire to the highest traction conductor should be 2 m.

For other provisions the Regulations should be referred to.
Annexure 1.5.2

Modifications to Electrical Overhead Distribution System at Stations and Yards where 25 kV, ac 50 Hz single phase traction is to be introduced.

1. It is essential that for an electrical overhead distribution system that:

a) There is adequate physical clearance from the 25 kV system so that maintenance personnel working on the former do not come within 2 m any point at a potential of 25 kV.

b) Electro-magnetically induced (EMI) voltage in the distribution system from a 25 kV traction currents remains within safe limits, and

c) Electro-statically induced discharge current due to Capacitive Coupling between 25 kV system and the power distribution system is within safe limits.

2. If the above safety conditions are not met with, the overhead distribution system shall be modified to bring the values within safe limits.

3. The safe limits for

a) Electro-magnetically induced voltages are
   i) For installation to which only trained and source personnel have access 60 V
   ii) For installations to which public or untrained staff have access 25 V

b) Electro-statically induced discharge current shall not exceed 8 mA

4. Neutral of a 3 phase, 4 wire earthed system should be earthed at only one point, that is at the substation.

5. In long metallic structures such as fencing or on over bridge, the electro-magnetically induced voltage shall not exceed 25 V.

6. Formula adopted or Electro-magnetically induced voltage.

Electro-magnetically induced voltage ‘E’ is given by the expression:

\[ E = 2\pi f k_r k_c M I L \]
Where,

\[ E \] is in volts
\[ f \] is frequency of power supply= 50 Hz
\[ k_r \] is coefficient dependent upon type of return circuit and has been empirically established by SNCF, the values are given below

<table>
<thead>
<tr>
<th>Rails per track available for traction current</th>
<th>Section having Double track</th>
<th>Section having Single track</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.39</td>
<td>0.56</td>
</tr>
<tr>
<td>1</td>
<td>0.53</td>
<td>0.69</td>
</tr>
</tbody>
</table>

\( k \) is cable screening factor and it is 1 for bare conductor and 0.8 for lead sheathed underground cable (figures adopted from SNCF)

\( M \) is mutual inductance in Henry, and is a function of average distance between the conductors and the earth resistivity.

\( I \) is current in amperes in OHE

\( L \) is length of parallelism in metres

7. The length of parallelism of an overhead conductor is measured as projected on the alignment of the OHE. The separation distance, which determines the value of \( M \) for a given value of earth resistivity is the average of the length of offsets from the alignment of OHE to the overhead conductor.

8. Table 1.5.2A.1 gives the voltage rise on an overhead distribution line due to induction from traction current. The table, obtained empirically by SNCF is adopted for use on Indian Railways. This table is applicable for following conditions:

a) The section is double track and all the four rails are available for traction current.
b) The current in OHE is 600 A.
c) The earth conductivity is \( 8 \times 10^{-2} \) s/m. The value of earth conductivity generally encountered is expected to be higher than this value, as such the values in the table should be safe for majority of the conditions.
9. To obtain the voltage rise on an overhead conductor having different environment, the values given in the Table 1.5.2A.1 are required to be modified. For example, to obtain the voltage rise on an overhead distribution line from an OHE on single track, with only one rail available for traction return current, the value obtained or the corresponding length of parallelism has to be modified to allow for:

a) Single track section: This will have a maximum current of 300 A. The figure obtained should be divided by 2. i.e. 300/600.

b) Only one rail available for traction return current, hence the value of $k_f$ adopted for double track, double rail section, being 0.39 is no longer applicable. The value of $k_r$ applicable for single track, single rail section is 0.69. The result obtained after modification as given in (a) above should be further modified by multiplying it with a factor of 0.69/0.39.

c) When booster transformer and return conductors are used the values of voltage rise are reduced further. As a rough approximation the values obtained from the table in para-C 8 above should be divided by 2.3 for a booster transformer spacing of 2.66 km and 1.7 for a transformer spacing of 4 km.

In three or four track section the value of $K_r$ chosen should be the same as for double track (that is 0.39) to be on the safe side, although actually it may be somewhat lower. If near sectioning posts the OHE currents are likely to be lower than 600 A the maximum lower value of current may be adopted reducing the voltage rise in the same proportion from 600 A as obtained from the table. The value of voltage rise so calculated is the final voltage rise anticipated in the metallic circuit due to EMI. A worked example is given below.

10. A Worked Example: See Fig. 1.5.A2.1 below giving the plan of an overhead line running along a double truck section proposed to be electrified at 25 kV.
The considerations are

a) In the above diagram, the projected length of the overhead line A, B, C, D, E on the electrified route is a, b, c, d, e a to e totals, say 0.8 km. Then this is the length of parallelism.

b) From the diagram average of the offsets at a, b, c, d and e are taken. This is found to be say 16 m. This is the mean distance between the two lines.

c) Although there are four rails, if the section is near a station there may be likelihood of track circuits being introduced in future. To be on the safe side only two rails are taken for return circuit.

On the above basis interpolating the readings of the table, included voltage comes to 50 V. If all four rails were available for traction the voltage rise expected would be 36 V. Both the values are within safe limits.

11. If it is found that the induced voltage due to electromagnetic induction is higher than the permissible limit, one or several of the means listed below may be adopted to bring the voltage down to safe limits:

a) Shift the point of feed from the end to the center of the line so as to reduce the parallelism.

b) Sectionalize the distribution line and feed short lengths separately.
c) Provide separate 25 kV/240V auxiliary transformers for different areas with short distribution lines.

d) Sectionalize the line through 1:1 isolating transformers.

e) Shift the distribution line farther away from the electrified track.

f) Cable the overhead line in lead sheathed or aluminum sheathed cables.

12. To assess the electro-statically induced current Table 1.5.2A.2 may be made use of. This table has also been obtained from SNCF. In case the discharge current is found to be above safe limits, the separation distance may be increased as to bring the value down to a safe limit. It is generally found that the electrostatic Induction presents little problem.
### TABLE 1.5.2A

<table>
<thead>
<tr>
<th>Characteristics of the track</th>
<th>Nature of the Conductor</th>
<th>LENGTH OF PARALLELISM IN Km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Return Circuit Consisting of all the 4 rails</td>
<td>Overhead Conductor</td>
<td>0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000 1.100 1.200 1.300 1.400 1.500 1.600</td>
</tr>
<tr>
<td></td>
<td>Conductor in Cable</td>
<td>0.333 0.666 1.000 1.333 1.666 2.000 2.333 2.666 3.000 3.333 3.666 4.000 4.333 4.666 5.000 5.333</td>
</tr>
<tr>
<td>Return Circuit Consisting of 2 rails</td>
<td>Overhead Conductor</td>
<td>0.073 0.147 0.220 0.294 0.368 0.441 0.515 0.588 0.662 0.736 0.810 0.883 0.957 1.030 1.104 1.173</td>
</tr>
<tr>
<td></td>
<td>Conductor in Cable</td>
<td>0.243 0.49 0.733 0.980 1.236 1.480 1.716 1.960 2.206 2.453 2.693 2.943 3.169 3.434 3.660 3.925</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean distance of the conductor from the axis of the two track system in metres</th>
<th>Total Electro-magnetically Induced Voltage (Volts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>5.51 11.03 16.53 22.00 27.50 33.01 38.50 44.10 49.60 55.10 60.60 66.00 72.00 77.00 83.00 88.00</td>
</tr>
<tr>
<td>10</td>
<td>5.32 10.64 16.00 21.30 26.60 32.00 37.30 42.60 47.90 53.20 58.50 64.00 69.00 74.00 80.00 85.00</td>
</tr>
<tr>
<td>12</td>
<td>5.14 10.28 15.42 20.60 25.70 30.80 36.00 41.00 46.30 51.40 56.50 52.00 67.00 72.00 77.00 82.00</td>
</tr>
<tr>
<td>14</td>
<td>4.77 9.54 14.31 19.00 23.80 28.60 33.40 38.30 43.20 48.10 52.90 57.80 62.70 67.20 72.00 76.00</td>
</tr>
<tr>
<td>16</td>
<td>4.55 9.11 13.65 18.20 22.70 27.30 31.90 36.50 41.00 45.50 50.00 54.50 59.00 64.00 68.00 73.00</td>
</tr>
<tr>
<td>18</td>
<td>4.41 8.22 13.33 17.60 22.00 26.50 30.90 35.30 39.70 44.10 48.50 53.00 57.30 62.00 66.00 70.00</td>
</tr>
<tr>
<td>20</td>
<td>4.23 8.44 12.66 18.90 21.50 25.80 29.50 33.90 38.00 42.20 46.40 50.50 55.00 59.00 63.00 67.00</td>
</tr>
<tr>
<td>25</td>
<td>4.04 8.08 12.12 16.10 20.20 24.10 29.30 33.40 37.60 41.00 44.40 48.60 52.00 55.60 61.00 65.00</td>
</tr>
<tr>
<td>30</td>
<td>3.67 7.34 11.00 14.70 18.40 22.00 25.70 29.40 33.00 36.70 40.40 44.40 47.70 51.40 55.00 59.00</td>
</tr>
<tr>
<td>40</td>
<td>3.30 6.60 9.00 13.30 16.50 19.10 23.10 26.40 29.70 33.00 36.30 39.60 43.00 46.00 49.50 53.00</td>
</tr>
<tr>
<td>50</td>
<td>2.94 5.88 8.82 11.80 14.70 17.60 20.50 23.50 26.50 29.40 32.30 35.30 38.20 41.00 44.00 47.00</td>
</tr>
<tr>
<td>75</td>
<td>3.43 8.48 12.66 18.90 21.50 25.80 29.50 33.90 37.50 41.00 44.40 48.60 52.00 55.60 61.00 65.00</td>
</tr>
<tr>
<td>100</td>
<td>2.05 4.11 6.15 8.20 10.30 12.30 14.40 16.40 18.50 20.50 22.50 24.60 26.60 28.70 31.00 32.80</td>
</tr>
<tr>
<td>150</td>
<td>1.61 3.22 4.83 5.44 8.00 9.70 11.30 12.90 14.50 16.10 17.70 19.30 20.90 22.50 24.00 25.80</td>
</tr>
<tr>
<td>200</td>
<td>1.33 2.64 3.96 5.28 6.65 7.90 9.20 10.50 11.90 13.20 14.50 15.90 17.20 18.50 19.80 21.10</td>
</tr>
<tr>
<td>250</td>
<td>1.10 2.20 3.30 4.40 5.50 6.60 7.70 8.80 9.90 11.00 12.10 13.20 14.30 15.40 16.50 17.60</td>
</tr>
<tr>
<td>300</td>
<td>0.68 1.75 2.64 3.52 4.40 5.30 6.20 7.00 8.00 8.80 9.70 10.60 11.40 12.30 13.20 14.00</td>
</tr>
<tr>
<td>400</td>
<td>0.59 1.18 1.77 2.35 3.00 3.50 4.10 4.70 5.30 5.90 6.50 7.10 7.70 8.30 9.00 9.50</td>
</tr>
<tr>
<td>500</td>
<td>0.40 0.80 1.20 1.60 2.00 2.40 2.80 3.20 3.60 4.00 4.40 4.80 5.20 5.60 6.00 6.40</td>
</tr>
<tr>
<td>600</td>
<td>0.29 0.58 0.87 1.16 1.45 1.74 2.00 2.30 2.60 2.90 3.20 3.50 3.80 4.00 4.30 4.60</td>
</tr>
<tr>
<td>700</td>
<td>0.22 0.44 0.66 0.88 1.10 1.32 1.54 1.78 2.00 2.20 2.40 2.64 2.86 3.10 3.30 3.50</td>
</tr>
<tr>
<td>800</td>
<td>0.12 0.26 0.38 0.52 0.65 0.78 0.91 1.04 1.17 1.30 1.43 1.56 1.70 1.82 1.95 2.10</td>
</tr>
<tr>
<td>900</td>
<td>0.13 0.26 0.38 0.52 0.65 0.78 0.91 1.04 1.17 1.30 1.43 1.56 1.70 1.82 1.95 2.10</td>
</tr>
<tr>
<td>1000</td>
<td>0.11 0.22 0.33 0.44 0.55 0.66 0.77 0.88 0.99 1.10 1.20 1.32 1.43 1.54 1.65 1.80</td>
</tr>
</tbody>
</table>
Table 1.5.2A.2
Electro-static induction due to 25 kV ac Traction
(The charged conductor is assumed to be at height of 6 m above rail level)

<table>
<thead>
<tr>
<th>Length of parallelism</th>
<th>0.100</th>
<th>0.200</th>
<th>0.300</th>
<th>0.400</th>
<th>0.500</th>
<th>0.600</th>
<th>0.700</th>
<th>0.800</th>
<th>0.900</th>
<th>1.000</th>
<th>1.500</th>
<th>2.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Of aerial Conductor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in km</td>
<td>0.95</td>
<td>1.89</td>
<td>2.04</td>
<td>3.79</td>
<td>4.74</td>
<td>5.69</td>
<td>6.64</td>
<td>7.58</td>
<td>8.53</td>
<td>9.40</td>
<td>14.5</td>
<td>18.9</td>
</tr>
<tr>
<td>8</td>
<td>0.72</td>
<td>1.43</td>
<td>2.14</td>
<td>2.86</td>
<td>3.58</td>
<td>4.28</td>
<td>5.01</td>
<td>5.73</td>
<td>6.44</td>
<td>7.16</td>
<td>11.0</td>
<td>14.5</td>
</tr>
<tr>
<td>10</td>
<td>0.56</td>
<td>1.11</td>
<td>1.66</td>
<td>2.22</td>
<td>2.78</td>
<td>3.63</td>
<td>3.88</td>
<td>4.44</td>
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<td>5.56</td>
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</tr>
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<td>0.88</td>
<td>1.35</td>
<td>1.76</td>
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<td>2.64</td>
<td>3.08</td>
<td>3.52</td>
<td>3.96</td>
<td>4.40</td>
<td>6.5</td>
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<td>0.89</td>
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<td>1.48</td>
<td>1.77</td>
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<td>2.66</td>
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<td>0.25</td>
<td>0.50</td>
<td>0.74</td>
<td>0.99</td>
<td>1.24</td>
<td>1.49</td>
<td>1.74</td>
<td>1.98</td>
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<td>3.5</td>
<td>5.0</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Length of parallelism</th>
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<th>3.000</th>
<th>3.500</th>
<th>4.000</th>
<th>4.500</th>
<th>5.000</th>
<th>5.500</th>
<th>6.000</th>
<th>6.500</th>
<th>7.000</th>
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</tr>
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<tr>
<td>of aerial conductor</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>in KM</td>
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<td></td>
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<tr>
<td>8</td>
<td>23.7</td>
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<td>38.0</td>
<td>42.5</td>
<td>47.5</td>
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<td>57.0</td>
<td>62.0</td>
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<td>71.0</td>
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<td>28.0</td>
<td>32.0</td>
<td>36.0</td>
<td>40.0</td>
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<td>46.5</td>
<td>50.0</td>
<td>53.5</td>
</tr>
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<td>15.5</td>
<td>17.5</td>
<td>20.0</td>
<td>22.0</td>
<td>24.0</td>
<td>26.5</td>
<td>28.5</td>
<td>31.0</td>
<td>33.0</td>
</tr>
<tr>
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<td>9.0</td>
<td>11.0</td>
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<td>14.5</td>
<td>16.0</td>
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<td>20</td>
<td>6.5</td>
<td>7.5</td>
<td>8.5</td>
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<td>12.5</td>
<td>13.5</td>
<td>15.0</td>
<td>16.0</td>
<td>17.5</td>
<td>18.5</td>
</tr>
</tbody>
</table>
Annexure 1.5.3

Survey and OHE Pegging Plan (Fig. 1.5.5)
Annexure 1.5.3 (Contd.)
Annexure 1.5.4
OHE Layout Plan (Fig. 1.5.6)
Annexure 1.5.4 (Contd.)
Annexure 1.5.5

CSD & SED Drawings (Fig. 1.5.7)
CHAPTER 6
ABSTRACT EXTIMATE AND COST BENEFIT ANALYSIS

1.6.1 General

As a result of the survey and finalization of the extent of work jointly agreed upon by the open line Railway, power supply Authorities and the Department of Telecommunications, the specifications and quantum of the work are finalised. Different disciplines, i.e. electrical, civil engineering and S&T engineering make realistic assessments of their portions of work and work out their respective cost estimates. The cost of the Project is then obtained after adding General Charges. The financial (and, if required, also the economic) viability of the project is then found out based on traffic forecasts. Further, a sensitivity analysis, involving percentage changes in cost of important inputs and their effect on remunerative-ness of the project is also taken up to ensure that the project remains viable, even when the cost of important inputs change subsequently. A further measure of confidence is obtained from carrying out Productivity Test on earlier completed project, by assessing the benefits accruing vis-à-vis those envisaged at the time of sanction of the project.

1.6.2 Cost Estimate

The list of works to be taken up for Railway Electrification are given below engineering discipline wise. Both the type of work and their quantum depend upon the peculiarity of the section chosen.

1.6.2.1 Civil Engineering

a) To increase clearances to suit 25 kV ac traction, wherever required:
   i) under foot over bridge
   ii) under road over bridges
   iii) under fly over bridges
   iv) Inside tunnels
   v) At entry points of through girder bridges.
   vi) To platform shelters
   vii) To water columns.

b) To remove obstructions to location of OHE structures, wherever, required by:
   i) slewing of tracks for adequate track centres.
ii) Diversion of drains, and/or water mains running alongside the tracks
iii) Shifting of buildings, block, huts, signal cabins, trolley and man refuges, and/or any other civil engineering structure.

c) To construct new civil engineering assets:

i) Erection of height gauges at level crossings, and safety screens at the road and foot over bridges.
ii) Sidings for contractors’ depots.
iii) Laying of track and its connection’s for electric locomotive sheds. OHE inspection cars, hot axle sidings, common loops, yard remodeling for change of traction or for any other work directly related to electrification.
iv) OHE and PSI workshop and maintenance depots, garages and sheds for OHE inspection cars and training schools.
v) Repeater stations, battery and relay rooms, cabins for Signal and Telecommunication installations.
vi) Buildings for traction substations, remote control center and remote control cubicles.
vii) Locomotive sheds, main and trip inspection
viii) Staff quarters and associated amenities such as roads, water supply etc.
ix) Acquisition of land and its development.

1.6.2.2 Electrical

a) Construction of OHE (including booster transformers and return conductors)
b) Erection of 132/220 kV power transmission lines.
c) Erection of traction substations.
d) Erection of supply control posts.
e) Erection of remote control equipment
f) Erection of machines, and provision of tools and plant for electric locomotive sheds. OHE and power supply installation depots and supply of road and rail vehicles for maintenance organization
g) Erection of auxiliary transformers for low voltage power supply to stations signal cabins, and level crossings.
h) Electrification of staff quarters, service buildings and their air conditioning.
i) Modification to railway’s power distribution network.
j) Monitoring of modifications to power line crossings of outside agencies to conform the Regulations for Power Line Crossings of Railway tracks.

1.6.2.3 Signaling Works
1.6.2.4 Telecommunication Works.

a) Laying and installing telecommunications cables including repeaters and terminal equipments.
b) Provision of new traction power control, remote control, loco control, emergency control circuits and connections.
c) Provision of new telephone exchanges and telephones and administrative trunk lines for traction maintenance personnel.
d) Modifications to talking and page back facilities in yards and to public address systems at stations.
e) Provision of emergency telephones to locomotives and maintenance personnel; provision of wireless facilities to breakdown gangs.
f) Monitoring of protective works taken up by Department of Telecommunications.

1.6.2.5 Cost estimates

The assessment of works are done in detail. Based on these the cost estimates are prepared engineering discipline wise duly allocating the cost to the appropriate major, minor and detailed head of account according to Indian Railways’ Accounts Code. The cost estimates include estimation of payment to the outside agencies such as:

a) Revenue department of state government for acquisition of land.
b) Owners of overhead power line crossings of tacks to modify their crossings to come in conformity with the Regulations.
c) Power Supply Authorities to provide traction power supply.

1.6.2.6 Ancillary Works.

A number of improvements are undertaken at the time of electrification of a section and also the responsibility for their execution rests with railway electrification project organization. Such works include route relay interlocking, increased communications channels in the cable, common loops or other yard remodeling not required for change of traction, which would be equally beneficial with diesel traction; such works should be justified individually and got sanctioned as separate works so that the remunerative-ness of the electrification project does not get affected by such works and funds are optimally utilised.
1.6.2.7 Component costs of Railway Electrification activity

The cost allocation heads in the Indian Railways Accounts Code indicate distribution of works costs according to the activity of different engineering disciplines; Civil engineering, Electrical and Signal & Telecommunications. For example, construction of loco shed would involve civil engineering works of development of land, buildings, track work and furnishing, electrical engineering works would include works for power supply and electrification of the buildings, indoor and outdoor illumination, air conditioning, provision of OHE and machines and tools and plant for the shed; the signaling works would include the entry and exit signals for the loco shed and the telecommunication works would include provision of telephones and control phones. It would be a good practice to compute the total cost of each such activity of installation by adding the cost of component works discipline wise on a spreadsheet, to obtain the entire cost incidental to setting up of the loco shed. A sample for such a spreadsheet for Tughlakabad electric loco shed giving the total “module cost” for “one unit” of loco shed is given in Annexure 1.6.1. Such an unit cost derived from similar exercise for all other major activities such as for substations, OHE, telecommunications cable work, signaling work, etc. reduced to per unit per route of track km as most suitable, permits comparison of costs with other electrification projects. Such a study also indicates the trend of costs, and provides means for scrutiny and cost control. A proforma for arriving at unit cost for major railway electrification activities is given in Annexure 1.6.2.

1.6.3 Financial appraisal of the Railway Electrification Project

1.6.3.1 Appraisal on discounted cash flow (DCF) technique

Based on the total cost of the project and the traffic forecast over the life of the project (taken as 5 years of construction activity followed by 30 years of maintenance and operation, total 35 years), cost benefit analysis is worked out on the discounted cash flow (DCF) technique. The basis of cost benefit analysis on DCF technique is given in Annexure 1.6.3. This analysis compares cash outflow on capital, repairs and maintenance and operation on two scenarios (a) and (b) indicated below. Common costs are excluded from the analysis

a) The section is taken up for full dieselisation, with new diesel locomotives assumed to have been introduced from the expected date of energisation of the OHE. (See Annexure 1.6.4: Cost benefit analysis for Railway Electrification projects; In regard to considering cost of new diesel locomotives in Diesel scenario instead of a mix of old and new as actually used on the route)
b) The section is electrified as envisaged in the project report and all traffic assumed to move on electric traction from the date of OHE.

The present worth of the cash flow over the 35 years of project life is discounted at minimum acceptable rate of discount i.e. the minimum rate of discount at which a project is considered viable is obtained, complete with due credits to the present worth with the depreciated return value of assets at the end of the project life for both the scenarios. If the present worth for both the forms of traction are equal, the traffic level is called the "break even" level of traffic. Diesel traction is more economical at a traffic density lower than this level and electric traction at this and above the level. To ascertain the actual internal Rate of Return (IRR) of the project at the envisaged traffic level the discounting factor is varied. The discounting factor at which the present worth of electric traction equals that of the diesel traction is the IRR of the Railway Electrification Project. All values of IRR above the prescribed minimum value (which varies from time to time and had been 10% till 1991) are considered acceptable for approval of the project. The basis for DCF technique for Cost Benefit Analysis is given in Annexure 1.6.3.

1.6.3.2 Assessment of Coaching and Goods Traffic

The most important criterion of selection of a route for Electrification is traffic density. Traffic survey, therefore, requires traffic forecasts being made by the open line Railway as well as by the Railway Board. An independent analysis of any further information in regard to major developments in the economy of the country or the region which may affect the forecasts of the Railway should also be made. The assessments and the forecast arrived at should be done in consultation with the Chief Operating Manager of the Railway and should have his acceptance. The level of traffic expected in the first year of electrification and the growth expected in the foreseeable future say up to about 15 years may be worked out. A relevant point to be considered is the likely diversions of traffic from other non electrified routes to the one being electrified due to greater mobility being offered by an electrified route having a better infrastructure. This synergy effect should be also carefully assessed and quantified in such a survey.

1.6.3.3 Norms and costs required for Project Appraisal

In addition to the capital cost of Railway Electrification, the annual cost of operation and maintenance for the two types traction, number and cost of new diesel and electric locomotives are required. The costs required to be taken in account are:
a) Capital Cost

<table>
<thead>
<tr>
<th>Electric Traction</th>
<th>Diesel traction</th>
</tr>
</thead>
<tbody>
<tr>
<td>i) Locomotives</td>
<td>Locomotives and Power packs</td>
</tr>
<tr>
<td></td>
<td>(number x cost per locomotive for both types of traction)</td>
</tr>
<tr>
<td>ii) Locomotive sheds</td>
<td>Locomotive sheds</td>
</tr>
<tr>
<td></td>
<td>(main and outstation)</td>
</tr>
<tr>
<td>iii) Fixed installations :</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Traction OHE, Sub-Station, supply control posts, Remote control &amp; ancillary electrical work.</td>
</tr>
<tr>
<td></td>
<td>Signalling, Telecommunications, Yard remodeling and Other civil engineering Works.</td>
</tr>
</tbody>
</table>

b) Cost of operation and maintenance

<table>
<thead>
<tr>
<th>Electric traction</th>
<th>Diesel traction</th>
</tr>
</thead>
<tbody>
<tr>
<td>i) Electric energy</td>
<td>diesel fuel</td>
</tr>
<tr>
<td>ii) Lubricants</td>
<td>Lubricants</td>
</tr>
<tr>
<td>iii) Traction distribution</td>
<td>-</td>
</tr>
<tr>
<td>iv) Locomotive operation and maintenance</td>
<td>Locomotive operation and maintenance</td>
</tr>
</tbody>
</table>

To obtain the above costs, use is made of published statistics of open line Railway. Costs of locomotives are obtained from Indian Railways’ locomotive production units.

1.6.3.4 Assessment of number of locomotives

A preliminary study may be done by simulating on a computer movement of different type of trains (express, stopping passenger and goods trains) over the section. Based on the train charts worked out after such a study, turn round time for locomotives may be worked out. The number of locomotives for each type of traction for the levels of traffic envisaged year wise can be now worked out. Since the Indian Railways have standardized for broad gauge the WDM2 type of
diesel engines and variations of WAM4 type of electric engines, adequate statistics are available of the norm of net tone km hauled per day per locomotive in use to be able to assess the number of locomotives required for goods traffic. For passenger traffic the statistics of km run per locomotive in use on passenger services per day is available. Both the statistics are conveniently used to obtain the total number of locomotives in use for the envisaged levels of traffic year wise for goods and passenger services. Another alternative for arriving at the number of locomotives for passenger services is to draw the locomotive links and work out the requirements. To arrive at the number of bare requirement of locomotives, additional ones required for multiple heading should also be added. To this bare necessity, ineffective percentage of locomotives (also taken from the Railway’s statistics), is added to cater for repairs and maintenance. The production units of Diesel locomotives Works, Varanasi and Chittaranjan locomotive Works, maintain the cost of manufacture of the WDM2 and WAM4 types of locomotives respectively as these locomotives are under regular production by them. The latest batch costs are obtained from these Production units for the purpose of appraisal. If new types of locomotives are to be used, it would be good practice to examine the cost benefit analysis of the new types vis-à-vis the above existing two types of locomotives in a separate exercise, limiting the cost benefit study for electrification of section to the use of WDM2 and WAM4 types of diesel and electric locomotives, their statistics of operation being adequately available on Indian Railways, while those for the new types would be only subjected to assessment based on their specifications of maintenance and operation.

1.6.3.5 Norms required for project appraisal and their sources

Table 1.6.1 below lists out the norms required for working out the cost benefit analysis and the sources from which they are extracted.

<table>
<thead>
<tr>
<th>Norm</th>
<th>Source</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>i) Gross tonne km per route km per annum</td>
<td>Railway’s statistics</td>
<td>For both types of traction</td>
</tr>
<tr>
<td>ii) Net tonne km per locomotive in use per day on goods traffic</td>
<td>-do-</td>
<td>-do-</td>
</tr>
<tr>
<td>iii) Locomotive km per loco in use per day on passenger traffic</td>
<td>-do-</td>
<td>-do-</td>
</tr>
<tr>
<td>iv) Ineffective percent of</td>
<td>-do-</td>
<td>-do-</td>
</tr>
</tbody>
</table>
locomotives on repairs & maintenance

v) Engine km to train engine km -do- -do-

vi) Fuel/electric energy consumption per 1000 gross tonne km separately for goods, express and stopping passenger services -do- -do-

vii) Consumption of lubricant per engine km -do- -do-

viii) Cost of fuel, energy and lubricants From latest costs as applicable at the point of supply obtained from the Railway, inclusive of taxes, Duty and cost of transport for each type.

ix) Cost of locomotives Latest batch costs obtained from diesel locomotive production units.

x) Cost of Diesel Power Latest batch cost from Diesel locomotive Production units

xi) Cost of Shed repairs per engine km Railway’s statistics For both types of traction

xii) Cost of POH per locomotive per annum -do- -do-

xii) Cost of repairs & Maintenance of:

Traction Distribution assets -do- For electrical Traction only per TKM basis

b) Telecommunication abstracted for electric traction on per route km -do-

c) Other electrical assets at 3% of cost of works -do-
d) Civil engineering assets at 2 ½ of cost of works

taxiv) Cost of locomotive operation Railway’s statistics For diesel & electric traction

1.6.3.6 Construction time schedule

A realistic time schedule of cash outflow is required to be taken into account for calculation of the “Present Worth” of the project. Experience has shown that 4 years are required to complete a project from commencement and cash outflow period five years. Following percentage of cash outflow per year may be assumed for an electrification project.

<table>
<thead>
<tr>
<th>Year</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>First year</td>
<td>5%</td>
</tr>
<tr>
<td>Second year</td>
<td>20%</td>
</tr>
<tr>
<td>Third year</td>
<td>40%</td>
</tr>
<tr>
<td>Fourth year</td>
<td>30%</td>
</tr>
<tr>
<td>Fifth year</td>
<td>5%</td>
</tr>
</tbody>
</table>

Total 100%

Accordingly the discounting of the cash outflow commences from the second year of the project.

1.6.3.7 Terminal value of Assets

The discounted terminal value of the assets at the end of 30 years of operation is created to the project as cash inflow in the calculation of the DCF. In calculating the terminal value the rate of depreciation is taken on ‘straight line’ and the life of the assets taken as provided in paragraphs 971, 981, 718 and 719 of Indian Railways General code. The life given in the Code for some important assets is given in Table 1.6.2.
1.6.2 Table

Life of Assets

<table>
<thead>
<tr>
<th>Assets</th>
<th>Life in year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel locomotives</td>
<td>36</td>
</tr>
<tr>
<td>Power pack for diesel locomotives</td>
<td>18</td>
</tr>
<tr>
<td>Electric Locomotive</td>
<td>35</td>
</tr>
<tr>
<td>Electrical fittings, office furniture</td>
<td>20</td>
</tr>
<tr>
<td>Cables, S&amp;T works, Preliminary works, Plant Equipment and loco shed machinery</td>
<td>30</td>
</tr>
<tr>
<td>Overhead power lines, Permanent way, Ballast, station Machinery &amp; OHE contact wire</td>
<td>40</td>
</tr>
<tr>
<td>Buildings</td>
<td>50</td>
</tr>
<tr>
<td>OHE (excluding contact wire), Bridgework, and fencing</td>
<td>60</td>
</tr>
<tr>
<td>Land</td>
<td>Indefinite</td>
</tr>
</tbody>
</table>

1.6.3.8 Statement of Cash Flows and internal Rate of Return of the Project

The cash flows for the two types of traction are now worked out. The statement of cash flows which should be worked out year wise are given in the table 1.6.3 below:
## Table 1.6.3

**Statement of Cash Flows**

<table>
<thead>
<tr>
<th>Item</th>
<th>Type of Traction</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Cost of Works</td>
<td>Loco sheds and Fuelling points</td>
<td>Electrification including loco Sheds</td>
</tr>
<tr>
<td>b) Cost of new Locomotives</td>
<td>Locomotives &amp; Power packs</td>
<td>Locomotives</td>
</tr>
<tr>
<td>c) Cost of diesel fuel &amp; electric energy</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>d) Cost of lubricants</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>e) Cost of operation</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>f) Cost of running repairs and POH of locomotives</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>g) Cost of repairs &amp; None maintenance of</td>
<td>Yes</td>
<td>As per norms mentioned in table 1.6.1 above.</td>
</tr>
<tr>
<td>i) Traction distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ii) Signal &amp; Telecom.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>iii) Civil Engineering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>iv) Electrical Engineering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>h) Residual value of assets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Locomotives &amp; power packs</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>- Fixed assets, Electrical and S&amp;T</td>
<td>None</td>
<td>yes</td>
</tr>
</tbody>
</table>

Having worked out the year wise cash flows for each type of traction on a spreadsheet, two exercises may be done as follows:
a) The present value of each of the cash flows is worked out by multiplying the total cash flow in a year by the appropriate discounting factor relevant to the year at the minimum acceptable rate of discount (12%). The total of all the discounted cash flows for each type of traction is found out. From this total of the cash outflows the present worth of the terminal value of the assets is deducted giving one value of present worth of Electric traction and another for diesel traction. The figures are compared, if the value of present worth of cash outflow for electric traction is found to be less than or equal to that of diesel traction the electrification project is considered viable.

b) The internal Rate of Return (IRR) of the electrification projects is found out as per the method indicated in Annexure 1.6.5. If the IRR is found to be equal or more than the minimum acceptable rate of discount, the electrification project is considered viable.

1.6.4 Break Even Level of Traffic Density

In the previous paragraph the method to obtain the IRR of a project at a given level of traffic density has been described. To obtain the level of traffic at which an Electrification project just becomes viable, (that is the present worth of the two type of traction equalize) following exercise is done:

The tales of cash flows discounted at the minimum acceptable rate of discount (12%) for the two types of tractions are bifurcated in two parts. In the first part, called LINE COSTS, the present worth of all the fixed assets viz capital, repairs, maintenance and operation of traction distribution, signaling and telecommunication, are totalled. These costs remain independent of traffic level. The second part called HAULAGE COSTS contain the present worth for capital costs of locomotives and power packs and the cost of locomotives operation (fuel, lubricant and staff), and their shed repairs and POH costs. This cost is for the envisaged level of traffic. Haulage costs are assumed to vary linearly with the volume of traffic, being zero for no traffic. This gives two values of the cost of traction under each type of traction viz.

<table>
<thead>
<tr>
<th>Traffic level</th>
<th>Present worth of cost of traction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Zero</td>
<td>Line costs</td>
</tr>
<tr>
<td>2) As envisaged for the project</td>
<td>Line costs + haulage costs</td>
</tr>
</tbody>
</table>

Table 1.6.4 gives the components of line and haulage costs
Table 1.6.4

Components of line and haulage costs

<table>
<thead>
<tr>
<th>Costs</th>
<th>Present worth of minimum acceptable Rate of discount for type of traction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electric</td>
</tr>
<tr>
<td>a) Line costs</td>
<td></td>
</tr>
<tr>
<td>i) Costs of Works</td>
<td>A</td>
</tr>
<tr>
<td>ii) Cost of maintenance of traction</td>
<td></td>
</tr>
<tr>
<td>distribution</td>
<td></td>
</tr>
<tr>
<td>Signal &amp; telecom &amp; Civil and electrical</td>
<td></td>
</tr>
<tr>
<td>Assets</td>
<td>B</td>
</tr>
<tr>
<td>iii) Residual value of assets</td>
<td>(-) C</td>
</tr>
<tr>
<td>b) Haulage costs</td>
<td></td>
</tr>
<tr>
<td>i) Cost of locomotives &amp; Power packs</td>
<td>E</td>
</tr>
<tr>
<td>ii) Cost of loco operation</td>
<td></td>
</tr>
<tr>
<td>Fuel/energy</td>
<td>F</td>
</tr>
<tr>
<td>iii) Lubricants</td>
<td>G</td>
</tr>
<tr>
<td>iv) Staff</td>
<td>H</td>
</tr>
<tr>
<td>v) Loco repairs &amp; maintenance</td>
<td>I</td>
</tr>
<tr>
<td>v) Residual value of Locomotive</td>
<td>(-) J</td>
</tr>
<tr>
<td>Total of (b)</td>
<td>E+F+G+H+I+J=K</td>
</tr>
</tbody>
</table>

A graph can now be drawn with ordinate as the present worth of traction and traffic density as the abscissa. One straight line for each type of traction is drawn connecting the value of present worth at zero and the envisaged levels of traffic. The traffic density level at the point of intersection of the two curves, at which the two present worth for diesel traction and the electric traction are equal, is the break even level of traffic. The graph shown in Fig. 1.6.1 diagrammatically indicates how to work out the break even level of traffic.
The above exercise is for a traffic density $t_b$. The break even level of traffic density $t_b$ is now found from a graph representing the points on straight lines of the two types of traction found the following:

<table>
<thead>
<tr>
<th>Traffic Density</th>
<th>Electric</th>
<th>Cost of traction for Diesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (O)</td>
<td>D</td>
<td>P</td>
</tr>
<tr>
<td>T</td>
<td>D + K</td>
<td>P + W</td>
</tr>
</tbody>
</table>

The $t_b$ is the level of traffic at which the two straight lines intersect.
### Module Cost of Tughlakabad Electric Loco shed

*(All figures in lakhs of rupees)*

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Description</th>
<th>Civil</th>
<th>Electrical</th>
<th>S&amp;T</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Earthwork</td>
<td>20.01</td>
<td>---</td>
<td>---</td>
<td>20.01</td>
</tr>
<tr>
<td>2.</td>
<td>Permanent way</td>
<td>146.08</td>
<td>---</td>
<td>---</td>
<td>146.08</td>
</tr>
<tr>
<td>3.</td>
<td>Buildings</td>
<td>541.34</td>
<td>---</td>
<td>---</td>
<td>541.34</td>
</tr>
<tr>
<td>4.</td>
<td>Residential Qtrs.</td>
<td>160.21</td>
<td>---</td>
<td>---</td>
<td>160.21</td>
</tr>
<tr>
<td>5.</td>
<td>General Elect.</td>
<td>---</td>
<td>113.26</td>
<td>---</td>
<td>113.26</td>
</tr>
<tr>
<td>6.</td>
<td>OHE</td>
<td>---</td>
<td>113.32</td>
<td>---</td>
<td>113.32</td>
</tr>
<tr>
<td>7.</td>
<td>M &amp; P</td>
<td>_</td>
<td>464.80</td>
<td>_</td>
<td>464.80</td>
</tr>
<tr>
<td>8.</td>
<td>Telecom</td>
<td>_</td>
<td>_</td>
<td>76.85</td>
<td>76.85</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>867.64</td>
<td>710.38</td>
<td>76.85</td>
<td>1654.87</td>
</tr>
</tbody>
</table>
**Railway Electrification**

**Proforma to Abstract Unit Costs of Activities**

(Cost in lakhs of rupees)

<table>
<thead>
<tr>
<th>SN.</th>
<th>Module</th>
<th>Unit</th>
<th>Quan-</th>
<th>Gene-</th>
<th>Cost discipline wise</th>
<th>Total</th>
</tr>
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</tbody>
</table>

1. Electrical

a) OHE
   - i) Regulated km
   - ii) unregulated km
   - iii) tramway, regulated km

b) Return conductor km

c) Booster Transformer unit
   - Stations

d) Traction substations unit

e) Supply control posts unit

f) Transmission lines km

g) Remote Control
   - i) Center unit
   - ii) Controlled posts unit

h) Payments to Power Supply Authorities L.S

i) Modifications to Railway’s Power Supply L.S. System

j) Modifications to Power Line Crossings unit

k) Auxiliary Transformer Stations unit

l) New Power Supply L.S. Arrangement
2. Civil Engineering

a) Loco shed unit
b) Loco outstation shed unit
c) Staff quarters unit
d) Maintenance Depots:
   i) Traction Distribution unit
   ii) Telecommunication unit
e) Modifications to structures to suit ac traction:
   i) Heavy overline unit.
   ii) Tunnels m
   iii) Light including screens, height gauges etc. L.S.
f) Yard Remodelling sidings, X-overs km

3. Signalling Works

a) New Color light Signals
   i) Way side Stations Unit
   ii) Large Stations Unit
b) Track circuits:
   i) On new Concrete sleepers km
   ii) On existing wooden sleepers km
c) Modifications to interlocking and station equipment:
   i) Way side stations unit
   ii) At large stations.
      - cabins unit
      - Panel unit
      - Route Relay unit
      - Route Relay interlocks
- any other system unit

4. Telecommunication Works

a) Telecom cable km

b) Microwave patching unit

c) Emergency Telephone unit & wireless

d) Payment to DOT for their protective works L.S.

5. Miscellaneous Works

Temporary sheds sidings etc. L.S.

6. Total cost Route km Track km
Discounted Cash Flow Technique for Cost Benefit Analysis of a Project

1. The discounted cash flow technique (DCF) gives a figure, known as its 'Present Worth' which is a measure of profitability. By comparing this figure of Present Worth between two projects their relative profitability can be assessed. To obtain this value, a 'life' for the project is assumed. For Railway electrification Projects this is taken as 35 years, comprising of 5 years of construction and 30 years at it's operation. During this life, annual cash flows are estimated: both; outflows, on account of capital investment of the project initially, and subsequently on account of its operation and maintenance and replacement of depreciated assets; and inflow on account of the accruing due to the project. The sum of the annual cash flows are discounted at appropriate rate of discount applicable for the year in which the cash flow occurs. These values are found from the table of present value of one unit (one Rupee) at different rates of discount for future years (Table 1.6a.3A.1). The residual value of the assets is calculated at the end of the project life. This is multiplied with the discount factor for the terminal year of the project and is considered as the cost cash Inflow at the end of the project life. The stream of annual discounted cash flows are now added together. This total of the annual discounted values of cash flows is the Present Worth of the project. Taking outflow as negative cash flow and inflow as positive, larger the value of the Present Worth, better is the return of the project. The Present Worth, therefore, assists in choosing between two competing projects. The discount factor chosen is the minimum acceptable rate at which an investment can be found profitable. The basis for adopting discount factors for future cash flow is the consideration that the future value of money today is less than its worth. if an amount of Rs. 100 is required to be spent one year from now and the bank gives an interest of 12%, then one has to find only Rs.89.30 today; if required after two years only Rs.79.70 need to be found today. The value of the Rupee in the ninth year would be Ps. 100 x (0.893).

2. The algebraic expression for the Present Worth 'PW' of cash flow 's' in the year 'n' at a discount rate of 'i' is
   \[ PW = \frac{s}{(1+i/100)} \]

3. Effect of inflation in discounting factor: Although inflation has not been considered in estimation of future cash flows on Indian Railways, if considered appropriate this may be taken into account. The effect of inflation is to diminish the future value of the Rupee further. If the cost inflation rate published by the government as 'c %' is taken into account, the value of the Present Worth is depressed by the some factor. The Real Value (RV) of money realized in years in future due to inflation is given by the expression:
RV = s/ ( 1 + c /100 )

The real rate of discount \( r \) is a combination of both the factors i.e. rate of discount and inflation. This is given by the expression:

\[(1 + r) = (1 + c)(1 + r)\]

For example the rate of Interest prevailing is 8% and the rate of Inflation is 7% then the discount rate \( r \) chosen is given by the expression:

\[(1 + r) = (1 + 8/100)(1 + 7/100) = 1.156\]

or. \( r \) should be 15.6%.

4. Table A.16.1 gives values of discount factors of Rupee 1 from 5% to 25% for a period covering from one year to 20 years. To obtain the internal Rate of Return (IRR) of a project, the annual cash flows are multiplied by trial discount factors and in each case the Present Worth found out. The discount factor of which the Present Worth becomes zero is the IRR of the project. However in public spending or infrastructural development, where pure profit is not the main motive, all projects which have positive Present Worth at the minimum acceptable discount rate are considered worthy of being taken up for execution.

5. For Railway Electrification Projects, as the cost of diesel traction is compared with that for electric traction, only cash outflows for both the types of traction are considered, the common costs being omitted from the assessment. This greatly simplifies the cost benefit analysis and identifies the incremental benefit for the type of traction for the traffic anticipated.

In working out the cost benefit analysis (CBA) for Railway Electrification there have been occasionally suggestions to refine the methodology through adopting more 'realistic' data. The reasons why such refinements are not adopted are discussed here.

1. **Cost of Electric and Diesel Locomotives:**

It has been suggested that in working out the CBA, cost of new electric locomotives, but of old diesel locomotives, which actually run over the section should be taken against the existing practice of taking cost of new locomotives for both the scenarios in CBA. Prima facie the argument appears logical but in the present state is fallacious. Indian Railways with various levels of traffic on their network, continue to add to their fleet of diesel and electric locomotives on additional traffic and on replacement account. As long as routes exist with level of traffic, which lie above the break even level, it can be argued that for the study on an incremental basis, new locomotives would be run on the section for both the scenarios. However, when a stage is reached as routes get electrified, that on energisation of a section there would be premature surrender of diesel locomotives, the extra capital cost of premature ordering of electric locomotive may have to be considered in the CBA. In other words at the stage of ordering new locomotives a study of the traffic density of the routes should be made to assess whether the highest traffic density routes will be more profitably run with new diesel or with new electric locomotives and the mixed of diesel and electric locomotives on additional or on replacement account ordered on such an Overall consideration. Accordingly, in the current situation when there is a continued production of new diesel locomotives, it is logical to consider new locomotives in the CBA for both the scenarios, while considering electrification of a section.

2. **Norms for fuel and electric energy consumption:**

It is suggested that the norms adopted for specific fuel/energy consumption (litre or kwh per 1000 gross tonne km), being a sensitive norm, should be taken as applicable for the section under consideration, averages as available in the Railways statistics should not be taken. The suggestion is valid, but for its impracticability, cost in conducting actual trials, and its limitations nullifying the efforts towards greater accuracy. Electrification having been taken up over be considered reliable. For electric locomotives, one will have to be content with trail with locomotives fitted with energy meters only on a electrified section. This it self is likely to bring to the study an element of doubt in the norm so established. Such a project, lasting months, would be worthwhile if it could give a greater accuracy affecting significantly the study. A special study may, however, be called for electrification proposed for an unusual section having, heavy gradients,
when incurrence of cost for extended trials for fuel consumption norm maybe justified. Over the routes, which are likely, to be taken up for electrification in foreseeable future such a situation is not likely to arise. In view of a number of variables computer studies are also not likely to be adequate.

4. Loss of line capacity during Electrification:

It has been suggested that the loss of line capacity during electrification should be quantified as cash outflow in the CBA for electrification. However, in such a situation it has to be assumed that the line capacity would have been actually used. Further, it is also to be considered that improved infrastructure associated with electrification would obviate need for some line capacity works, which would then logically go towards credit to electrification. Delaying line capacity works including electrification till the route gets saturated should be avoided as the very work expected to ameliorate the condition of saturation would hinder its implementation. Such a question complicates the issues by rising hidden costs and makes it difficult to quantify the benefits objectively.
Method of Determining Internal Rate of Return (IRR)

First step for determining the IRR is to calculate present worth of two options viz. Diesel Traction and Electric Traction for two trial discount rates, the trial rates being so chosen that in one case the value of differences of present worth of electric traction (say $E_r$) and present worth of diesel traction ($D_r$) is positive and in other case, negative.

With reference to Fig. 1.6.5A.1 below.

at trial rate of discount $i_1$, $> 0$, and

at trial rate of discount $E$, < 0

the IRR is the rate at which $E =$
Annexure 1.6.6

Worked Example

Break Even Level of Traffic & Sensitivity Analysis


The cash flows at a discount factor of 10% for Wardha Ballahrshah Railway Electrification Project is taken from the Project Report in Table 1.6.6A.1, cash flows are aggregated under 7 items as shown therein:

Table 1.6.6A.1

Present worth at 10% discount factor (as acceptable in 1984)

(all figures in Lakhs of rupees)

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Item</th>
<th>Diesel</th>
<th>Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Traction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Cost of Works</td>
<td>146</td>
<td>2310</td>
</tr>
<tr>
<td>2</td>
<td>Cost of Rolling Stock</td>
<td>1062</td>
<td>819</td>
</tr>
<tr>
<td>3</td>
<td>Cost of Power Packs</td>
<td>49</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Maintenance of Fixed Assets</td>
<td>31</td>
<td>290</td>
</tr>
<tr>
<td>5</td>
<td>Operation &amp; Maintenance of Locomotives</td>
<td>3646</td>
<td>1564</td>
</tr>
<tr>
<td>6</td>
<td>Residual value of fixed assets</td>
<td>(-) 3</td>
<td>(-) 57</td>
</tr>
<tr>
<td>7</td>
<td>Residual Values Of Locomotives</td>
<td>(-) 22</td>
<td>(-) 13</td>
</tr>
<tr>
<td></td>
<td>Total cost of Traction</td>
<td>4909</td>
<td>4913</td>
</tr>
</tbody>
</table>

(Note (-) sign denotes cash inflow)

The above figures are now divided between Line and Haulage costs. Line costs are represented by serial Nos. 4 & 6 and haulage costs by the serial nos. 2, 3, 5 and 7. While the Line Costs remains constant, haulage costs are assumed to vary linearly with traffic. The traffic for the above haulage cost being 35.44 gross million tonnes per route km per annum (GTKM/RKM/a).

To assess the effect of variation in the break even level of traffic on changes in the capital cost of Works, exercises are done with the Present Worth of cost of works for electrifications being increased by 10% in one exercise and reduced by
10% in the other. Table 1.6.6A.2 below gives the costs divided in Line costs and Haulage costs. The table gives under electric traction three figures of three scenarios under columns. I, II and III having cost of works at 110%, 100% and 90%. 
Table 1.6.6A.2

Cost of Traction in Line and Haulage costs
(For level of traffic of 35.44 GTKM/RKM/a)

<table>
<thead>
<tr>
<th>SN</th>
<th>Item</th>
<th>Cost of Traction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Diesel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(All figures in Lakhs of Rupees)</td>
</tr>
<tr>
<td>1.</td>
<td>Cost of Works</td>
<td>146</td>
</tr>
<tr>
<td>2.</td>
<td>Maintenance of fixed assets</td>
<td>31</td>
</tr>
<tr>
<td>3.</td>
<td>Residual Value of fixed assets</td>
<td>(-)3</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>174</td>
</tr>
<tr>
<td>HAULAGE COSTS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Cost of Rolling Stock</td>
<td>1062</td>
</tr>
<tr>
<td>5.</td>
<td>Cost of Power Pack</td>
<td>49</td>
</tr>
<tr>
<td>6.</td>
<td>Operation &amp; Maintenance of locomotives</td>
<td>3646</td>
</tr>
<tr>
<td>7.</td>
<td>Residual value of Locomotives</td>
<td>(-)22</td>
</tr>
<tr>
<td>TOTAL 4 to 7</td>
<td></td>
<td>4735</td>
</tr>
<tr>
<td>TOTAL Cost of traction</td>
<td></td>
<td>4909</td>
</tr>
</tbody>
</table>

Similarly another exercise is done with cost of Works remaining constant but with cost of operation, of which fuel/electric energy constitutes the major component, varied in two scenarios as follows:

a) Cost of Diesel Locomotive Operation Increased by 10%. and

b) Cost of Electric Locomotive operations Increased by 10%. These are now shown in Table 1.6.6A.3.
Table 1.6.6A.3
(all figures in lakhs of rupees)

<table>
<thead>
<tr>
<th>SN.</th>
<th>Item</th>
<th>Cost of Traction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Diesel</td>
</tr>
<tr>
<td>1</td>
<td>LINE COSTS</td>
<td>174</td>
</tr>
<tr>
<td>2</td>
<td>HAULAGE COSTS</td>
<td></td>
</tr>
<tr>
<td>a)</td>
<td>Cost of Diesel locomotive operation increased by 10%</td>
<td>5100</td>
</tr>
<tr>
<td>b)</td>
<td>Cost of Electric Locomotive operation increased by 10%</td>
<td>4735</td>
</tr>
</tbody>
</table>

Total Traction Costs

|     | with haulage costs as per 2(a) above | 5274   | 4913    |
|     | with haulage costs as per 2(b) above | 4909   | 5069    |

A graph is now drawn with traffic density as abscissa and Present worth of traction costs as ordinate, each type at traction for each scenario being represented by a straight line calculated in the two tables A.6.6.2 and A.6.6.3. above. The points of intersection of the line representing the Diesel and Electric traction yield the different break even levels. These levels as found from the graph are summarized in Table 1.6.6A.4 below:

Table 1.6.6A.4

<table>
<thead>
<tr>
<th>SN.</th>
<th>Scenario</th>
<th>Break Even level of traffic density (GMT/Rkm/annum)</th>
<th>Percent change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>As per Project Report</td>
<td>35.49</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>When cost of works Is increased by 10%</td>
<td>35.86</td>
<td>+ 9.5</td>
</tr>
<tr>
<td>3</td>
<td>When cost of works is reduced by 10%</td>
<td>32.12</td>
<td>- 95</td>
</tr>
<tr>
<td>4</td>
<td>When cost of operation of electric locomotives increase by 10%</td>
<td>3796</td>
<td>+ 696</td>
</tr>
</tbody>
</table>
5. When cost of operation of diesel locomotives increase by 10%  

30.76 - 13.3

The above exercise shows that the capital cost of electrification is a sensitive input forwarded by the cost of operation of diesel locomotives, and cost of electric locomotive operation being the least sensitive amongst those considered above. Similar exercises should be done with other Inputs.

Figure 1.6.6A.1 containing the graph for determining the break even level and the sensitivity of the inputs is given on the next page.
Evaluation of a Project on Economic Cost Benefit Analysis

1. A proposed capital investments are subject test for profitability. While for a commercial organization the main aim is to maximize profits, investments on national level is subject test for benefit to the society. The economic analysis focuses on welfare of the public as opposed to purely financial profit. Analysis on DCF is adopted for both the analyses. For economic analyses, the cost figures employed are slightly different, being net of duties and taxes and altered to take in account the economic factors: and the discount factors are also different being dependent on public spending.

2. For Indian Railway which is subject to scrutiny by the Parliament of its Contribution for the general Revenues of the Government of India. Financial remunerativeness of its capital expenditure is essential. But since the Indian Railway constitute a major infrastructure for the Nation, its major projects also need to be examined for Social Costs and benefits on Economic Analysis. Such projects are New Lines, Gauge conversion, electrifications or Major investments in workshop or Production Units. If a project, on economic analysis also, is found adequately remunerative, it is considered fit for approval.

3. In the economic analysis following constitute the basic consideration for acceptability of a project The Project should:

   a) Help increase in aggregate consumption of the public.

   b) Help redistribute wealth through increase in consumption by the poorest classes.

   c) Help provide training in skills and vocation and increase employment.

   d) Aid ecology and balance of nature.

   e) Help conserve scarce resource such as fossil fuels.

   f) Help in achieving self reliance to the Nation.

   g) Help improve economy of a favoured group or an area or be in line with the avowed policy of the Government.

   h) Use a technology which can be sustained and maintain.
i) Provide Consumer’s surplus.

4. Externalities: There are some considerations which are pervasive but cannot be imparted an appropriate value for inclusion in the cost benefit analysis. Such considerations are called externalities and at times may favoured taking up a project. For example, provision of electrically operated commercial rail services may, by reducing road traffic through the city, result in reduced pollution and congestion yielding improved health and reduced accidents in the city in addition to the quantified benefits. These advantages are externalities. There may also be negative internalities though risk of thefts of OHE, which may result in traffic dislocations or need to police them. While carrying out the economic analysis the externalities also need to be examined in a narrative form.

5. Inputs for Economic Analysts:

The algebraic equation for economic analysis can be expressed as:

\[
\text{Social gains} = \text{Social benefits} - \text{Social costs}
\]

In other words the present day consumption sacrificed by the public by choosing a project for future benefit is in the real sense the social cost of the project. Accordingly the economic study for Railway electrification uses costs which are adjusted from the market costs as follows:

a) Prices adopted are net of taxes and duties which are in the nature of transfer payments. Market prices do not represent true costs.

b) Tradeable commodities in which the country is net importer are valued at their C.I.F. prices.

c) Electric energy and diesel oil are valued at cost including delivery costs at the nominated point on the Railway Network. The cost of electricity is, the cost of production and not the cost charged by the Power Supply Authorities.

d) Cost of residential quarters, being in the nature of a social obligation is not taken in to account.

e) Shadow Pricing is resorted to in order to give due importance to the most desirable features of the project, such as,

i) Foreign exchange may be given a premium of say 15% to 20% to denote its scarcity value

ii) Fossil liquid fuels and metals such as copper which are considered to be exhaustible in not too distant future may be given a further premium of say, 10 to 15%.

iii) Creation of employment opportunities in a country having chronic unemployment being most desirable, labour cost of the project may be taken at a lower value, say of 60% of the prevailing market rate.
6. The comparison between economic and financial cost benefit analysis is given below

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost Benefit Analysis</th>
<th>Economic</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Method of appraisal</td>
<td>DCF</td>
<td>DCF</td>
</tr>
<tr>
<td>b) Gain</td>
<td>Commercial</td>
<td>Social</td>
</tr>
<tr>
<td>c) Evaluation</td>
<td>On market costs</td>
<td>On modified costs high when capital is scarce i.e. postponement of consumption to the public causes severe hardship.</td>
</tr>
<tr>
<td>d) Rate of Discount</td>
<td>On market cost of capital 10% till 1991 12% at present.</td>
<td>12% at present.</td>
</tr>
<tr>
<td>e) Choice of project</td>
<td>That which gives maximum profit.</td>
<td>That which gives maximum benefit to public.</td>
</tr>
<tr>
<td>f) Shadow Pricing</td>
<td>Not applicable</td>
<td>Adopted to high light desirable features to national economy.</td>
</tr>
</tbody>
</table>

For example, the government policy may consider favouring the rural sector. Similarly, the preference may be to projects in a particular backward area; or a project saving in fossil liquid fuel, being, in line with government's policy. Such projects may have to be given greater emphasis. A value judgment has to be introduced in the economic analysis. One means to introduce this judgment through the use of “Shadow” pricing of the inputs.

The discussion in the text is in accordance with the economic analysis carried out in “Study of Relative Economics between Diesel and Electric Traction.”
CHAPTER 7
RECONNAISSANCE SURVEY

1.7.1 Introduction

A regular Railway Electrification survey takes months to prepare the Project Report. It requires a Survey Organization to be set up, the Survey being a part at the Surveys sanctioned by the Ministry of Railways and taken up on the zonal Railways. Such a survey is subject to administrative delays. Frequently for routes identified for Railway Electrification, it is desired to make a rapid assessment of its feasibility and cost. At this stage it is not necessary to go into details of preparation of plans, but merely to ensure feasibility and to obtain an approximate idea of cost, say within 10 TO 15 % of its likely cost and ascertain the likely rate of return on the capital. A Reconnaissance Survey carried out rapidly within about six weeks at this stage with the existing Project Organization and where no project organization exists, with the open line organization, can provide in the Reconnaissance Survey Report all the basic data within a degree of accuracy necessary for the administrative decision to take up the project. Result of such a survey may be used either to sanction a Project for Electrification of a route, particularly for routes with high density of traffic, or to sanction a detailed survey. The Reconnaissance Survey bases its study on averages of volume of work carried out in the earlier projects and on unit costs derived from one or two projects completed recently or nearing completion. A quick inspection at the route is carried out and discussions with the open line officials, the power supply authorities concerned, and the Department of Telecommunications are held. These normally yield adequate data to prepare the Reconnaissance Survey Report. The methodology which may be adopted is described in this chapter. The officer belonging to the Electrical discipline coordinates.

1.7.2 Traffic Survey

The traffic survey is based on the open line Railway’s statistics of existing and forecast traffic data. As these forecast refer generally to more immediate future, for electrification study these data have to be extended to longer perspective at say 15 to 23 years. Assistance from, the perspective planning figures of the Railway and of the Railway Board should also be obtained to arrive at the traffic forecast figures for the survey. As electrification is taken up on high traffic density important routes adequate forecast data is generally available which can be collected and presented. The operating officer entrusted with the survey presents the forecast data year wise in terms of nett tonne km per km per day for goods and passenger km per day per km for passenger traffic for the route. In the forecast he has also to cover the following issues:

a) Whether heavy haul goods trains are expected to run on the route,

b) Will change of traction points need yard remodelling.
c) Will lines for the industrial sidings or to mining areas need to be wired, if so, the route lengths which will have to be added to the electrified section and the traffic expected on these lines.

1.7.3 Signal and Telecommunications Survey
This survey includes:

a) Type and condition of the existing signal Installations on the route.
b) Major signaling works proposed or in hand on the route, either as pure signaling works or as part of other remodelling or doubling works.
c) Details obtained from the DOT of sections lengths where they require BT and RC to be provided on the OHE. Their consent to the use of 2 x 25 kV AT system should also be obtained.

1.7.4 Civil Engineering Survey
This survey includes the general description of the route, the details which are Important from the aspect of adequacy of electrical clearances for passage of OHE and the construction works being taken up. Following items need to be examined:

a) The terrain, its meteorological conditions and the type of soil encountered along the route.
b) Heavy overlines structures such as road over bridges, flyover bridges and head room available.
c) Long deck type and through girder bridges.
d) Tunnels.
e) Remodeling and doubling works and their targets which may affect Electrification works.

1.7.5 Electrical Engineering Survey
The officer belonging to this discipline works as the coordinating officer for the survey in obtaining data, and decisions involving more than one department. Electrical Survey inter-alia includes:

a) Information and commitment in regard to Traction Power Supply from State Electricity Board and or other power supply authorities,
   i) Availability of power, its tariff, and locations of points of supply,
   ii) Tentative Location of traction substations,
iii Cost to be borne by the Railway for the capital works of power supply authority to effect supply.

b) Information from open line authorities in regard to;
   i An idea of approximate track km to be wired in major yards,
   ii Whether a new electric loco shed is required for the route, if so. Its likely location,
   iii Whether a new Remote Control Center is required or the existing one may be extended/augmented.

1.7.6 Maps, Plans and drawings to be obtained

Maps, plans and drawings and working time table are required to be obtained from, the open line and the power supply authorities , These are:

a) From the Open Line:
   I Roll diagram of the section
   II Route maps of the contiguous electrified sections showing thereon the locations of traction substations, power supply transmission lines, the electric loco sheds and the Remote Control Centers.
   III Section Working Time Table

b) From the Electricity supply Authorities :
   I Route map of EHV power transmission lines and substations as existing
   II Plans for new substations and EHV transmission lines expected to be constructed in the area in near future: plans of the State Electricity authority as well as those of Central Electricity Authority should be collected.

1.7.7 Motor Trolley Inspection

The details collected and discussions held with the open line officials give to a large extent, the quantum of the work involved pertaining to three engineering disciplines. Armed with this information, the line officers of all the disciplines viz. civil, electrical, operating, and signal & telecommunication conducting the reconnaissance survey, carry out a joint inspection of the route by motor trolley or OHE inspection car. Apart from the installation pertaining to their own discipline the team should note the following points:

a) At Major yards: their suitability for change of traction, if new lines are required then availability of land for the extension: approximate km of yard lines to be wired.

b) At Stations: type of signalling and block instruments, additional track circuits to be provided requiring re-sleepering on concrete sleepers.
c) Clearance under heavy overline structures, through girder bridges and tunnels. A general idea of improving the clearance as found feasible from the site conditions.

d) Availability of suitable site for location of an electric loco shed at the preferred point.

d) Availability of suitable sites for traction substations, maintenance depots, staff quarters and for construction depots and their sidings.

f) General idea of terrain, flood levels, length of route likely to be formed as being exposed location, curves, gradients, and overhead power line crossings.

g) All weather road approaches to the route.

1.7.8 Assumption of Norms

To estimate the volume of work some assumption may be as good approximations for working out the quantum of work and its cost. These are based on averages over a number of projects completed in the past. These are:

<table>
<thead>
<tr>
<th>Item</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Ratio of track km to route km</td>
<td>2.4 to 2.6</td>
</tr>
<tr>
<td>b) Distance between traction substations</td>
<td></td>
</tr>
<tr>
<td>i) with BT &amp; RC</td>
<td>40 to 50 km</td>
</tr>
<tr>
<td>ii) Without BT &amp; RC</td>
<td>50 to 80 km</td>
</tr>
<tr>
<td>iii) with 2 x 25 kV AT system</td>
<td>80 to 100 km</td>
</tr>
<tr>
<td>c) Interval between Supply Control Posts</td>
<td>One or two block sections</td>
</tr>
<tr>
<td>d) Number of 25 /0.240 kV Auxiliary transformers for power supply to cabins, level crossings and stations</td>
<td>20 to 25 per 100 route km</td>
</tr>
</tbody>
</table>

1.7.9 Establishment of ‘Module’ unit costs and total cost of Work.

A break up of the entire Project work in component ‘Module’ activities covering all the engineering disciplines is shown in the spread sheet as given at Annexure 1.6.1. Module costs are converted /worked out to per unit basis for a few recently completed projects. Percentage changes in the costs, which may have occurred since their completion should be assessed and applied to update these unit costs. For the project under survey, having obtained the work content on completion of the reconnaissance, unit costs thus obtained may be applied to obtain the
cost of the project. From the total cost so calculated the overall cost per track km and cost per route km should be derived. This gives a general comparison of the cost and the trend of costs of the Electrification projects. If, however, there are significant peculiarities in the project under examination, these need to be examined on their own merit closely. For example so for Indian Railways have no experience on execution of work for 2 x 25 kV AT system as such quick assessment of cost through previously determined 'Module' unit costs will not be possible for electrification at this system and a detailed estimation may be called for. A worksheet shown in Annexure 1.7.1 gives the proforma to be adopted for working out the Project costs from 'Module' Unit costs of component works. Further break up of costs department-wise, for preliminary expenses or for general charges etc. may also be done to analyze cost trends and exercise scrutiny. An example of such cost break up is given in Annexure 1.7.2.

1.7.10 Remunerativeness of the Electrification Project.

On obtaining the total cost of the project, cost benefit on DCF technique is possible using the anticipated traffic densities and the Railway's statistical data for operation and maintenance as explained in Chapter 6. As an alternative, pending detailed study, a quick assessment of the expected IRR is also possible, using a previously prepared Nomogram. This is based on the assumption that for a given cost per route km for electrification the IRR is dependent on traffic density. To construct the Nomogram, one or two recently completed projects, (also selected for calculation of unit costs) are taken. The discounted cash flows are divided between line and haulage costs, in accordance with the example shown in Chapter 6 for calculation of the Break Even level of traffic. Tables of cash flows for haulage costs are made out for different traffic densities and these figures are selected such that for the given costs of electrifications and different traffic densities IRR values of 10% to 24% is obtained. This exercise is repeated for a 10% increase in cost of work. Two series of point are obtained for the actual cost and for the 10% increased cost for each project. Two projects, when chosen give a measure of the likely scatter in the assessed value of expected IRR on the Nomogram. Curves are now drawn for each project with abscissa giving traffic density in gross million tonnes per route km per annum and the ordinate giving the value of IRR. Two Lines, one at cost and the other at 110% of the cost are drawn for each completed project. Each curve is labelled giving its cost per route km. This graph having 4 lines pertaining to two project serves as a Nomogram to ascertain the IRR, expected for the project under examination; the point being found by inspection, corresponding to the expected traffic density and interpolated amongst the curves on an imaginary line representing the cost per route km as calculated from the prepared estimate, the two sets of curves of the completed projects yield a range, in which the IRR of the project under examination is expected to
grow Fig. 1.7.1 Illustrates this exercise. Such a study of remunerativeness is not possible for extension of electrification on short spurs or those interconnecting two electrified routes, as the synergy effect on the electrified network due to this being predominant, can be justified at much lower traffic densities, but needs a more detailed study of improved traffic mobility.

1.7.11 Practical examples in the form of Annexures as detailed below are enclosed:
Annexure 1.7.3 Index Plan (Fig. 1.7.2)
Annexure 1.7.4 Index Section (Fig. 1.7.3)
COST ASSESSMENT OF R.E. PROJECT BASED ON ‘MODULE COSTS’  
Annexure

1.7.1.

SECTION : ____________
RAILWAY : _____________

<table>
<thead>
<tr>
<th>S. N.</th>
<th>ITEM</th>
<th>UNIT</th>
<th>QT Y</th>
<th>UNIT COST</th>
<th>MATRIX OF COMPONENT COSTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ELEC</td>
<td>CIVIL</td>
</tr>
<tr>
<td>1</td>
<td>ROUTE KILOMETRES</td>
<td>Km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>TRACK KILOMETRES</td>
<td>Km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>WAY SIDE STATIONS</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>LEVEL CROSSINGS</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>JUNCTION STATIONS</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>MAJOR YARDS</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>TRACTION SUB-STATIONS</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>SSP's AND SP's</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>TRASMISSION LINES</td>
<td>Km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>REMOTE CONTROL CENTRE</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>OHE WORKSHOP &amp; DEPOTS</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>PSI WORKSHOP &amp; DEPOTS</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>BOOSTER TRANSFORMER STATIONS</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>AUXILIARY TRANSFORMER STATIONS</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>ELECTRIC LOCO SHEDS</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>STAFF QUARTERS</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>YARD REMODELLING &amp; TRACK WORK</td>
<td>Km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>MODIFICATION TO CIVIL ENGG. STRUCTURES</td>
<td>LS/Km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>COLOUR LIGHT SIGNALS</td>
<td>UNIT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>INTER LOCKING &amp; TRACK CIRCUITS</td>
<td>UNIT &amp; (Km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>for RES LEE PERI NG</td>
<td></td>
<td></td>
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<td></td>
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<td>---</td>
<td>------------------</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>21</td>
<td>TELECOM CABLE INSTALLATIONS</td>
<td>Km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>MISC. PAYMENTS TO D.O.T, S.E.B. ETC</td>
<td>LS/Km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>GENERAL ADMIN. &amp; CONST. ORGN.</td>
<td>LS / Km</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Annexure 1.7.2

Break up of Unit Cost of Railway Electrification in Different Activities

1. To enable monitoring of costs of Railway Electrification activities so as to effect their control, an analysis of the cost of the project component activity wise is required. This helps comparison of the costs with other Railway Electrification Projects. For a typical project the distribution of costs discipline-wise in per cents is as below approximately:

- Electrical Engineering  54.3 %
- Civil Engineering  14.5 %
- S.& T. Engineering  31.2 %

(In the above percentages the administrative and general charges are included prorata.)

2. Table 1.7.2A. gives an analysis of costs per route km and cost per track km of two Railway Electrification Projects completed in 1980s. It is expected that although individual costs may change with time the relative percentages should remain about the same. The projects considered are:
   a) Jhansi – Itarsi Railway Electrification Project
   b) Gangapur City - Ratlam Railway Electrification Project

<table>
<thead>
<tr>
<th>Tab 1.7.2A.</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SN.</strong></td>
<td><strong>Item</strong></td>
</tr>
<tr>
<td>01</td>
<td>OHE, PSI, &amp; Remote Control</td>
</tr>
<tr>
<td>02</td>
<td>Traction Substations &amp; Transmission lines</td>
</tr>
<tr>
<td>03</td>
<td>Loco Shed</td>
</tr>
<tr>
<td>04</td>
<td>Telecom. Works</td>
</tr>
<tr>
<td>05</td>
<td>Signaling Works</td>
</tr>
<tr>
<td>06</td>
<td>Civil Engg. Works</td>
</tr>
<tr>
<td>07</td>
<td>Payments to DOT &amp; Power Supply Authorities</td>
</tr>
<tr>
<td>08</td>
<td>Miscellaneous &amp; General Charges</td>
</tr>
<tr>
<td>TOTAL COST PER:</td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>----------</td>
</tr>
<tr>
<td>(i) ROUTE km</td>
<td>36.89</td>
</tr>
<tr>
<td>(ii) TRACK km</td>
<td>13.64</td>
</tr>
</tbody>
</table>

Note: In the columns giving percentages above

  i) refers to cost excluding miscellaneous and general charges.
  ii) refers to cost including miscellaneous and general charges.
Annexure 1.7.3

Index Plan (Fig. 1.7.2)
CHAPTER 8
FORMAT OF THE PROJECT REPORT

1.8.1 Summary

The Project Report for Railway Electrification should be uniform in chapters and contents. This ensures clarity and assists comparison with other Railway Electrification project reports. It also ensures that neither any important item is left out nor is it bulked with matter not relevant to the subject. The report should consist of two Volumes covering details as below:

Volume -I

The details of the Project; the construction works proposed, the operation and maintenance facilities being set up, the cost estimates and the cost benefit analysis. It should include the details of construction organization, the construction machinery and transport vehicles and the construction depots to be set up.

It should indicate the assets being created, the operation and maintenance organisation required on commissioning, the major maintenance and emergency equipment and vehicles to be provided for maintenance.

Volume -II

Drawings covering the sectioning diagrams of stations and yards, the General Supply Diagram, the EHV transmission system of the State Electricity Authorities relevant to the supply of power from normal and emergency sources; Facilities to be provided for operation and maintenance of electric traction services, the organisation charts for construction and for maintenance. Annexure may contain records of important decision taken with different authorities such as finalisation of location of electric loco shed, the traction power supply points, and the section to be provided with booster transformer and return conductors as well as the decision to include nominated remodelling works in the electrification designs or to execute them. The reference and authority to the norms and costs taken for the cost benefit analysis should be included in the annexure.

1.8.2 Contents of Volume-I

The chapters of volume should be organised as below:

1.8.2.1 Chapter-I - Highlights of the Project

It should contain general highlights of the project done with the route map, special features if any, the importance of the route to Indian Railways and the advantage, the Electrification is expected to give to the Railways. The chapter should include
briefly the highlights of the contents of the different chapters of the report as executive summary. It should include

- Traffic, existing and forecast through about next 15 years.
- The forecast of locomotives required and their basis.
- The extent of wiring to be done in yards, at stations and for the private sidings
- Description of the terrain, extent of stretches within ‘exposed’ and ‘polluted’ zones, gradients and type of soil.
- Power supply arrangements finalised with Supply authorities.
- Remote control and emergency control arrangements
- Provision of electric locomotives sheds and outstation maintenance facilities.
- Routing of ODCs, special restrictions to their movement, if any.
- Remodelling and doubling works under progress, or sanction and the extent to which to be taken in account in designs of OHE.
- Sections to be provided with booster transformers and return conductors.
- Sections to be provided with 2 X 25 kV AT system.
- Existing signalling system and works to be done
- Details of Telecommunications cables, size and specifications, to be provided, additional circuits to be introduced.
- Total cost of the Project, major advantages accruing to the Railways as a result of the project and the IRR expected.
- The time schedule for completion of the project.
- Important technological advancements and/or economy majors introduced.

1.8.2.2 Chapter-II- Traffic Survey

It should contain the details of traffic forecast figures and the basis for arriving at the figures. The assumption made should be recorded. It should, inter alia contain the following:

- Existing goods and passenger traffic,
- Forecast of traffic for next 15 years and its basis,
- Forecast of special type of trains such as long haul goods or super fast trains, passenger trains
• Assessment of locomotives required for goods and passenger services and their basis.

1.8.2.3 Chapter III: Civil Engineering, containing:

• Topography of the terrain, rivers, bridges and tunnels, and the ruling gradient.
• Track structure, plans for its upgradation.
• Important civil engineering works to be taken up for:
  a) Locomotive shed,
  b) Remote control Centre,
  c) Service buildings,
  d) Staff quarters,
  e) Yard remodelling and slewing of track,
  f) Open line civil engineering construction works and their coordination with electrification works,
  g) Works of improvements to clearances to overline structures, through girder bridges, tunnels, water columns and platform shelters to suit 25 kV ac traction clearances.
  h) Important technological advances and economy measures proposed to be adopted.

1.8.2.3 Chapter IV: Electrical Engineering, containing:

• Designs of the system adopted, whether conventional 25 kV A.C., or with BT and RC, or 2x25 kV AC AT system or any other system,
• Designs of OHE adopted and its basis,
• Design of Power Supply equipment,
• Designs of Remote Control system adopted.
• Arrangement made for traction power supply, its reliability and arrangements for emergency power supply from electricity authorities and from the adjacent electrified sections.
• Tariff negotiated on power supply, means to be provided to overcome the penal provisions,
• Maintenance facilities for electric locomotives.
• Maintenance facilities for OHE, PSI and Remote Control, their locations and provision of road and rail emergency and maintenance vehicles
• Technological improvements and economy measures introduced.

1.8.2.5 Chapter V: Signal Engineering, containing:

Existing Signals, and the proposed colour light signals,
- Signalling works proposed at major stations and yards.
- Modifications proposed for train passing block Instruments,
- Existing Interlocking and their proposed modifications,
- Existing track circuits, their proposed modifications and new track circuits proposed (giving track km to be resleepered with concrete sleepers for the purpose)
- The programme of work indicating the programme of non interlock working at stations.
- Maintenance facilities to be provided for the new Installations,
- Important technological improvements and economy measures proposed.

1.8.2.6 Chapter VI: Telecommunication Engineering, containing:
- System of telecommunications proposed, size of the cable, location of the repeater stations,
- Additional traction control circuits to be introduced
- Emergency Control Telephones
- New administrative telephones, additional local exchanges, and trunk lines to be added for the electric traction service.
- Maintenance facilities for the new telecommunications Installation.
- Technological Improvements and economy measures proposed.

1.8.2.7 Chapter VII: The Construction Organization, Containing:
- Administrative set up.
- The scheme of work, time schedule as worked out through Critical path Method / Programme Evaluation and Review Technique (CPM/PERT).
- The field organisation, department wise, and programme of work of each discipline covering, in addition:-
  - Electrical: location of contractor’s depots requirement for construction equipment, and programme of traffic blocks for work.
  - Civil Engineering: programme of work on bridges and tunnels involving traffic blocks,
  - Signalling: programme of non-interlock working,
  - Telecommunications: Monitoring the programme of modifications of the DOT circuits and removal of their overhead crossings
• Scheme of Coordination internal and external to the project organization and of periodic review of progress of Works.

1.8.2.8 Chapter VIII: The Maintenance Organisation
It should contain the recommended maintenance and operating organisation for the electrical and signal & telecommunications discipline for the assets created based on approved yardsticks and current usage on open line organisation.

1.8.2.9 Chapter IX: Financial Appraisal
It should contain details of cost estimates, the norms and the sources and authority for the norms adopted. Following details should be included:

• Basis of the cost estimates.
• Norms adopted for CBA, their source and authority
• Cost Estimates for the work,
• Cash outflow year wise for
• Construction phase, and
• Operation and maintenance phase.
• DCF Tables,
• IRR of the Project and break even level of traffic,
• Sensitivity Analysis,
• Unit and ‘Module’ costs, cost per route and track km, cost discipline wise and activity wise.
• Comparison of the costs and cost break up with those of recently completed projects or those nearing completion,

1.8.3 Contents of Volume II
The volume II should contain the following drawings and charts:

• The sectioning diagram,
• The General Supply Diagram
• Grid Substation interconnection diagram of Power Supply Authority,
• Telecommunication Cable tapping diagram,
• Location of OHE, PSI and Remote Control maintenance depots
• Location of Telecommunications maintenance depots
• Maintenance organisation charts for:
• OHE,
• PSI & Remote control,
• Electric locomotives,
• Signalling,
• Telecommunications.
• Operating organisation chart for:
• Remote Control,
• Traction locomotive Control,
• CPM/PERT chart for the programme of work

• ANNEXURES

Copies of policy decisions affecting Electrification works, and of letters or minutes of the meetings containing important decisions should be annexed, notably

a) Location of Power Supply Points, Financial commitments made to the supply authority for affecting the Power supply.
b) Decisions regarding freezing yard remodelling works and/or future works to be taken in design of Electrification works.
c) Source/ authority for the norms and costs adopted for estimates and for working out the CBA,
d) Decisions in regard to modifications of heavy over head lines structures agreed to by the open line,
e) Any other policy issues vital to the project.

-----
CHAPTER - 9

ESTIMATION OF QUANTITIES

1.9.1 General

As soon as a project is sanctioned, some items of supply, which are either controlled or need a long lead-time are required to be ordered. In addition items of work to be included in the schedule of the tenders have to be quantified quite frequently even before the drawings are finalized. The method of estimation and the formulae used for such estimations is furnished in this report. These are based on experience of past projects. Estimation of items which can be counted off or directly measured from finalized drawings are not given as their estimation requires no further explanation.

1.9.2 Critical Materials

Railway Electrification requires large quantities of steel sections, galvanized or painted, cement, and copper. Their availability in the country has passed through periods of shortages. Steel sections of required sizes cut to required lengths have to be included in the manufacturing programme of the steel plants. After manufacture they have to be fabricated and then galvanized. In view of their requirement in bulk, the transportation and the processes are cumbersome and take time. Cement has till recently been controlled requiring advance planning to be done. The country is a net importer of copper and zinc (required for galvanizing); at times special imports may need to be arranged. Other items solely required for Railway Electrification such as 25 kV solid core insulators, section insulator assemblies or regulating equipment also need advance planning, since the approved manufacturers will produce them only if a demand in economic lots exists from such projects, there being no other customers. These materials are considered critical as their timely availability is essential. The list, however, is dynamic and varies from time to time. It is a prudent practice to draw up a list of such critical materials on sanction of a project and commence action for their procurement. In addition, at times it is desirable to draw up the schedule of quantities for the tenders to be invited for OHE erection work even prior to finalisation of the entire set of pegging plans. These quantities may be estimated within to -25 to +25 per cent of the actual requirement. For estimation of such quantities within the above percentage, empirical formula has been evolved by the Railway Electrification project authorities. These are given below in Table 1.9.1.

Table 1.9.1 Formula for approximate estimation of quantities for selected items
<table>
<thead>
<tr>
<th>S.N.</th>
<th>Item</th>
<th>Unit</th>
<th>Requirement per Track km Open route</th>
<th>Yard</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Cement for OHE</td>
<td>tonne</td>
<td>23</td>
<td>24.6</td>
</tr>
<tr>
<td>2.</td>
<td>Copper for conductors and droppers excl. catenary</td>
<td>tonne</td>
<td>1.141</td>
<td>1.218</td>
</tr>
<tr>
<td>3.</td>
<td>Catenary, cadmium copper</td>
<td>tonne</td>
<td>0.780</td>
<td>0.765</td>
</tr>
<tr>
<td>4.</td>
<td>Catenary, aluminium alloy</td>
<td>kg</td>
<td>384.3</td>
<td>410</td>
</tr>
<tr>
<td>5.</td>
<td>Aluminium conductors</td>
<td>kg</td>
<td>521.6</td>
<td>---</td>
</tr>
<tr>
<td>6.</td>
<td>Steel, Galvanized 93 mm² anticreep wire</td>
<td>kg</td>
<td>105</td>
<td>92</td>
</tr>
<tr>
<td>7.</td>
<td>Structural steel + SPS</td>
<td>tonne</td>
<td>8.4</td>
<td>9.5</td>
</tr>
<tr>
<td>8.</td>
<td>Zinc for galvanizing</td>
<td>kg</td>
<td>546</td>
<td>617</td>
</tr>
<tr>
<td>9.</td>
<td>Bracket tube 29.9/38 mm dia</td>
<td>m</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>10.</td>
<td>-do- 40.9/49 mm dia</td>
<td>m</td>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>11.</td>
<td>OHE Bracket assembly</td>
<td>no.</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>12.</td>
<td>Section insulators</td>
<td>no.</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>13.</td>
<td>Regulating equipments</td>
<td>no.</td>
<td>1.6</td>
<td>2.7</td>
</tr>
<tr>
<td>14.</td>
<td>Mild steel structure bond</td>
<td>no.</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>15.</td>
<td>Register and stay tube 28.4/33.7 mm dia</td>
<td>m</td>
<td>85</td>
<td>95</td>
</tr>
<tr>
<td>16.</td>
<td>Insulator, bracket</td>
<td>no.</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>17.</td>
<td>-do- stay</td>
<td>no.</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>18.</td>
<td>-do- 9 tonne</td>
<td>no.</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>19.</td>
<td>-do- section</td>
<td>no.</td>
<td>0.4</td>
<td>1.0</td>
</tr>
<tr>
<td>20.</td>
<td>-do- post</td>
<td>no.</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>21.</td>
<td>25/0.24 kV AT</td>
<td>no.</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>22.</td>
<td>ATD</td>
<td>no.</td>
<td>1.33</td>
<td>2</td>
</tr>
<tr>
<td>23.</td>
<td>Termination Assembly</td>
<td>no.</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>24.</td>
<td>Guy Rods</td>
<td>no.</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

[Note: Cement calculations are based on presumption of 20 foundations of having average volume 3.5 cu.m. & ratio of 1:2:4.

Zinc calculations are based on 65 kg zinc required per tonne of steel for depositing 610 gm./sq. m. (non polluted area)]

**1.9.3 Conductors required for OHE**

For the different types of conductors used in the OHE extra lengths over the lengths measured from the pegging plans are required to be provided as erection allowance.
Amount of raw copper required to produce this length of finished copper conductor requires further manufacturing allowance to be provided. The allowances to be provided for and the weight per meter of the conductors are given in Table 1.9.2 for use in their estimation of tonnage.

Table 1.9.2

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Item</th>
<th>weight (kg/m)</th>
<th>Extra allowance in % for erection</th>
<th>manufacture</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>Copper conductors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1)</td>
<td>65 mm$^2$ cadmium copper catenary wire</td>
<td>0.5973</td>
<td>2.5</td>
<td>7.5</td>
</tr>
<tr>
<td>2)</td>
<td>150 mm$^2$ cadmium copper span wire</td>
<td>1.1692</td>
<td>2.5</td>
<td>7.5</td>
</tr>
<tr>
<td>3)</td>
<td>107 mm$^2$ hard drawn contact wire</td>
<td>0.9612</td>
<td>2.0</td>
<td>4.5</td>
</tr>
<tr>
<td>4)</td>
<td>105 mm$^2$ annealed jumper wire</td>
<td>0.982</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>5)</td>
<td>50 mm$^2$</td>
<td>0.452</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>6)</td>
<td>7 mm dia</td>
<td>0.342</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>7)</td>
<td>5 mm dia</td>
<td>0.1746</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>b)</td>
<td>Other wires and conductors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8)</td>
<td>93 mm$^2$ galvanized steel anticreep wire</td>
<td>0.7314</td>
<td></td>
<td>5.0</td>
</tr>
<tr>
<td>9)</td>
<td>SPIDER all aluminium return conductor</td>
<td>0.652</td>
<td></td>
<td>5.0</td>
</tr>
<tr>
<td>10)</td>
<td>RACOON ACSR earth wire</td>
<td>0.318</td>
<td></td>
<td>5.0</td>
</tr>
<tr>
<td>11)</td>
<td>Aluminium alloy catenary</td>
<td>0.3203</td>
<td></td>
<td>5.0</td>
</tr>
</tbody>
</table>
1.9.4 Estimation of lengths of the conductors

The lengths of the conductors are estimated from the finalized lengths indicated in the pegging plans. Some conductors are used at more than one location. For copper conductors, aluminium alloy catenary and for the 93 mm² anticreep wires the formula adopted to calculate their lengths are given below,

As measured from the pegging plan | Length required in km
--- | ---
a) 65 mm² cadmium copper catenary wire,
- For ONE, ‘a’ track km | a
- for ‘b’ no. of head spans:
  @ of 0.065 m per span | 0.065b
  Total | (a + 0.065b)
( Note : The anti creep is now 93 mm² galvanized steel, wire)
b) 107 mm² copper contact wire
- For normal OHE, a track km | a
- For Tramway type OHE,
  ‘b’ track km | b
- For section insulator
  stiffeners @ 4 m per insulator
  For ‘c’ no. of section
  Insulators | (0.004 x c)
  Total length of conductor | (a + b + 0.004xc)
c) 105 mm² anchored copper jumper wire:
- @ 5m per
  Overlap say, ‘a’ nos.
  turn-outs say ‘b’ nos.
  isolating switches, say, ‘c’ nos.
  25 kV feeder terminations, say ‘d’ nos.
  cross overs say, ‘e’ nos.
  Total conductor length In km | 0.005x(a+b+c+d+e)
d) 50 mm$^2$ annealed copper jumper wire:
- 8 m per track km of OHE for 'a' track km of OHE 0.008xa
- 7 m per Insulated overlap for 'b' nos. of overlaps 0.007xb

Total conductor length 0.001x(8a+7b)

e) 7 mm$^2$ annealed copper dropper wire:
- 1.7 m per bracket approx., 22 brackets/km. length for 'a' km of OHE 0.0374xa

f) 5 mm dia, copper dropper wire:
- 180 in per track km of OHE, length for 'a' km of OHE 0.18xa
  [approximately 1m for each dropper]

g) 93 mm$^2$ galvanized steel anti creep
- 144 m per anti creep.
  length for 'n' no. of anti creeps 0.144 x n

h) SPIDER all aluminium conductor:
- length of 25 kV feeder wire : 'a' km
- length of return conductor : 'b' km
- length of cross feeders at supply control posts : 15 m * 4 nos. per post, for 'c' no. of posts = 0.06 * 'c' km
- length of feeders from traction substations to feeding posts : 'd' km

Total length of the conductor ( a+b+0.06c+d )

i) Aluminium alloy catenary:
- Total length of complete OHE : 'a' km
  Total conductor length a

j) RACOON ACSR Earth wire:
- Length of double rail track circuits : 'a' km
- Length of track in tunnels: 'b' km.
- Length of track with prestress concrete masts: 'c' km.

Total conductor length: (a+b+c)

1.9.5 Ordering of materials for projects

Before ordering materials for new projects as per assessments made, surpluses available from completed projects should be accounted for, to reduce the inventory level. Apart from the materials required for completion of the project, on completion, some stock of materials has also to be handed over to the open line, hence provision for these should also be made.
PART- 2

POWER SUPPLY INSTALLATIONS
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<th>Title</th>
<th>Page No.</th>
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</thead>
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<td></td>
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<td></td>
</tr>
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<td></td>
</tr>
</tbody>
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Chapter 1

SINGLE PHASE TRACTION LOADS FROM THREE PHASE NETWORKS

2.1.1 Single Phase Power Versus Three Phase Power

Single-phase loads fed from a balanced three-phase system introduce a current and voltage unbalance in the system. These unbalances i.e. the inequalities of the currents and voltages of the three phases create some undesirable effects on the other three phase loads connected to the network.

The distinctive characteristic of single phase power is that it pulsates at double the system frequency and, power is transmitted as wave pulses. If the instantaneous values of voltage and current are $E_m \sin \omega t$, $I_m \sin(\omega t - \phi)$ respectively where $\phi$ is the phase angle between the voltage and current and if the RMS values are $E$ and $I$ respectively, the instantaneous power is given by –

$$E_m \sin\omega t \times I_m \sin(\omega t - \phi) = EI \cos \phi - EI \cos(2\omega t - \phi)$$

The total power consists of constant part $EI \cos \phi$ which represents the average value and a pulsating component of double angular frequency $2\omega$ for which the average value is zero, because the positive and negative half waves of the cosine function within the unit of time cancel one another. Hence, Single phase power pulsates with power maxima and minima following one another in periodic sequence.

\[\text{FIG. 2.1.1}\]
e = voltage, I = current, Pt = Instantaneous power, 
Ps = Apparent volt-ampere, Pw = active volt-ampere

Fig. 2.1.1 Single phase system

The nature of three phase power is altogether different. It is symmetrical when the three current and voltage values are equal and the phase displacements are 120 electrical degrees. A three phase system is equal to the sum of the powers of the three individual single phase systems. The three pulsating single phase powers cancel out in summation; leaving only the active component of constant value with respect to the time i.e. P = 3 EI Cos(φ)(Fig.2.1.2). Thus, there is a fundamental difference between the power flow in single phase and three phase systems.

Fig. 2.1.2

Pt1, Pt2 and Pt3 are instantaneous double frequency components of the three phases.
Pt = average power axis (per phase)
Pw = constant total power
Pt1 = EI Cos(2ωt - φ)
\[ P_{12} = E_1 \cos(2\omega t - \frac{4\pi}{3} - \phi) \]
\[ P_{13} = E_1 \cos(2\omega t + \frac{4\pi}{3} - \phi) \]

### 2.1.2 Resolution of Unbalanced three phase systems into Symmetrical Balanced Systems

The three phase emfs of the generators are always equal and displaced at 120° to one another. However, in an unbalanced system the voltages at any point whatever cannot be equal and the phase displacement also is different from 120°. Hence at any point whatever in an unbalanced three phase system, the voltages taken between parts of phases or between each phase and neutral no longer gives a symmetrical system. The instantaneous power variations are due to the phase currents being no longer the same at every instant, which in turn is caused due to unequal voltage drops in different phases. It is well known that unbalanced three phase systems can be resolved into symmetrical components. Three unbalanced vectors can be expressed as the sum of three systems of balanced vectors. Three balanced vectors are vectors which are equal in magnitude and differ in phase by 120° and can be represented by \( E_1, E'_1 = E_1 e^{4\pi i/3} \), \( E''_1 = E_1 e^{2\pi i/3} \) where \( E_1 \) is the reference vector.

If \( E_a, E_b, E_c \) are the unbalanced voltages in a three phase system, and if \( E_0, E_1, E_2 \) are the reference vectors of zero, positive and negative phase sequence systems respectively then

\[
E_a = E_0 + E_1 + E_2 \\
E_b = E_0 + a^2 E_1 + aE_2 \\
E_c = E_0 + aE_1 + a^2 E_2
\]

where, \( a = e^{i2\pi / 3} \), \( a^2 = e^{i4\pi / 3} \) and \( 1 + a + a^2 = 0 \)

or alternatively

\[
E_0 = \frac{1}{3}(E_a + E_b + E_c) \\
E_1 = \frac{1}{3}(E_a + aE_b + a^2 E_c) \\
E_2 = \frac{1}{3}(E_a + a^2 E_b + aE_c)
\]
In the above the terms in $E_1$ represent a positive phase sequence system of balanced vectors, $E_2$ represent a negative phase sequence system of balanced vectors and $E_0$ a zero phase sequence system of vectors which are equal. It can be seen that with symmetrical loading, only a positive sequence system appears and negative sequence system and the associated losses are the direct result of unbalance.

The positive sequence system has the same direction of rotation as the generator phase voltages, the negative sequence system has the opposite direction of rotation and the zero sequence system has the same magnitudes and phase relationships in all the phases. Figure 2.1.3(a) shows the graphical method of resolution of unbalanced vectors into symmetrical components.

Pure single phase load can be resolved into two three phase systems of equal magnitude, but rotating in opposite directions and both positive and negative sequence currents corresponds
to $1/\sqrt{3}$ times the single phase current. Fig. 2.1.3(b) indicates the resolution of single phase system into positive and negative sequence systems.

### 2.1.3 Voltage Unbalance (Coefficient of Dis-symmetry)

The coefficient of dis-symmetry $K$ or the factor of unbalance is defined as the ratio of negative sequence voltage to the positive sequence voltage, i.e.,

$$K = \frac{E_2}{E_1}$$

and the coefficient of asymmetry is expressed as the ratio of zero sequence voltage to the positive sequence voltage

$$\alpha = \frac{E_0}{E_1}$$

Single phase traction loads tapped across two phases never give rise to zero sequence components and as such, the value of $\alpha$ is always zero.

With single phase loads, the Coefficient of dis-symmetry can be obtained as

$$K = \frac{Z_2}{Z_2 + Z_m}$$

where $Z_2$ = negative sequence impedance of the entire three phase network up to the point of tapping of single phase load.

$Z_m$ = Single phase load impedance.

The impedances can be measured or calculated. Generally, the value of $Z_2$ is low and $Z_m$ very high. It can be seen that the repercussions of single phase loads are reduced as one goes away from the point of tapping and approaches the generating stations, because the value of $Z_2$ is reduced further and further as the length of transmission lines and the number of transformers included get reduced.

### 2.1.4 Positive and Negative Sequence Impedances of Network

Static equipment like transmission lines in the network and transformers have their negative sequence impedance value the same as their positive sequence impedance value. For synchronous machines like alternators this is different. The rotor of an alternator does not block the normal direct flux which turns at the same angular speed but it opposes the
penetration of an inverse flux which with respect to rotor turns at twice the synchronous speed. The normal flux has a complete closed magnetic circuit through stator and rotor where the negative sequence flux has only leakage path to stator as this does not transverse the rotor windings which form an obstruction.

The direct synchronous reactance of an alternator is normally used in calculations under normal service conditions and sustaining short circuit conditions whereas the inverse reactance can be approximately equated to the leakage reactance which is much less than the synchronous reactance. But in a transient condition at the instant of short circuit the rotor circuits especially the damper windings oppose any variation of flux. Under these conditions at the initial instant of short circuit the direct impedance corresponds to the leakage impedance which is also called the sub-transient reactance which is very nearly equal to negative sequence impedance. Thus the direct and the negative sequence impedences of the network as viewed from the single phase tapping point at the initial instant of short circuit can be equated.

The different impedances of Turbo and Hydro alternators are usually as follows:-

<table>
<thead>
<tr>
<th></th>
<th>Direct or positive sequence impedance</th>
<th>Sub-transient reactance</th>
<th>Negative sequence reactance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbo-alternators</td>
<td>130%</td>
<td>11%</td>
<td>11%</td>
</tr>
<tr>
<td>Hydro-alternators</td>
<td>90%</td>
<td>20%</td>
<td>20%</td>
</tr>
</tbody>
</table>

2.1.5  Permissible Voltage Unbalance

If the single phase power tapped between two conductors is $P$ at a voltage $E$ the power in volt-ampere

$$P_m = \frac{E^2}{Z_m}$$

If the direct impedance of the network at the point of tapping is $Z_1$ (per phase value) then the short circuit power at the point of tapping is

$$P = 3(E/\sqrt{3})^2\left(1/Z_1\right) = E^2/Z.$$

where $E$ = line voltage.

Assuming that the negative sequence impedance $Z_2$ of the network is equal to the positive sequence impedance $Z_1$ at the instant of short circuit then

$$P_{SC} = E^2/Z_2$$

where $P_{SC}$ = initial short circuit power.
\[ K = \frac{Z_2}{Z_2 + Z} = \frac{E^2 / P_{SC}}{E^2 / P_{SC} + E^2 / P_m} = \frac{P_m}{P_{SC} + P_m} \]

since \( P_m \) is negligible compared to \( P_{SC} \)
then \( K = \frac{P_m}{P_{SC}} \)

The coefficient of dis-symmetry can be approximately equated to the ratio of single phase load to the three phase short circuit power at the point of tapping. It can be observed that \( K \) the ratio of \( \left( \frac{Z_2}{Z_2 + Z_m} \right) \) is a vector having modulus and phase values.

The phase angle of \( K \) which is the displacement of negative sequence voltage from positive sequence voltage is also equal to \( \phi_2 - \phi_m \) where \( \phi_2 \) is the phase angle of negative sequence impedance and \( \phi_m \) that of load impedance. If \( \phi_2 - \phi_m \) is say \( \theta \) then the three phase voltages in terms of system nominal voltage would be given by

\[ V_{12} = V \sqrt{1 + K^2 + K(Cos\theta + 3\sqrt{Sin\theta})} \]
\[ V_{23} = V \sqrt{1 + K^2 - 2KCos\theta} \]
\[ V_{31} = V \sqrt{1 + K^2 + K(Cos\theta - 3\sqrt{Sin\theta})} \]

The value of \( \phi_2 \) is usually 75° and that of load is about 45° (considering a worst case) then \( \phi_2 - \phi_m = 30° \). The three phase voltages for different values of \( K \) with value of \( (\phi_2 - \phi_m) = 30° \) would be as under:

<table>
<thead>
<tr>
<th>Value of K</th>
<th>Voltages (reference voltage is 100 V)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase 1-2</td>
</tr>
<tr>
<td>2%</td>
<td>101.73</td>
</tr>
<tr>
<td>3%</td>
<td>102.60</td>
</tr>
<tr>
<td>5%</td>
<td>104.36</td>
</tr>
</tbody>
</table>

It is seen that the true voltage between phases 3-1 is practically equal to the positive sequence voltage and that it does not vary with the factor of unbalance i.e. with the magnitude of the single phase load. The other two voltages between phases vary in practice in percentage approximately in proportion to the factor of unbalance.
Generally the following percentages of voltage unbalance can be allowed for the durations indicated without any harmful effects:

- Instantaneously: ... 5%
- For 2 hours: ... 3%
- Continuously: ... 2%

### 2.1.6 Current Unbalance

The current unbalance is the ratio of negative sequence current to rated current. This also represents the ratio of the single phase power supplied to the nominal power of alternator.

When a three phase alternator feeds an unbalanced load the negative sequence components of currents produce a field in the air-gap which has twice the synchronous speed with respect to rotor and induce currents of a frequency 2f. In case of low speed alternators with salient poles usually installed in hydel stations the rotors are fitted with adequate damper windings and these induced currents do not cause any undue heating and a greater unbalance can be withstood. But the case is different with high-speed turbo alternators which are not fitted with damper windings. The currents induced due to the inverse fields are localized at the ends and cause excessive heating.

Turbo alternators can normally withstand the following unbalance currents for given duration.

<table>
<thead>
<tr>
<th>Ratio of negative sequence current to rated current</th>
<th>Acceptable period</th>
</tr>
</thead>
<tbody>
<tr>
<td>60%</td>
<td>Half a minute</td>
</tr>
<tr>
<td>45%</td>
<td>1 &quot;</td>
</tr>
<tr>
<td>35%</td>
<td>2 minutes</td>
</tr>
<tr>
<td>28%</td>
<td>3 &quot;</td>
</tr>
<tr>
<td>20%</td>
<td>5 &quot;</td>
</tr>
<tr>
<td>12%</td>
<td>10 &quot;</td>
</tr>
<tr>
<td>8%</td>
<td>Continuously</td>
</tr>
</tbody>
</table>

These ratios and the durations mainly depend on the dampers and the thermal capacity of the rotor. Modern turbo-alternators are designed to sustain an unbalance of about 10 to 15% continuously. The corresponding values for hydel generators are usually 15 to 20%. There are also various empirical formulae to determine this unbalance. One such empirical rule expresses the time ‘t’ in seconds during which an unbalance ‘u’ can be sustained (ratio of negative sequence current to rated current) as $u^2t = 30$.

The empirical formula gives greater values for unbalance than those indicated in the table above for periods less than an hour. It can be seen that if the negative sequence current is zero, there is no single phase power and if negative sequence current is equal to rated current then the power supplied by the alternator is entirely single phase power.
Current unbalance causes shifting of the neutral point in the voltage vector system due to the fact that the differing phase currents passing through the various impedances between power station and consumer give rise to voltage drops differing in magnitude and phase relationship. Voltage asymmetries are therefore not dependent solely on the magnitude of the single phase loads but also on the place in the network where the loads occur. They are most in evidence at the consumer point and decrease as the power station is approached. When the single phase load is combined with a balanced three phase load the percentage unbalance decreases rapidly with increase of three phase load.

2.1.7 Effects of Unbalance

The negative sequence components of currents produce reverse rotating fields in the generators which induce heavy current in the damper windings. In cases where the generators do not have adequate damper windings, the negative sequence currents induce odd harmonics in stator and even harmonics in rotor. Transmission losses are greater with unbalanced loads than with similar balanced loads. This is because even in an unbalanced system power transfer is only due to positive sequence currents whereas the negative sequence components produce power oscillations with average value zero: but however add to the transformer and line losses in a similar way as reactive currents. For transmission of a given load in kVA over a three phase line as a symmetrical three phase load, the line losses are only half of those for the same amount of load when supplied as single phase load. With pure single phase loading, the three phase line can only carry at the most $1/\sqrt{3}$ times the permissible balanced power. Conversion of single phase loads into balanced loads i.e. the elimination of negative sequence current system may at times be economical even from the point of view of reduced transmission losses.

Unbalanced loads cause unequal voltage drops and cause voltage unbalance which is maximum at the point of tapping of the single phase load. This unbalance is not the same at all points of network and will get reduced proportionately as one gets, further away from the tapping point towards the generating stations or to machines presenting very low negative sequence impedance. Unbalance produces reverse rotating fields in synchronous and induction motors thereby reducing their useful torque and life and increasing their losses. The life of lamps also will be affected if the normal voltage is not maintained. These considerations do not apply to the small consumers who are given single phase loads for simplicity. It can be considered that a multiplicity of small loads balance one another to give approximate symmetry. If the unbalanced loads are small in number but individual demands are great, there is less mutual balancing.

It is quite obvious that consumers of energy expect that supply authorities to maintain a symmetrical three phase voltage system. It is, therefore, reasonable on the part of supply authorities to insist that all consumers who impose considerable single phase loads, should limit their load to such reasonable values so as not to distort the voltage symmetry of the whole or a part of the network.

2.1.8 Measurement of Unbalance
Direct measurement of positive and negative sequence system is valuable and it gives an idea of the usefulness of the balancing equipment installed if any. For this purpose instruments called sequence instruments and sequence networks are used. The principle consists of measuring two line currents through current transformers and producing the necessary de-phasing by sequence networks. The positive and negative sequence components of currents can be expressed in terms of the line currents by the equations:

\[
I_1 = \frac{1}{\sqrt{3}} (I_a + I_b e^{i60}) e^{i30}
\]

\[
I = \frac{1}{\sqrt{3}} (I_a e^{i60} + I_b) e^{-i90}
\]

\[
I_1 = \frac{1}{\sqrt{3}} \left[ I_a + I_b e^{i60} \right] e^{i30}
\]

\[
I_2 = \frac{1}{\sqrt{3}} \left[ I_a e^{i60} + I_b \right] e^{-i90}
\]
With a sequence network fed by two current transformers corresponding to the above equation, the voltage drops are rectified and measured by voltmeters $V_1$ and $V_2$ which can be calibrated directly in positive and negative sequence amperes (Fig. 2.1.4). Interposing transformers are necessary if one of the secondary terminals of both the current transformers has to be earthed.

In another method, the stator of an induction motor is fed from the three phase network, the unbalance of which has to be measured. The rotating field created is the resultant of the positive and negative sequence fields. Under such conditions, if the rotor of the induction motor is rotated at the same speed and same direction as that of positive sequence field, the resultant current induced in rotor is only due to negative sequence currents at frequency twice the supply frequency. The induced rotor voltages can be collected at slip-rings and when rectified, filtered and amplified, enable the direct measurement of unbalance.

### 2.1.9 Methods for Reducing Unbalance Caused by Single Phase Loads

Certain amount of balancing can be achieved by resorting to Vee connected (open delta) of Scott connected transformers. With Scott connected transformers the single phase load is opposed by an equal load of opposite phase as the fluctuation of power in one phase is $EI\cos(2\omega t - \phi)$ and in other $EI\cos(2\omega t - \phi - \pi)$.

### 2.1.10 Substation Connections for Traction supply

It may at first appear that by employing suitable transformer connections a single phase load connected to the secondary can be supplied as a more or less balanced load from the three phase network. There are also connections like delta-star, star-delta and star-zigzag with which a single phase secondary load is associated with currents in all three wires in the three phase system. But in all cases when these single phase loads cause currents in the three conductors in the primary side it can be shown by resolution according to principle of symmetrical components that magnitudes of positive sequence and negative sequence currents are equal, for a given single phase load in all types of transformer connections. There is thus no possible transformer connection which can distribute a single phase load equally on all the three phases of the supply network.

When planning the single phase 50 Hz traction supplies from a three phase network measures are to be taken to distribute the single phase load of the railway as evenly as possible amongst the three phases in a geographic region with the object of avoiding harmful effects on the three phase consumers in the neighborhood of the single phase traction sub-stations and on the three phase alternators feeding the high tension network.
Certain amount of balancing can be achieved by connecting successive sub-stations with single phase transformers to different phases of the supply. When the transformers in each sub-station are connected to different phases of the supply system then certain amount of balancing occurs at the sub-station itself.

2.1.11 Single Phase Sub-stations

A simple arrangement would, therefore, be to connect consecutive substations on different phases. Two transformers are usually provided in a sub-station, one being a stand by. The high tension switchgear is of particularly simple construction as only two of the three conductors of the three phase network need be brought in to each sub-station. On the 25 kV side, a neutral or dead section is located approximately midway between two consecutive substations as the adjacent substations are fed from different phases. Thus no double ended feed to contact wire is possible with this type of transformer connections. The scheme of connections is simple but the voltage drops are considerable. However with double track the impedance of the overhead equipment and consequently the voltage drop can be reduced by paralleling the tracks at every 10 to 15 km. Fig.2.1.5 indicates this type of connection.
It is necessary from the operational viewpoint that the train services should be maintained even when one substation is out of commission due to failure of HT supply or for any other reason. In such emergencies the neighboring substations have to extend the feed beyond the neutral section in order to feed the affected section.

2.1.12 Two Phase Sub-stations

These are sub-stations where there are two separate bus bar systems on the low tension side. Because of the phase differences they must be kept electrically separate. The relative phase displacement may be either 90° with Scott connected transformers or 120° with Vee connected single phase transformers. In such a system there should be at least two transformers in each sub-station. All the three phases are needed at each sub-station. The connections of the transformers are
arranged in such a sequence that the catenary between adjacent sub-stations can be fed from both ends.

In Fig.2.1.6 traction substations with V-connected single phase transformers are shown. In one sub-station the two transformers are connected between R-Y, and Y-B, and in the adjacent sub-station transformers are connected between Y-B, B-R and so on. With this arrangement double-ended (limited to normal supply condition) feed is possible under favourable grid conditions when the voltage drop gets considerably reduced. As two transformers are in the circuit always even when the load is low, the losses will be more. Further, with two separate bus bars with different phases the simplicity of layout and operation is lost. The specific advantage in this arrangement comes at mid section i.e. neutral section in form of better voltage level as compared to one given by single phase connection arrangement.
2.1.13 Scott Connected Transformers

In a Scott connection, two single phase transformers B and H called the base and height elements respectively, having similar secondary windings but having a primary turns ratio $\sqrt{3}/2:1$ are connected as shown in Fig.2.1.7, 2.1.8a and 8b. Since Scott connected group requires all the three phases, the HV side of the sub-station must be three phase. In order to enable the use of identical transformers for purposes of interchangeability it is necessary for the primary winding to have the necessary tappings such that it can either be used as the height element or base element.

There is a $90^\circ$ phase displacement on the LV side and hence two separate bus bar systems with a neutral section in front of sub-station have to be provided. Neutral sections on the overhead equipment are also provided midway between two sub-stations. Under certain favourable grid conditions the contact wire can be fed from both ends. But in order to avoid the transfer of active or reactive power through the overhead equipment in case of any differences of voltage and phase between the HT sub-stations, this is not resorted to generally. These differences may be small if the traction sub-stations are fed from a EHV sub-station connected by low impedance transmission lines which is generally the case on 132 kV/220 kV grid. Therefore, in such cases it may be possible to feed the contact wire from both ends as the impedance of the traction circuit is comparatively higher than that of EHV network which prevents more than a very small transfer of active and reactive power through overhead equipment. In order to make this parallel feed possible, the sub–stations are to be arranged in such a way that the adjacent sides of neighboring sub-stations have the same phase.

The special feature of Scott connection is that equal simultaneous loading of the secondary quadrate phases gives balanced load on the three phase primary side of the network. If the loads are unequal on the secondary side, say $P_1$ and $P_2$ the unsymmetrical single phase load on the network is $P_1-P_2$ whereas with only a single phase transformer the unbalanced single phase load would be $P_1 + P_2$ (say $P$). The voltage unbalance caused by a Scott connected transformer loaded in an unbalanced way is approximately

$$K = \frac{P_1 - P_2}{P_{\text{SC}}} = \frac{J_1 - J_2}{J_1 + J_2} \frac{P}{P_{\text{SC}}}$$

Where $P_{\text{SC}}$ is the short circuit level of the network at that point and $J_1$ and $J_2$ are the currents in the two elements.
SCOTT CONNECTED TRANSFORMERS

THREE PHASE/TWO PHASE CONNECTION

FIG. 2.1.7
With V-connected (open delta connection) single phase transformers the voltage unbalance is approximately

\[ K = \sqrt{\frac{P_1^2 + P_2^2 + 2P_1P_2\cos120^\circ}{P_{SC}}} \]

where \( P_1 \) and \( P_2 \) are the phase loads of the two transformers.

For comparative purposes, the equivalent single phase loads for different loads on the two sections in case of Scott and open delta connections are given below for calculating the voltage unbalance.
Equivalent single phase load

<table>
<thead>
<tr>
<th>Power in the two sections</th>
<th>Equivalent single phase load</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1 + P_2$</td>
<td>With Scott connection</td>
</tr>
<tr>
<td>$P_1 - P_2$</td>
<td>With open delta</td>
</tr>
</tbody>
</table>

$P_1 = P_1^2 + P_2^2 + 2P_1P_2\cos120^\circ$

Generally in the Scott connected sub-stations a third transformer is provided as a stand-by and is used only in emergencies when one of the two service transformers suffers damage. The height and base elements are identical and the necessary alteration can be performed by a simple change in external connections.

Scott connections help in reducing unbalance when the sub-sections are fed at relatively low voltage (i.e. 66 kV or less) where the short circuit levels are low.

2.1.14 Limitations of the conventional 25 kV system

The conventional 25 kV single-phase system of traction using mostly 2 x 12.5 MVA transformers with traction substations spaced at 50 to 80 km apart can cater to the normal traffic requirements admirably on many routes. Increase in traffic over the years results in excessive voltage drop in the catenary. One method to overcome the problem is to replace the existing transformers at traction substations with high power 21.6 MVA transformers. However in course of time with progressive rise in trailing loads, speeds and frequency of train services especially on trunk routes the voltage drop would become unacceptable and before long the need for additional substations will be felt. The conventional power supply schematic virtually calls for near doubling of substations and a corresponding increase in the number of neutral sections which is an unavoidable adjunct of this system. Further increased catenary currents with rail/earth return accentuate the problem of electromagnetic induction and the consequent interference with communication circuits. The rail potential also rises with increased load current.

The problem of electromagnetic interference is sought to be mitigated by providing booster transformers with return feeders. The primary winding (25 kV) of the Booster transformer which is a 1:1 ratio transformer is inserted at fixed intervals of 2.66 km at the insulated overlaps created for this purpose in the catenary while the secondary (3 kV) winding is connected to the return conductor through which the current is made to return to the traction substation. The return conductor is connected to the rail midway between booster transformers to provide the path for the return flowing via the locomotive to the rail. This system effectively suppresses the inductive interference in
neighbouring tele-communication lines. The screening factor which is the ratio of the induced voltage with BT and RC to the induced voltage without BT and RC is around 0.025 for through current. This system though useful in containing the induction problem, however accentuates the voltage drop as booster transformers and return feeders add additional impedance to the traction circuit. In addition arcing at booster transformer overlaps especially at higher speeds and load currents poses special maintenance problems.

2.1.15 2 x 25 kV AT feeding system

To overcome the above limitations and problems, a 50 kV feeding system or 2 x 25 kV AT system was developed and is currently used in Japan, France, USSR and Australia. It is introduced on Indian Railways on Bina- Katni- Anuppur- Bishrampur sections of West Central and South Eastern Railways.

In the conventional system the secondary winding of the high tension 220/132/110 kV/25 kV step down transformer is connected at one end to the catenary and the other end to the rails which are used for return circuit. The 2 x 25kV supply consists of a single phase high tension 50 kV step down transformer whose secondary winding is connected at one end to the catenary and the other end to a feeder carried on a super mast the mid point of the secondary winding being connected to the rails. Every 10 to 15 km or so 54/27 kV auto transformers are installed whose outer terminals are connected between the catenary and the feeder and whose midpoint is connected to the rail.

The feeder and the catenary are in phase opposition and both are at a potential of 25 kV with respect to the rail. This allows the operation of 25 kV locomotives without any modifications. The transport of energy on the traction network being at 50 kV, it is possible by allowing the same voltage drop as on a single 25 kV system, the spacing between the substations can be doubled.

For a new line the choice between a single 25 kV and 2 x 25 kV system is made with the object of reducing the total investment to the minimum, considering the advantage accruing from the use of 2 x 25 kV system.

The transformers in the substation have primary voltage of 132 or 220 kV and a secondary voltage of 55 kV with center tap so that the catenary and the feeder can be fed at 27.5 kV, the center tap being connected to rail.

The substations are so located that in normal condition train operations on schedule should be capable of being kept even when one substation fails and the feed is extended from the adjacent substations. The substation capacity should be such as to meet the instantaneous maximum demand as well as the continuous hourly maximum demand. There should be adequate reserve to permit normal functioning in case of equipment inspection or trouble. The capacity should be enough to meet the future possible increase in trains and also be able to cope up with dislocation and disorder of train operations whenever it takes place.
2.1.16 **Scott and modified Wood – bridge transformer connections with AT feeding**

The Scott connected transformer with AT comprises of main phase winding M and Teaser phase winding T. The voltage of main winding is 132 kV and that of teaser is $132 \times \sqrt{3}/2 = 114.3$ kV. The secondary of both the windings are at 54 kV. The primary is fully balanced when the secondary loads are equal.

In the modified Wood-bridge transformer the primary is a star connection and the secondary is a delta connection in a combination of two sets to obtain the single phase output of the two sets. The single phases of these two sets are called A phase and B phase. The B phase will be connected with the step-up transformer (auto transformer) with winding ratio $1:\sqrt{3}$ to be made equal to A-phase in voltage. When the transformer is used in extra high tension power grid with effective grounding system, the insulation level of primary windings can be economical as the primary winding has a neutral terminal. The three phases on primary are balanced when the loads on each of the single phase sides is same both in magnitude and phase angle. As the neutral potential of primary winding is always constant, the neutral point current will not flow with the load on A–Phase or B –Phase or both A and B phases.
The reason for this is that the impedance of windings on the secondary side seen from the primary side of the transformer is the same in each phase. Therefore the effect of induction on telecommunication line through the neutral point current of the transformer will be reduced. However when the three phase side voltage of electric power grid is unbalanced the neutral point current of primary windings will flow.

2.1.17 Harmonics in traction circuit and remedial measures
The load currents of locomotives/EMUs of thyristor phase control type have usually a higher percentage of harmonic currents as compared to straight diode rectifier type units. The harmonics may affect the electric power signaling and telecommunication equipment.

The allowable limits for voltage wave distortion on electric power grid in Japan are as under:

<table>
<thead>
<tr>
<th>Electric power</th>
<th>$V_n$</th>
<th>$\sqrt{\sum V_n^2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above 154 kV</td>
<td>0.5 %</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Below 66 kV</td>
<td>1.0 %</td>
<td>2.0 %</td>
</tr>
</tbody>
</table>

It is essential to select the control method for loco and EMUs that generates the minimum high level harmonics. The effect of higher harmonics on electric power equipments, tele-communication and signaling circuits are briefly discussed herein.

**Harmonic Interference on power equipments**

Due to the wave distortion on account of many high harmonics, in the voltage and current wave-form, the characteristics of protective relays may get affected.

**Harmonic Interference on communication circuits**

The high harmonics induce noise voltages on telecommunication circuits. The measures against such interference are of three kinds. On the locomotives and EMUs the typical method of reducing high harmonics is to increase the number of divisions on the secondary windings of the main transformer. This would naturally increase the cost of rolling stock. Measures on telecommunication system side include insertion of isolating transformers, use of shielded cables etc. Sheathing with steel tape raises the permeability and is of much effect. The smaller the value of ground resistance of the sheath and the value of sheath resistance the greater the effect. Generally no induction voltage appears between two lines, when the electric potential to ground of each line is equal. But the lines will be out of balance due to the differences of electrostatic capacity and impedance of each line. The cables may have a balance but the equipment connected to the cables causes reduction in the balance of lines. To make up for an unbalance of the line it is advisable to insert coils which assure a high impedance against the ground and a low impedance between the lines (N shaped repeating coils). Other methods include use of carrier systems with the use of frequency not affected by induction noise. Abnormal voltages are drained to ground by use of draining coils, surge arrestors etc. Use of BT and AT feeding systems would also incidentally reduce the induced noise voltages to certain extent.
References

1. The effects of Single-phase loads and their conversion into three-phase loads: Vikton Aigner.


5. M. Garreau – “Cours de Traction Electrique”.
Chapter 2

DETERMINATION OF THE VOLTAGE DROP IN THE CATENARY

2.2.1 Introduction

With any system of traction, it would be necessary to predetermine the voltage drop in the catenary system for a given pattern of traffic for arriving at the most economical spacing of the substations as well as the cross section of the catenary comprising the contact wire and the catenary. The determination of voltage drop on the catenary is rather difficult because the load currents drawn by different trains on the section constantly vary (unlike the static loads on power distribution system) as the moving trains negotiate various gradients at different speeds. In addition, the voltage drop in the substation transformers and the fluctuations in the high-tension supply makes the problem more difficult.

2.2.2 General Considerations

The voltage at the pantograph of the locomotive varies as it moves along from a maximum value near a substation to a minimum value at the Sectioning Post or midway between two consecutive paralleled substations. The current drawn by the locomotive and the impedance of the catenary system including the return circuit determines the voltage drop, on which the efficiency of transmission of power through the catenary system depends. Any type of locomotive designed for a particular voltage is capable of giving satisfactory performance only within a certain range of voltage variation from the nominal voltage. The maximum value of the catenary voltage is governed by the design of the locomotive, the performance of especially that of its auxiliaries, would not be satisfactory below a certain minimum voltage.

The permissible variations recommended by the UIC for different nominal voltages of the catenary are as under.

<table>
<thead>
<tr>
<th>System of traction</th>
<th>Nominal Voltage V</th>
<th>Maximum Voltage V</th>
<th>Minimum Voltage V</th>
<th>Minimum Instantaneous Voltage V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct current</td>
<td>(a) 1,500</td>
<td>1,800</td>
<td>1,000</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>(b) 3,000</td>
<td>3,600</td>
<td>2,000</td>
<td>--</td>
</tr>
<tr>
<td>Single phase</td>
<td>16 2/3Hz 50 Hz</td>
<td>15,000</td>
<td>16,500</td>
<td>12,000</td>
</tr>
<tr>
<td></td>
<td>25,000</td>
<td>27,500</td>
<td>19,000</td>
<td>17,500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>11,000</td>
</tr>
</tbody>
</table>

The catenary voltage variations should be within these permissible limits. In actual practice, in the zone fed by a substation, there may be several trains drawing different currents depending on their
trailing loads, speeds and the gradients of the track. Knowing the relative positions of various trains and their power demands, the impedance of the traction circuit and the voltage of the substation, the catenary voltages can be calculated to ensure that the values are within the permissible limits indicated above.

From the graphic train charts, the positions of various trains at any given instant can be fixed from which the distances of the different trains from the substation can be computed. The resistance offered to the forward motion of trains comprises of the tractive resistance which varies with the speed and the grade resistance which is positive or negative depending on whether the train is negotiating an up gradient or a down gradient. To this value the accelerating effort, if any, positive or negative as the case may be, is to be added. Knowing the total resistance and the speed, from the fundamentals of mechanics, the power required can be computed.

Actually one has to start the graphical construction from the voltage of the farthest locomotive, which is unknown, to obtain the incoming voltage at the substation which is given. This has to be obtained by successive approximations. Starting from the vector \( U_{12} \) the voltage at the transformer output terminals of the substation \( U_5 \) is arrived at, and to this, the internal drop of the transformer is to be added to obtain the input voltage \( U_0 \). (See Fig 2.2.1).

At the time of consideration of a new electrification project, it will be necessary to determine the voltage drops under different conditions of traffic to arrive at the economical spacing of the substations. Even with the existing installations it will be necessary to check the voltage drop whenever the traffic pattern changes.

Though in principle it appears easy to calculate the voltage drops, the equations become more complicated when the currents taken by different trains situated at various points along the track which in turn depend upon the catenary voltage, the voltage variations at the outgoing terminals of the substations and the effect of paralleling the tracks at intervals have to be considered.

A graphical method for quick determination of the voltage drop is described in Annexure 2.2.2.
The various factors affecting the voltage drop for a given load are:

i) Impedance of the traction circuit.

ii) Permissible current densities in the overhead conductors.

iii) Internal drop in traction transformers.

iv) Paralleling of the catenary or overhead equipment.

v) Feeding arrangements of the catenary – (Single or double ended feed)

vi) Influence of the power factor of the locomotives.
The above considerations are dealt with one by one.

### 2.2.3 Impedance of the Traction Circuit

The impedance of the traction circuit can be calculated easily with ac traction, it merely consists of the resistance of the catenary and rail return circuit which can be determined if the cross sections of both are known.

In dc traction resistance per Km of the catenary (at 40°C) is obtained from the empirical formula $18.8/A$ where $A$ is the sectional area of the catenary in mm$^2$. The resistance of return circuit depends on the type of rails, the type of bonding and the insulation resistance of the track with respect to earth which alone determines the quantity of return current leaking to the earth. The return circuit resistance per kilometer is obtained by an empirical formula $0.9/W$, where $W$ is the weight in kg/m of the rail.

The determination of the impedance of the traction circuit in case of single phase traction is more difficult. The value of the kilometric impedance varies considerably for the same section of equivalent copper with the relative disposition of the various elements of the catenary. It also varies with the nature of the soil and is influenced by the presence of parallel tracks. The reactance component of the impedance predominates and as such the total impedance is little affected by the cross section of copper but depends largely on the type of carrier and its distance from the contact wire. The kilometric impedance of traction circuit reduces with increased distance but is nearly constant when the length is more than 10 Km. The following are the measured values of the kilometric impedance of single and multiple tracks for the overhead equipment which consists of a cadmium copper catenary of 65 mm$^2$ section (copper equivalent 40 mm$^2$) and a contact wire of 107 mm$^2$ without RC and BT. The measured values of the impedance with earth conductivity of $2 \times 10^{-2}$ S/m are as under:

<table>
<thead>
<tr>
<th>Single OHE</th>
<th>0.41 /70°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double OHE</td>
<td>0.24 /70°</td>
</tr>
<tr>
<td>Three OHE</td>
<td>0.18 /70°</td>
</tr>
<tr>
<td>Four OHE</td>
<td>0.171 /70°</td>
</tr>
<tr>
<td>Five OHE</td>
<td>0.16 /70°</td>
</tr>
</tbody>
</table>

The impedances can also be calculated from fundamentals, by using the formulae and the method given in Annexure 2.2.1. Generally, it is seen that the calculated values are less than the measured values.

### 2.2.4 Permissible current density in the overload conductor
The permissible current densities should be within acceptable limits of temperature rise of the catenary. For a maximum contact wire temperature of 80°C which is obtained after 20 minutes with a wind velocity of 1 m/s, the admissible current density in contact wire is 4.7 A/mm². In practice a figure of 4 A/mm² for copper and 2 A/mm² for steel are adopted. An overload of 50 percent for three minutes following a continuous output can be allowed. For the maximum demands imposed by the given traffic conditions, the maximum line current can be calculated from which the equivalent copper section of catenary can be determined. For the odd currents that are usually met, a total copper equivalent of 150 mm² has been used for the overhead equipment. In fact, it is the current rating rather than the voltage drop which becomes the governing factor, with reasonable substation spacing.

2.2.5 Internal drop in the traction transformer

In addition to the voltage drop in the catenary there is the internal voltage drop in the transformer which is not insignificant and which increases with a poor power factor. High impedance transformers are used for increasing the safety in the event of short circuits, which may be frequent in service. For a primary voltage of 132 kV, the percentage impedance values of 7.5, 10, 12.5, 13.5 and 20 MVA transformers are usually 7.5, 8.5, 10, 11.5 and 12.5 respectively. The magnitude of the internal voltage drop can be visualized when it is known that these impedances correspond to about 13 to 21 of double track.

2.2.6 Paralleling of the Overhead Equipment.

The overhead equipment of two tracks is paralleled at all the switching stations. This, in fact, corresponds to a scheme of bilateral feed as indicated in the Fig.2.2.2.
For simplicity, consider the case of overhead equipment fed at one end in case of dc. If the resistance per km of OHE is $p$, the resistance at a distance $d'$ is $pd$. Now, if there are two tracks, which are connected in a parallel at an infinite number of points the resistance at any point $x$ is $px/2$ and at a distance $d'$ is $pd'/2$. If the OHE is parallel only at one end the locus of the resistance is a parabola passing through $pd/2$ when $x = d$. If there is another paralleling in between, the resistance will be represented by two successive parabolas. The resistance at any point in between is not the same in proportion, and if the proportionate value is adopted then a correction has to be applied. This can be taken into account by increasing the distance by $e$.

Similar correction can also be applied in the case of ac to the calculated value of the kilometric impedance of a double or multiple track as the paralleling of the tracks is only done at switching stations which are usually 10 to 15 km apart.
2.2.7 Feeding arrangements of the catenary

The voltage drop will be very much less if the catenary can be fed at both ends with the substations working in parallel. Fig. 2.2.3 gives the voltage drop for a constant load moving along from substation A to substation C. It can be seen that with normal working conditions the voltage drop with single ended feed is double as compared to double ended feed. The situation is still worse when substation B is out of commission and when the feeds of substations A and C have to be extended up to B.

A parallel operation of substations is possible if the adjacent traction substations are fed from the same phase of the primary high-tension network. This is not possible in places where the grid is not capable of withstanding the unbalance effects imposed by traction loads. Generally adjacent substations are fed from different phases so as to reduce the effects of unbalance.
With open delta type and Scott type connections it is possible to go in for parallel operation if the adjacent sides of neighboring substations have the same phasing. Such special types of substation connections are not in tune with the inherent simplicity of the single-phase traction system and as such are not resorted to generally. With parallel operation there may also be transfer of active or reactive power through the overhead equipment depending on the magnitude of differences of voltages and phase between the H.T. substations.

2.2.8 Influence of the Power factor of the Locomotives on the Voltage Drop

The power to be developed by a locomotive depends on the load and speed as well as the gradients on the section. If a locomotive develops active power ‘P’ at an efficiency ‘n’ and power factor $\cos \phi$, the apparent power in VA is $P/(n \cos \phi)$. Therefore, the lower the power factor the greater is the apparent power demand. A poor power factor thus not only increases the line currents for the same active power but also increases the line voltage drop. Thus, the voltage drop in the overhead equipment, the current in the OHE and the apparent power demand at the substation, the efficiency of the installations as well as the power factor at the input of the substation depend on the efficiency and the power factor of the locomotive.

The average power factor of rectifier locomotives is about 0.8. It rises to a value of 0.8 as soon as the speed exceeds one third the maximum speed and afterwards it remains more or less constant over the entire range of speed.

2.2.9 Methods of Improving line voltage

It may be pointed out that no special measures are generally required if proper spacing of substations has been chosen at the initial stages. However, in course of time, to cater to the increased traffic, it may be at times necessary to adopt methods for improving line voltage on difficult sections.

Partial compensation of the voltage drop can be obtained by using series condensers. This arrangement reduces the line reactance. If ‘C’ is the capacitance inserted in series with the line reactance ‘L0’ then the net reactance will be $L_0 - (1/C \omega)$. The line can thus be entirely compensated and will behave as a simple resistance if $L_0 - (1/C \omega) = 0$ or $C = 1/L\omega^2$. The voltage drop is considerably reduced even if the load power factor is poor. But series condensers produce over voltages depending on the currents flowing through them. When there is no load current they have no function and no over-voltage is to be feared. These banks of capacitors can either be connected at one point on the network or can be distributed at several places along the network. They should not be located too near the substations as that would increase the fault current in the transformer but they give good results when distributed over the last two thirds of the section. As capacitors can not support overloads at short circuit conditions without risk of damage, arrangements should be made to shunt them automatically in a few hundredths of a second whenever the voltage or the current through them exceeds a pre-determined value. The inherent disadvantage with the use of series capacitors is the possibility of obtaining a resonant condition at sub-harmonic frequencies.
Condensers can also be connected in parallel with the contact wire to improve the power factor and also the line voltage. Apart from high rating of capacitors with this arrangement there are losses due to circulating currents even in the absence of any load.

Voltage drop can also be compensated by using on-load regulators or tap changers in the substation transformer. The regulators may be incorporated in the transformer itself or it can be a separate auto-transformer connected after the main transformer. The regulator should act automatically and maintain a fixed voltage irrespective of load conditions. This way the voltage drop in the transformer only can be compensated, but the voltage drop in the overhead equipment remains uncompensated. It is possible to compensate the voltage drop in the overhead equipment also by increasing the substation output voltage correspondingly. But this method of regulation is generally not suitable for traction loads because the loads are of moving nature and if the voltage drop at the farthest end has to be compensated fully, there is a risk of over voltages for the trains near the substation.

On load regulators can also be installed on the overhead equipment away from the substations maintaining a fixed voltage on the output side of the regulator, it may be less expensive if the regulator is incorporated in the transformer.

2.2.10 Transmission efficiency of the catenary system

One of the reasons for adopting a high catenary voltage is to improve the transmission efficiency by reducing the line losses. In case of ac traction, the instantaneous efficiency of traction circuit for a single load supplied equals $\frac{(V - \Delta V)}{V}$, where $V$ is the substation sending end voltage and $\Delta V$ is the voltage drop up to the pantograph, and $(V - \Delta V)$ being the voltage at pantograph. Therefore, the voltage and $V$ is the voltage drop up to the pantograph, and efficiency is directly obtained from the voltage drop.

It is not the same case with single phase system because out of the active and reactive components of the voltage drop, it is only the active component which causes the line losses.

Let the substation sending end voltage be $V$ and the voltage at the pantograph of a train be $V_1$ then the efficiency of the line

$$n = \frac{V_1 \cos \phi}{V_1 \cos \phi + I^2 R} = \frac{V_1 \cos \phi}{V_1 \cos \phi + I R}$$

but $V = V_1^2 + I^2 Z^2 + 2V_1 I Z \cos(\Psi - \phi)$

Let $V_1/V = \alpha$ and replacing $Z$ by $R/\cos\Psi$ the equation becomes
\[ V_1 = \alpha^2 \left\{ \frac{V_1^2}{\cos^2 \Psi} + \frac{R^2}{\cos^2 \Psi} + 2V_1 \frac{\cos(\Psi - \phi)}{\cos \Psi} \right\} \]

\[ IR = V_1 \cos \Psi \left\{ \sqrt{\cos^2 (\Psi - \phi) + (1 - \alpha^2) \alpha^2} \right\} \]

Substituting this value in above equation the efficiency of transmission is

\[ n = 1 + \frac{\cos \Psi}{\cos \phi} \sqrt{\cos^2 (\Psi - \phi) + \frac{1 - \alpha^2}{\alpha^2} \cos (\Psi - \phi)} \]

In dc the efficiency of catenary (n) is simply equal to \( a \).

For a 10 per cent voltage drop, the transmission efficiency in case of dc is 90 percent. For the same percentage voltage drop the efficiency in ac system is 95.7 per cent if \( \cos \phi = 0.8 \).

In fact it is the overall power factor at the traction substation which really affects the tariff. It is always lower than the locomotive power factor due to high reactance of the overhead equipment and the transformer.

The efficiency and the power factor of any locomotive usually drops with a decrease in speed. Therefore operation of locomotives at a speed much less than the rated speed is always uneconomical from the point of view of voltage drops and energy losses apart from the reduced utilization of the locomotive capacity.
Annexure 2.2.1

Calculation of impedance of traction circuit

The impedance of the traction circuit comprises of the following in case of a single track.

1. Self impedance of the catenary comprising the contact wire and carrier.
2. Mutual impedance of the carrier and the contact wire of same track.
4. Mutual impedance of the rails of the same track.
5. Mutual impedance of the catenary and the rail earth return circuit.

In addition for the multi track sections the following factors are to be considered.
6. The mutual impedance between the various catenaries.
7. Mutual impedance between various tracks.

1. **Self impedance of the catenary (or any earth return conductor) in ohm/km.**

\[
Z_{\text{eff}} = R_{\text{eff}} + \frac{\pi \omega}{2} 10^{-4} + j\omega \left( \frac{\mu}{2} + 1 + 2\log_e 2 / P \alpha \delta \right) 10^{-4}
\]

- \( R_{\text{eff}} = \) Effective resistance of catenary/km
- \( P = \) radius of the conductor. For two or more parallel conductors the value of \( P = 4\sqrt{r_1 r_2 d^2} \) where \( r_1 \) and \( r_2 \) are the radii of the conductors and \( d = \) distance between them.
- \( \mu = \) permeability of material (copper \( \mu = 1 \))
- \( \alpha = \sqrt{4 \pi r \omega} \)
- \( r = \) earth conductivity
- \( t = \) Bessel constant (1.7811)

The factor \((1 + 2\log_e (2/\alpha t))\) depends on soil conductivity and freq., this value varying between 19 and 25. For average soil conditions it is 20.

\[
Z = R_{\text{eff}} + \frac{\pi \omega}{2} 10^{-4} + j\omega \left( \frac{\mu}{2} + 1 + 2\log_e 2 / \alpha t - 2\log_e p \right) 10^{-4} \quad \text{......(1)}
\]

2. **Mutual impedance between two parallel conductors having earth return**
\[ Z = \frac{\pi \omega}{2} 10^{-4} + j \omega \left( 1 + 2 \log_e 2 / \alpha - 2 \log_e d \right) 10^{-4} \text{ ohm/km} \] ... (2)

where \( d \) = distance between the two conductors.

3. **Impedance of one pair of conductors connected at one end**

See Figure below Annex 2.2.1 on the left top for this example:

\[ Z = Z_1 + Z_2 - 2Z_{12} \]

\[ R_1 + R_2 + j \omega \left( \mu_1 / \mu_2 / 2 + 2 + 4 \log_e 2 / \alpha t - 2 \log_e P_1 - 2 \log_e P_2 \right) 10^{-04} - 2j \omega \]

\[ (1 + 2 \log_e 2 / \alpha t - 2 \log_e d) \]
If the two conductors are identical

\[ Z = 2R + j\omega (\mu + 4\log e \ d / P) \text{ ohm/km} \]  

\[ \ldots \ldots (3) \]

4. **Impedance of two conductors in parallel**

See previous figure Annex 2.2.1 on top left

\[ Z = \frac{Z_1Z_2 - Z^2}{Z_1 + Z_2 - 2Z_{12}} \]

If \( Z_1 = Z_2 \)

\[ Z = \frac{1}{2} (Z_1 + Z_{12}) \]  

\[ \ldots \ldots (4) \]

5. **Impedance of rails**

See previous figure Annex 2.2.1 on top left

a) If two rails are connected at one end from equation (3)

\[ Z = 2R + j\omega (\mu_s + 4\log e \ d / P)10^{-04} \text{ ohm/km} \]

\[ R = R_{50} + R_{\text{joint}} = 3R_{ac} + R_{\text{joint}} \text{, } R_{ac} = 31*10^{-4} \text{ ohm/km} \]

Resistance of one joint (not bonded) is equivalent to two meters of rail and 50 joints are assumed per km.

\[ R_{\text{joint}} = 50 \times 2 / 1000 \times 93 \times 10 = 93 \times 10^{-4} \text{ ohm.} \]

\[ R = 0.093 + 0.0093 = 0.1023 \text{ ohm/km} \]

**Average permeability of rails = 12**

Equivalent radius of rails i.e. effective radius for same area, \( P = 10 \text{ cm} \)

\[ Z = 2 \times 0.1023 + j314 (12 + 4\log e 145/10)10^{-04} \text{ for gauge 1.45m} \]

\[ = 2 + j0.713 = 0.74 \angle 74^\circ \]

b) Impedance of two rails in parallel: one track
\[
Z_1 = Z_2 = R + \frac{\pi \omega}{2} 10^{-4} + j \omega(\frac{1}{2} + 1 + 2 \log_e 2 / \alpha t - 2 \log_e P) 10^{-4}
\]
\[
= 0.1507 + j 0.673 \\
\cdots \cdots (5)
\]
\[
Z_{12} = \frac{\pi \omega}{2} 10^{-4} + j \omega(1 + 2 \log_e 2 / \alpha t - 2 \log_e d) 10^{-4} \text{ ohm/km}
\]
\[
= 0.494 + j 0.245
\]
\[
Z = 1/2 (Z_1 + Z_2) = 0.1 + j 0.459
\]

c) Impedance of two tracks

See previous figure Annex 2.2.1 on the right

\[
Z = 1/2 (Z_1 + Z_{12})
\]
\[
Z_{12} = \frac{\pi \omega}{2} 10^{-4} + j \omega(20 - 2 \log_e 345) 10^{-4}
\]
\[
= 0.0484 + j 0.261 \\
\cdots \cdots (6)
\]
\[
Z_1 = 0.1 + j 0.46
\]
\[
Z = 0.074 + j 0.36 = 0.367 \angle 78.4^\circ
\]

6. Total OHE Impedance

i) OHE of one track (which is really the impedance of two circuits (catenary & contact wire in parallel)

Impedance of one catenary

\[
Z = Z_1 Z_2 - Z_2^2 / (Z_1 Z_2 - 2Z_{12}) = 0.183 + j 0.564 \\
= 0.59 \angle 72^\circ \\
\cdots \cdots (7)
\]

ii) OHE of two tracks (in parallel)

\[
Z = (Z_1 + Z) / 2
\]

From (7)
\[
Z_1 = 0.183 + j 0.564
\]
From (6)

\[ Z_{11} = \frac{\pi \omega}{2} 10^{-4} + j\omega(20 - 2\log_10 345)10^{-4} \]

\[ = 0.0484 + j0.261 \]

\[ Z = 0.116 + j0.413 = 0.438 \angle 74^\circ \]

7. Impedance of the traction circuit

Average height of OHE = 650 cm above rail level.

\[ Z_{CR} = \frac{\omega \pi}{2} 10^{-4} + j\omega(20 - 2\log_10 650)10^{-4} \]

Impedance per km of OHE, \( Z = Z_{OHE} - Z_{CR}^2 / Z_R \)

For single track \( Z = 0.159 + j0.454 = 0.48 \angle 71^\circ \)
two tracks $Z = 0.084 + j 0.278 = 0.29 \angle 73^\circ$

From the above formulae double track impedance with outer rails available for return current and with all four rails available for return current for various values of soil conductivity have been calculated to be as under:

<table>
<thead>
<tr>
<th>Soil conductivity S/m</th>
<th>Double track Impedance /Km (outer rails available for return current)</th>
<th>Double track Impedance /Km (all four rails available for return current)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \times 10^{-1}$</td>
<td>$0.252 \angle 70^\circ 36'$</td>
<td>$0.234 \angle 0^\circ$</td>
</tr>
<tr>
<td>$10^{-1}$</td>
<td>$0.276 \angle 72^\circ 39'$</td>
<td>$0.248 \angle 71^\circ 52'$</td>
</tr>
<tr>
<td>$2 \times 10^{-2}$</td>
<td>$0.286 \angle 72^\circ 54'$</td>
<td>$0.252 \angle 72^\circ 36'$</td>
</tr>
<tr>
<td>$5 \times 10^{-3}$</td>
<td>$0.299 \angle 73^\circ 27'$</td>
<td>$0.257 \angle 72^\circ 51'$</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>$0.30 \angle 73^\circ 9'$</td>
<td>$0.259 \angle 72^\circ 48'$</td>
</tr>
</tbody>
</table>
Annexure 2.2.2

Graphical Determination of the Voltage at the Pantograph of a Locomotive

$U_1$ be the Voltage at the pantograph
$\phi_1$ be Power factor angle of the Locomotive such that
$P_{a1}$ being Active power of the Locomotive, $P_{s1} = U_1 \cos \phi_1$
$Z_1$ be Loop Impedance of overhead equipment, rails etc ($\psi_1$ is the impedance angle)
$Z_S$ be Substation transformer Impedance ($\psi_S$ is the angle)
$I$ be Load current (of the locomotive)
$U_E$ be Voltage at the substation
$\phi_E$ be Power factor at substation
Let O'M be U. MN is the voltage drop (IZ) due to the loop impedance of the overhead catenary system including that of the return path. The voltage drop in the substation transformer is represented by NO

\[ \angle SON = \psi_S - \phi_E, \quad OS = IZ \cos(\psi_S - \phi_E) \]

\[ \angle P'NM = \psi_1 - \phi_E, \quad NP = SP = IZ \cos(\psi_1 - \phi_E) \]
Taking the co-ordinates of the point M from the origin at O,

\[ X = -IZ_S \cos (\psi_S - \phi_E) - IZ_1 \cos (\psi - \phi_E) \] ……(a)

\[ Y = -IZ_S \sin (\psi_S - \phi_E) - IZ_1 \sin (\psi - \phi_E) \] ……(b)

From equation ……(a)

\[ X + \{IZ_S (\cos \psi_S \cos \phi_E + \sin \psi_S \sin \phi_E) + (IZ_1 (\cos \psi_1 \cos \phi_E + \sin \psi_1 \sin \phi_E)) \} = 0 \]

or

\[ X + I(\cos \phi_E \cdot \{Z_S \cos \psi_S + Z_1 \cos \psi_1\} + \tan \phi_E (Z_S \sin \psi_S + Z_1 \sin \psi_1)) = 0 \] (I)

Similarly from (b)

\[ Y + I(\cos \phi_E \cdot \{Z_S \sin \psi_S + Z_1 \sin \psi_1\} - \tan \phi_E (Z_S \cos \psi_S + Z_1 \cos \psi_1)) = 0 \] (II)

Eliminating I from equations (I) and (II) we get

\[ \tan \phi_E = \frac{X(Z_S \sin \psi_S + Z_1 \sin \psi_1) - Y(Z_S \cos \psi_S + Z_1 \cos \psi_1)}{X(Z_S \cos \psi_S + Z_1 \cos \psi_1) + Y(Z_S \sin \psi_S + Z_1 \sin \psi_1)} \] (III)

We can express the equation of the locus of M in terms of any two known variables. After getting the locus of M from two sets of equations the intersection point of the two loci gives the exact location of M for a given set of conditions.

**Case (I)**

To determine the locus of M from \( Z_1 \) and \( \phi_1 \):

If \( \phi_1 \) is the load power factor

\[ y = PO' \tan(\phi_E - \phi_1) \]

But \( OP + PO' = OO' = -U_E \)
\[
PO = -U_E - OP = -U_E - X = (X + U_E)
\]
\[
y = -(X + U_E) \tan(\phi_E - \phi_1) = (X + U_E) \tan(\phi_E - \phi_1)
\]
\[
y/x + U = \frac{\tan \phi_1 - \tan \phi_E}{1 + \tan \phi_1 \tan \phi_1}
\]
or \[
\tan \phi_E (y \tan \phi_E + x + U_E) = (x + U_E) \tan \phi_1 - y
\]
\[
\tan \phi_E = \frac{(x + U_E) \tan \phi_1 - y}{(x + U_E) + y \tan \phi_1}
\]

From equations (III) and (IV) eliminating \( \phi_E \)

\[
\frac{X(Z_s \sin \psi_s + Z_1 \sin \psi_1) - (Z_s \cos \psi_s + Z_1 \cos \psi_1)}{X(Z_s \cos \psi_s + Z_1 \cos \psi_1) + Y(Z_s \sin \psi_s + Z_1 \sin \psi_1)}
\]
\[
= \frac{(x + U_E) \tan \phi_1 - y}{x + U_E + y \tan \phi_1}
\]

This can be also written as follows:-

\[
(x^2 + xU_E)(Z_s \sin \psi_s + Z_1 \sin \psi_1) - (xy + yU_E)(Z_s \cos \psi_s + Z_1 \cos \psi_1)
+ xy \tan \phi_1(Z_s \sin \psi_s + Z_1 \sin \psi_1) - y \tan \phi_1(Z_s \cos \psi_s + Z_1 \cos \psi_1)
\]

\[
(x^2 + xU_E) \tan \phi_1(Z_s \cos \psi_s + Z_1 \cos \psi_1) + (xy + yU_E) \tan \phi_1(Z_s \sin \psi_s + Z_1 \sin \psi_1) - xy(Z_s \cos \psi_s + Z_1 \cos \psi_1) - y(Z_s \sin \psi_s + Z_1 \sin \psi_1)
\]

or,

\[
(x^2 + y^2)(Z_s \sin \psi_s + Z_1 \sin \psi_1 - Z_s \cos \psi_s \frac{\sin \phi_1}{\cos \phi_1} - Z_1 \cos \psi_1 \frac{\sin \phi_1}{\cos \phi_1}) +
U_E X(Z_s \sin \psi_s + Z_1 \sin \psi_1 - Z_s \cos \psi_s \tan \phi_1 - Z_1 \cos \psi_1 \tan \phi_1) - yU_E
-(Z_s \cos \psi_s + Z_1 \cos \psi_1 + Z_s \sin \psi_s \tan \phi_1 + Z_1 \sin \psi_1 \tan \phi_1) = 0
\]

\[
x^2 + y^2 + U_E \{(x - y) \frac{Z_s \cos(\psi_s - \phi_1) + Z_1 \cos(\psi_1 - \phi_1)}{Z_s \sin(\psi_s - \phi_1) + Z_1 \sin(\psi_1 - \phi_1)} = 0
\]

This represents a circle passing through O and O' and centre is at
\[ x = \frac{U_E}{2}, y = \frac{U_E}{2} \{ Z_s \cos(\psi_s - \phi_1) + Z_1 \cos(\psi_1 - \phi_1) \} \]

**Case (II)**

To determine the locus of \( M \) from \( \phi_1 \) and \( P_{a1} \)

\[
P_{a1} = U_E \cos \phi_1 = \cos(\phi_1) - i(\sin \phi_1)
\]

\[
= iU_E \cos \phi_1 - i^2 (Z_s \cos \psi_s + Z_1 \cos \psi_1)
\]

Eliminating \( I \) and \( \phi_1 \) from this equation and equations (I) and (II) :-

For this purpose the value of \( I \) is substituted from (I)

\[
I = \frac{x}{(Z_s \cos \psi_s + Z_1 \cos \psi_1) \cos \phi_1 + (Z_s \sin \psi_s + Z_1 \sin \psi_1) \sin \phi_1}
\]

\[
P_{a1} = \frac{xU_E}{\{(Z_s \cos \psi_s + Z_1 \cos \psi_1) + (Z_s \sin \psi_s + Z_1 \sin \psi_1) \tan \phi_1 \} + x^2 (Z_s \cos \psi_s + Z_1 \cos \psi_1)}
\]

\[
\cos \phi_1 \{(Z_s \cos \psi_s + Z_1 \cos \psi_1) + (Z_s \sin \psi_s + Z_1 \sin \psi_1) \tan \phi_1 \}^2
\]

or,

\[
P_{a1} = \left[(Z_s \cos \psi_s + Z_1 \cos \psi_1) + (Z_s \sin \psi_s + Z_1 \sin \psi_1) \tan \phi_1 \right]^2
\]

\[+ xU_E \{(Z_s \cos \psi_s + Z_1 \cos \psi_1) + (Z_s \sin \psi_s + Z_1 \sin \psi_1) \tan \phi_1 \} + x^2 (Z_s \cos \psi_s + Z_1 \cos \psi_1) (1 + \tan^2 \phi_1) = 0
\]

From equation (III)

\[
\tan \phi_1 = \frac{x(Z_s \sin \psi_s + Z_1 \sin \psi_1) - y(Z_s \cos \psi_s + Z_1 \cos \psi_1)}{x(Z_s \cos \psi_s + Z_1 \cos \psi_1) + y(Z_s \sin \psi_s + Z_1 \sin \psi_1)}
\]

This can also be written as

\[
Z_s \cos \psi_s + Z_1 \cos \psi_1 = (Z_s \sin \psi_s + Z_1 \sin \psi_1)^2 \tan \phi_1 + y
\]
On substitution of this value in equation (VII), after simplification the following relationship can be obtained:

\[ P_{a1}(Z_s \sin \psi_s + Z_1 \sin \psi_1) = -\left( \frac{x \tan \phi_E + y}{1 + \tan^2 \phi_E} \right) (U_E + x - y \tan \phi_E) \]

\[ Z_s \sin \psi_s + Z_1 \sin \psi_1 = -\left( \frac{x + U_E - y \tan \phi_E}{P_{a1}(1 + \tan^2 \phi_E)} \right) (x \tan \phi_E + y) \]

From above \[ Z_s \cos \psi_s + Z_1 \cos \psi_1 = -\left( \frac{x + U_E - y \tan \phi_E}{P_{a1}(1 + \tan^2 \phi_E)} \right) (x - y \tan \phi_E) \]

Eliminating \( Z_1 \) from the above equations and on further simplification after substituting for the value of \( \tan \) the expression in equation (IV) the following can be obtained:

\[ x^2 + y^2 + U_E (x - y) \left( \frac{1}{\tan(\psi_1 - \phi_1)} \right) \frac{Z_s P_{a1} \sin(\psi_s - \psi_1)}{\cos \phi_1 \sin(\psi_1 - \phi_1)} = 0 \]  

(VIII)

This is the equation of a circle having its centre at

\[ x = -\frac{U_E}{2}; \quad y = \frac{1}{2 \tan(\psi_1 - \phi_1)} \]

and radius is given by the relationship

\[ R^2 = \frac{U_E^2}{4} + \frac{1}{4 \tan^2(\psi_1 - \phi_1)} + \frac{Z_s P_{a1} \sin(\psi_s - \psi_1)}{\cos \phi_1 \sin(\psi_1 - \phi_1)} \]

or

\[ R = \left( \frac{U_E^2}{4} + \frac{1}{4 \tan^2(\psi_1 - \phi_1)} + \frac{Z_s P_{a1} \sin(\psi_s - \psi_1)}{\cos \phi_1 \sin(\psi_1 - \phi_1)} \right)^{1/2} \]

(A) From the above equations, the locus of \( M \) in terms of \( \phi_1 \) and \( Z_1 \) is given by equation (V) which is a circle as represented by
\[ x^2 + y^2 + U_E \left\{ (x - y) \frac{Z_s \cos(\psi - \phi_1) + Z_1 \cos(\psi_1 - \phi_1)}{Z_s \sin(\psi - \phi_1) + Z_1 \sin(\psi_1 - \phi_1)} \right\} = 0 \]

Coordinator of centre

\[ x = -\frac{U_E}{2}, y = \frac{1}{2} U_E \frac{1}{\tan(\psi_1 - \phi_1)} \]

(B) The locus of M in terms of and \( P_{a1} \) is given by equation VIII which is a circle as represented by:

\[ x^2 + y^2 + U_E \left( x - \frac{y}{\tan(\psi_1 - \phi_1)} \right) - \frac{Z_s P_{a1} \sin(\psi_s - \psi_1)}{\cos \phi_1 \sin(\psi_1 - \phi_1)} = 0 \]

Coordinator of centre:

\[ x = -\frac{U_E}{2}, y = \frac{1}{2} \frac{1}{\tan(\psi_1 - \phi_1)} \]

(C) To find M, the intersection of the above two circles is to be determined. For this purpose, the above two equations (V) and (VIII) are equated

\[ yU_E = \frac{1}{\tan(\psi_1 - \phi_1)} \left\{ Z_s \cos(\psi_s - \phi_1) + Z_1 \cos(\psi_1 - \phi_1) \right\} + \frac{Z_s P_{a1} \sin(\psi_s - \psi_1)}{\cos \phi_1 \sin(\psi_1 - \phi_1)} = 0 \]

On simplification,

\[ y = \frac{P_{a1} \sin(\psi_s - \phi_1) + Z_1 \sin(\psi_1 - \phi_1)}{U_E \cos \phi_1} \]

This is an equation of a straight line parallel to the x axis and the value of the ordinate (or distance from x axis) is given by the above.

**Construction of the graphical charts**

(i) with \( Z_1 \) and \( \phi_1 \) as variables the locus of M is a circle passing through O O’ (refer to Fig.2.2.2A.1) and centre is at \( x = -\frac{U_E}{2} \) and the ordinate is given by

\[ C = \frac{U_E}{2} \frac{Z_s \cos(\psi_s - \phi_1) + Z_1 \cos(\psi_1 - \phi_1)}{Z_s \sin(\psi_s - \phi_1) + Z_1 \sin(\psi_1 - \phi_1)} \]
$Z_1$ and $\psi_s$ are known and also $\psi_1$. Therefore a graph is drawn between $C$ and $Z$ for various values of $\phi_1$, the locomotive power factor. So far a known value of $\phi_1$ and $Z_1$ there is thus only one value of $C$.

(ii) The locus of the intersection of two equations (V) and (VIII) is given by

$$y = \frac{P_{a1} + Z_s\sin(\psi_s - \phi_1) + Z_1\sin(\psi_1 - \phi_1)}{\cos\phi_1}$$

$$= \frac{P_{a1}}{U_E}, \text{ where } A = \frac{Z_s\sin(\psi_s - \phi_1) + Z_1\sin(\psi_1 - \phi_1)}{\cos\phi_1}$$

$Z_s$ and $Z_1$ as well as being known, graph is drawn for various values of between $A$ and $Z_1$. The value of $A$ for any value of $Z_1$ is thus known.

(iii) On a sheet of paper, the axis $O'O$ and (equal to $U$) is drawn and the loci of $M$ for different values of $C$ are drawn. The centers of all the circles lie on the perpendicular bisector of the axis $O'O$ and the ordinates of the centers are given by the relationship

$$C = \frac{U*Z_s\cos(\psi_s - \phi_1) + Z_1\cos(\psi_1 - \phi_1)}{Z_s\sin(\psi_s - \phi_1) + Z_1\sin(\psi_1 - \phi_1)}$$

The loci of the intersection points is given by $y = -P_{a1} * A$

The parallel lines to X axis for various values of $y$ are also drawn on the same sheet.

For a given set of values of $C$ and $Y$ the point $M$ is given by the intersection of the straight line for that value of $Y$ with that of the circle representing the given value of $C$. To facilitate quick reading of the voltage, the constant voltage circles (with centre $O$) are also drawn.

To determine the input kVA at the substation

From the diagram Fig.2.2.2A.1, it can be seen that

$$OM^2 = OA^2 + AM^2 = i^2\{Z_s\sin(\psi_s - \phi_1) + Z_1\sin(\psi_1 - \phi_1)\}^2 + i^2\{Z_s\cos(\psi_s - \phi_1) + Z_1\cos(\psi_1 - \phi_1)\}^2$$

$$OM^2 = Z_s^2\sin^2(\psi_s - \phi_1) + Z_1^2\sin^2(\psi_1 - \phi_1) + 2Z_1Z_s\sin(\psi_s - \phi_1)\sin(\psi_1 - \phi_1)$$

$$+ Z_s^2\cos^2(\psi_s - \phi_1) + Z_1^2\cos^2(\psi_1 - \phi_1) + 2Z_1Z_s\cos(\psi_s - \phi_1)\cos(\psi_1 - \phi_1)$$
\[ Z_s^2 + Z_1^2 + 2Z_1Z_s\cos(\psi_s - \phi_1 + \phi_1) = Z_s^2 + Z_1^2 + 2Z_1Z_s\cos(\psi_s - \psi_1) \]

OM (which represents the voltage drop)

\[ \text{OM} = \sqrt{Z_s^2 + Z_1^2 + 2Z_1Z_s\cos(\psi_s - \psi_1)} \]

Or, \( I = \frac{\text{OM}}{\sqrt{Z_s^2 + Z_1^2 + 2Z_1Z_s\cos(\psi_s - \psi_1)}} \)

Input VA = \( U_E I \)

\[ P = \text{OM} \times K \] where the constant \( K \) is given by the expression

\[ K = \frac{U}{\sqrt{Z_s^2 + Z_1^2 + 2Z_1Z_s\cos(\psi_s - \psi_1)}} \]

The values of the constants \( A, C \) and \( K \) for different values of the variables are evaluated and tabulated (see Tables 2.2.2A.1, 2, 3 and 4). The curves indicating the relationship between \( Z \) and the above constants are also drawn. See Fig.2.2.2A.2, 3, 4, 5, 6.

The nominal voltage of the catenary is 25 kV and if a regulation of about 7 percent (a value which is obtained for usual impedance values of the transformer) between the no load and nominal voltage is assumed. The no load voltage of the catenary will be 1.07 \( \times \) 25 = 26.7 kV. The calculations are based on this no load voltage. The calculations pertaining to the various constants are given in tables 2.2.2A.1 to 4.

### Table 2.2.2A.1

<table>
<thead>
<tr>
<th>( \text{Cos} )</th>
<th>0</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values of ( A \times 10^6 ) for ( Z_1 = \text{(in ohm)} )</td>
<td>185</td>
<td>224.5</td>
<td>284</td>
<td>362</td>
<td>481</td>
<td>580</td>
<td>679</td>
</tr>
</tbody>
</table>
Table 2.2.2A.2

\[ C = \frac{Z_s \cos(\psi - \phi_1) + Z \cos(\psi_1 - \phi_1)}{Z_s \sin(\psi - \phi_1) + Z \sin(\psi_1 - \phi_1)} \times \frac{U_E}{2} \]

<table>
<thead>
<tr>
<th>Cos</th>
<th>Values of C x 10^3 for Z = (in ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>0.65</td>
<td>17.6</td>
</tr>
<tr>
<td>0.70</td>
<td>15.3</td>
</tr>
<tr>
<td>0.75</td>
<td>13.3</td>
</tr>
<tr>
<td>0.80</td>
<td>11.3</td>
</tr>
<tr>
<td>0.85</td>
<td>9.4</td>
</tr>
<tr>
<td>0.90</td>
<td>7.5</td>
</tr>
<tr>
<td>0.95</td>
<td>5.3</td>
</tr>
<tr>
<td>1.00</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 2.2.2A.3

\[ K = \frac{U_E}{\sqrt{Z_s^2 + Z_1^2 + 2Z_sZ_1\cos(\psi - \psi_1)}} \]

<table>
<thead>
<tr>
<th>Z_s in ohms</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5030</td>
</tr>
<tr>
<td>2</td>
<td>3690</td>
</tr>
<tr>
<td>5</td>
<td>2625</td>
</tr>
<tr>
<td>10</td>
<td>1767</td>
</tr>
<tr>
<td>15</td>
<td>1330</td>
</tr>
<tr>
<td>20</td>
<td>1063</td>
</tr>
<tr>
<td>25</td>
<td>879</td>
</tr>
</tbody>
</table>

Table 2.2.2A.4

\[ \alpha \text{ versus } \cos \psi_E \]
Note on the use of curves for calculating the Voltage of the Receiving End, Power Factor at the Substation end & Efficiency of Transmission

i) Fig.2.2.2A.2 gives values of A (a constant) versus Z for various power factors of loads.

ii) Fig.2.2.2A.3 gives the values of C (another constant) versus Z (line impedance) for different load power factors.

iii) Fig.2.2.2A.4 gives values of K (another constant) versus Z.

iv) Fig.2.2.2A.5 gives values of $\cos \psi_E$ (power factor at feeding point or substation) versus in degrees (difference in the phase angles of feeding point (or substation) and the receiving end).

v) Fig.2.2.2A.6 gives the values of voltage of receiving end for various values of $Y$ (another constant) and $C$ (constant referred to above).

a) **To find the voltage at receiving end**

Let there be loads $P_1$, $P_2$, $P_3$, .....$P_n$ at distances $l_1$, $l_2$, $l_3$, .....$l_n$ from the feeding point. All the loads at any given time between the substation or feeding point and neutral section are to be considered and let $\phi_1$ be the power factor angle of each of the loads.

Then the distance of the centre of gravity of the total load $P$ from the feeding point is:

$$\frac{P_1 l_1 + P_2 l_2 + P_3 l_3 + \ldots + P_n l_n}{P_1 + P_2 + P_3 + \ldots + P_n} = \frac{\sum P_i l_i}{\sum P_i}$$

The following values of the impedance of the line (catenary including return circuit) are used:-

$Z = 0.41 \text{ Ohm/single track km.}$
Z = 0.24 Ohm/double track km.

The total impedance for a length I = z x l = Z ohm.

Knowing the value of Z the constants C and A can be obtained from the Fig.2.2.2A.1 and 2. (The power factor of the load can be obtained from the locomotive characteristics and usually varies between 0.75 to 0.85.

Value of the constant Y = P x A (where P is the total load i.e. \( P_1 + P_2 + \ldots P_n \) or \( P \)).

Now from Fig.2.2.2A.6 the voltage at the receiving end is indicated by the intersection of these values of C and Y (values of C are indicated by circles and values of Y by horizontal lines parallel to X axis). Other values of C and Y not indicated, can be interpolated. The values of voltage are given by concentric circles with O’ as centre. The voltage of the intersection point (of C and Y referred to above) can be read directly with the help of these concentric circles.

The following example illustrates the method described above for a double track section:-

<table>
<thead>
<tr>
<th>Distance from substation or feeding point in km</th>
<th>Load offered by trains in kw</th>
<th>Kw x km</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>1,190</td>
<td>2,737</td>
</tr>
<tr>
<td>2.2</td>
<td>2,120</td>
<td>4,664</td>
</tr>
<tr>
<td>14.3</td>
<td>2,030</td>
<td>29,029</td>
</tr>
<tr>
<td>36.2</td>
<td>1,940</td>
<td>70,228</td>
</tr>
<tr>
<td>45.2</td>
<td>1,830</td>
<td>82,716</td>
</tr>
<tr>
<td>-------</td>
<td>----</td>
<td>-------</td>
</tr>
<tr>
<td>9,110</td>
<td>1,89,374</td>
<td>---------</td>
</tr>
</tbody>
</table>

I = \( \frac{1,89,374}{9,110} \) = 20.79 km

Z₁ = 20.79 x 0.32 = 6.65 ohm

Assuming \( \cos \phi_1 = 0.8 \)

From Fig.2.2.2A.3 \( C \times 10^3 = 15.8 \)
From Fig.2.2.2A.4 \( K = 2.280 \)
From Fig.2.2.2A.2 \( A = 358 \times 10^{-6} \)

\( Y = P \times A = 9,110 \times 358 \times 10^{-6} = 3.26 \)
From Fig.2.2.2A.6 at the intersection of C = 15.8, Y = 3.26 : voltage is 21.4 kV.
Thus the voltage at the receiving end can be obtained.

**Power Factor at Sending End**

Join the intersection point (of C and Y) to origin (Fig.2.2.2A.6). This line cuts the arc indicating the values $\phi_2$ of in degrees (difference of the phase angles at the feeding point or substation and the receiving end) and from Fig.2.2.2A.5 for a given value of $\phi$ the value of $\cos \phi_E$ (power factor at substation or feeding point) can be obtained with a given power factor of the load.

**Efficiency of transmission**

From Fig.2.2.2A.4 the value of constant K can be obtained for the given value of Z. From Fig.2.2.2A.6, the intersection point of values C and Y can also be read in terms of the values of concentric circles drawn from centre o. This value multiplied by the value of K gives the input power in kVA.

Knowing the input power in kVA, input power factor $\cos \phi$ (as indicated above and the load (X) the efficiency of the transmission can be obtained.

**Power factor**

Join the intersection point to O’. This line cuts the arc at $\alpha = 9^\circ$. From Fig.2.2.2A.6 for $\alpha = 9^\circ$ input power factor $\cos \phi_E = 0.7$.

**Efficiency of transmission**

The intersection point gives the value of 6.5 (on the concentric circles with centre o). Input power in kVA = 6.5 x 2210 = 14,800 (2280 is the value of K for Z = 6.65 ohms).

\[
\text{Efficiency of transmission} = \frac{9,110}{0.700 \times 14,800} = 0.88 \text{ or } 88\%
\]

The voltage at the receiving end should not go down below 19 kV normally and in exceptional cases instantaneous values should never go down below 17.5 kV.

With the above method it would be possible to obtain the voltage at the farthest end of the catenary under different loading conditions. Sometimes it may not be necessary to obtain the actual catenary
voltage at the farthest end and instead it might suffice to check whether the receiving end voltage is at least 19 kV, which is the permissible lower limit for normal working. For such a quick check a set of curves are shown in Fig. 2.2.2A.7 to indicate the maximum permissible demand from the voltage drop consideration (for a minimum receiving end voltage of 19 kV) and the Megawatt kilometer thereof for a single track, double track, three track and four track layouts. For instance, on a double track section at a distance of 25 km from the substation the maximum demand that can be taken is 10.5 MW. It means either a single concentrated load of 10.5 MW at 25 Km or a sum total of several demands to that extent occurring at varying distances from the feeding post whose centre of gravity is situated at a distance of 25 Km from the feeding post can be allowed.

**Conclusion**

Though the proof of the method for determination of the voltage drop described above appears involved it can be seen that practical application is relatively easy. It is very useful in practice for determining the voltage drops on different sections under varying traffic conditions.
FIG. 2.2.2A.2

\[ \phi_l \cos \theta = 1.0 \]
\[ \phi_l \cos \theta = 0.95 \]
\[ \phi_l \cos \theta = 0.90 \]
\[ \phi_l \cos \theta = 0.85 \]
\[ \phi_l \cos \theta = 0.80 \]
\[ \phi_l \cos \theta = 0.75 \]
\[ \phi_l \cos \theta = 0.70 \]
\[ \phi_l \cos \theta = 0.60 \]
FIG. 2.2.2A.4
\( \cos \phi \text{E} \)

\( \cos \phi = 1.0 \)
\( \cos \phi = 0.95 \)
\( \cos \phi = 0.90 \)
\( \cos \phi = 0.85 \)
\( \cos \phi = 0.80 \)
\( \cos \phi = 0.75 \)
\( \cos \phi = 0.70 \)
\( \cos \phi = 0.65 \)

FIG. 2.2A.5
MAXIMUM PERMISSIBLE DEMANDS FOR RECEIVING END VOLTAGE OF 19 kV ON THE CATENARY

**FIG 2.22A7**

- **SINGLE TRACK**
- **DOUBLE TRACKS**
- **THREE TRACKS**
- **FOUR TRACKS**
References

1. The different types of single phase locomotives considered from the view point of their repercussions on the supply – M. Bernard.

2. Voltage drops in the contact wires in 50 Hz single phase traction – M. Bernard.


5. Course de Traction Electrique – Garreau
Chapter 3

DETERMINATION OF TRAIN PERFORMANCE

2.3.1 Fundamentals of train dynamics

In any electrification scheme, in order to arrive at an economical spacing of the substations, it will be necessary to calculate the maximum demand and the voltage drops and also their installed capacity. The annual energy consumption has also to be estimated. It will also be necessary to calculate the inter-station running timings for different loads on the various sections to be electrified in order to prepare the graphic train charts for operating the train services. All the above data can be obtained from speed distance curves. There are several methods which were devised by different engineers for determining the speed distance curves and one practical such method with its application is illustrated.

The following symbols are used.

- \( F \) - Total tractive effort available at the rim of the locomotive which is a function of the speed.
- \( F_a \) - Accelerating effort required to impart an acceleration “\( a \)” to the train.
- \( F_r \) - Tractive resistance to forward motion which is a function of the speed.
- \( F_s \) - Effort required to overcome a gradient of slope “\( s \)”.
- \( L, W \) - Weights of the locomotive and trailing load respectively in tonne.
- \( V \) - Speed of the train at any instant (km/h).

The total resistance offered to the forward motion of a train comprises of tractive resistance, grade and curve resistance and the accelerating effort.

2.3.2 Accelerating effort

The fundamental equation for the acceleration of a body in a horizontal direction is:

\[ F_a = ma \]

where \( m \) = mass that is being accelerated.

\( a \) = acceleration.

Acceleration can also be obtained from the equation of motion:
\[ a = \frac{dv}{dt} \quad F_a = ma = m\frac{dv}{dt} \]

The acceleration of a train comprising a locomotive of weight \( L \), hauling a trailing load \( W \) and the mass of which is \( (W+L)/g \) can be obtained from the above equation.

However, the above relation holds good if the body that is accelerated has no rotating parts. But in the case of electric trains the wheels, motor armature, gears have to be accelerated in an angular direction. In order to take this into consideration the weight of the train is suitably increased by a factor “\( K \)” which depends on the number of wheels and motors, type of motor, etc. This weight is called the accelerating weight of a train. In order to calculate precisely the value of \( K \), it would be necessary to know the weights and radii of gyration of each of the rotating parts. For a locomotive this value of \( K \) may be as high as 1.2 and for an electric multiple unit this may be about 1.1 to 1.15. For freight trains this value will be of the order of 1.03. On the average a value of 1.06 can be adopted as a reasonable approximation.

Accelerating effort \( F_a = \frac{(W+L)}{g} \) \( K \frac{dv}{dt} \).

### 2.3.3 Tractive resistance:

The resistance that is offered to the forward motion of trains consists of the mechanical resistance as well as the air resistance. Several tests were conducted in different countries to determine the train resistance at various speeds taking into account the prevailing local conditions (such as the gauge, tyre profile and rail surfaces and atmospheric condition). There are thus many empirical formulae. The formulae used on Indian Railways are based on the tests conducted by C.W. Clarke on the former GIP, Railway and published in “Dynamometer Car Report No.11”. The tractive resistance formulae can be expressed in the form \( A + Bv + Cv^2 \) where the constants have the following significance:

- **\( A \)** - Constant which takes into account the journal friction plus rolling friction and track resistance. This varies with load, type of rolling stock, and type of bearings and method of lubrication.

- **\( Bv \)** - Represents the resistance due to flange friction etc., which varies with speed. This depends on the condition of rail and tyre surface and condition of road bed.

- **\( Cv^2 \)** - Represents air resistance, which varies as the square of the speed. This depends on the direction of prevailing wind and climatic conditions.

The following empirical formulae based on Clarke’s tests are used to determine the tractive resistance on level tangent track for different types of rolling stock.

- **Passenger stock** : \[ r = 1.43 + 0.0054v + 0.000253v^2 \]
- **Freight stock** : \[ r = 1.38 + 0.0064v + 0.0002v^2 \]
where,

\[ r = \text{resistance in kgf per tonne of the train weight.} \]
\[ v = \text{speed in km/h.} \]

To obtain the locomotive resistance, the following empirical formula can be used:

\[ R_L = 0.65L + 13n + 0.01Lv + 0.052v^2 \]

where,

\[ L = \text{weight of the locomotive in tonne.} \]
\[ n = \text{number of axles} \]
\[ v = \text{speed in km/h} \]

With the above formulae the total tractive resistance for the forward motion of the train (loco + trailing load) at any speed can be determined.

If the locomotive resistance at a given speed is \( R \) and the specific resistance of the trailing load of the same speed as evaluated from the above formulae is ‘\( r \)’, then the total tractive resistance \( F_r = R_L + W_r \).

### 2.3.4 Grade and curve resistance:

Whenever a train negotiates an up gradient, the gravitational effect produces a force which tends to cause motion down the gradient or in other words, a resistance to upward motion which can be called the gradient resistance. If \( \theta \) = inclination of the gradient to the horizontal and total weight of the train is \( (W+L) \), then the gravitational force \( F_S \) acting down the gradient (or the grade resistance for upward motion) = \( (W+L) \sin \theta \).

Grades are expressed in terms of distance (along the track) corresponding to a rise of one unit or in mm/m or in per thousand.

If the slope is \( s \) per thousand and the train weight \( (W+L) \) expressed in tonne, the value of \( F_S \) in kgf is obtained from \( F_S = (W+L)s \).

The grade resistance \( F_S \) may be positive or negative depending on whether the slope is upwards or downwards.

Curved track can be equated to a fictitious gradient, the value of which depends on the radius of the curve as well as the gauge. To take this into account the values of actual gradients are increased (in cases of up gradients) or reduced (in case of down gradients) by a value corresponding to the
2.3.5 Total resistance to the forward motion of locomotive and the trailing load:

If the available tractive effort of the locomotive of weight $L$, hauling a trailing load $W$ at a speed $v$ on a compensated grade of $s(\%)$ is $F$, the effort available for acceleration at a speed $v$ is given by the relation:

$$F_a = F - \{(R_L + Wr) + (W + L)s\}$$

i.e. $F_a = F - \{(R_L + Ls) + W(r + s)\}$

When the acceleration is zero, the train reaches an equilibrium state and the tractive effort of the locomotive is just enough to overcome the train resistance including that of grade if any. The speed at which this happens is known as the equilibrium speed of the train on the particular gradient.

When $F_a = 0$, $F = (R + Ls) + W(r + s)$

$F$, $R$, $r$ are the functions of speed. There are three variables i.e. the trailing load, corrected gradient and the equilibrium speed. If two of them are known, then the third can be determined. The trailing load that can be hauled at an equilibrium speed $v$ over a compensated gradient $s$, or the compensated gradient over which the locomotive can haul a trailing load $W$ at an equilibrium speed $v$ can easily be determined.

But it is not possible to determine the equilibrium speed mathematically in view of the fact that $F$, $R$, $r$ are functions of $v$. Moreover, it is not possible to express $F$, exactly as a function of speed which will hold good for any value of $v$. So it would be necessary to adopt graphical methods for determination of equilibrium speeds as explained subsequently.

On a section where the graded stretches are short in length but frequent, which is usually the case in practice. It is not quite often that a locomotive can attain equilibrium speed and maintain it before it strikes a different gradient. The speed at any given instant, in such cases, can be obtained from the general equation governing the motion of the train, namely,

$$F_a = Km \frac{dv}{dt} = F - (F_r + F_s)$$
It is also necessary to determine the time taken and the distance “D” traversed during which period the speed changes from $v_1$ to $v_2$. They can be obtained by

\[ t = \int_{v_1}^{v_2} \frac{Km}{F - (F_r + F_s)} \, dv. \]

and the distance is obtained by –

\[ D = \int_{v_1}^{v_2} \frac{Kmv}{F - (F_r + F_s)} \, dv \]

The term $F_s$ is constant depending on the compensated gradient. $F$ and $F_r$ are functions of speed. The value of $F_r$ can be substituted in an equation but, as indicated earlier, it is not possible to express $F$ likewise and, therefore, it is not possible to integrate the above equations mathematically.

The problem has, therefore, to be solved by graphical methods and different methods are adopted by different railways.

2.3.6 Coefficient of adhesion and its variation with speed:

For a given surface (and weather condition) the coefficient of adhesion at start depends on the design of the locomotive, the connections of motors at start (full parallel, series parallel or series) and the method of application of voltage to the traction motors at start (whether the voltage variation is smooth and gradual or in steps). Further the coefficient of adhesion falls with speed and several empirical formulae have been evolved based on tests and practical experience. Coefficient of adhesion $f_v$ at any speed $v$ is given by one empirical formula as

\[ f_v = f_0 \frac{8 + 0.1v}{8 + 0.2v} \]

where $v =$ speed in km/h

$f_0 =$ coefficient of adhesion at start.

For modern locomotives the coefficient of adhesion may reach 40 to 50% under favourable conditions but a consistent practical value of 0.33 can be assumed at start.

2.3.7 Speed-tractive effort characteristics of locomotive:

The starting point is the speed-tractive effort characteristics of the locomotives. These are obtained either by actual type tests or predetermined for the contemplated designs of the traction motors of a locomotive.
Fig.2.3.1 gives speed-tractive effort characteristic of a typical single-phase ac locomotive. The portion AB is the average effort at start during the notching period. This is limited by one of the two factors, i.e. the overload rating of the traction motors or the available adhesion. This fact as to which of the above two factors impose the limitation can be verified by drawing the adhesion curve. In the example given at Fig.1, it is the adhesion, which imposes a limit.
A tangent to this adhesion curve is taken as the limiting line so as to ensure that at every point there is enough adhesion available.

As the current permitted at start is more than the continuous rating current of the motors the effort and the current decrease up to the point C which corresponds to the continuous rating. The portion BC
corresponds to a notch beyond which the motor may not admit any overload. Thereafter the curve follows CD which is the average curve during the passage of later notches (from full field) to weak field and CD meets DE, which is the later characteristic of the motor.

A curve showing the train resistance on level (loco + trailing load under consideration) for various speeds is also drawn on the same figure.

From the equation of motion it is seen that

\[ F_a = F - \{(R_L + Wr) + (W + L)s\} \]

The compensated gradient over which the locomotive can haul the trailing load W at an equilibrium speed \( v \) can be obtained from the following equation.

\[ s = \frac{F - (R + Wr)}{W + L} \]

In the above equation \( F, R_L \) are usually expressed in kgf, \( W \) and \( L \) in tonne. Value of \( s \) is obtained as kfg/tonne. For a grade of 1 mm/m the grade resistance is 1 kgf/tonne. Therefore, \( s \) gives the value directly in mm/m. Hence one may replace the graduation in kgf/tonne by an equivalent graduation in mm/m of grade.

A curve between the speed versus the gradient as obtained from the formula can be drawn as indicated in Fig.2.3.2. This curve will be most useful in directly comparing the capabilities of different locomotives.

Consider a point P where \( OP = v \). This point corresponds to a grade “s” say. The train traveling at an equilibrium speed \( v \) over a gradient \( s \), may strike a new gradient \( s_1 \) or \( s \). The train tends to accelerate or decelerate depending upon whether the tractive effort available at that particular speed is more than the train resistance (including the grade effect) or less. With this acceleration or deceleration the train tends to attain the new equilibrium speed \( v \) or \( v_1 \) corresponding to the grade \( s_1 \) or \( s_2 \).

In fact \( s_2 - s \) and \( s_1 - s \) represent algebraically, to a certain scale, the acceleration:

\[ (W+L) (s_2 - s) = F_1 = \{(W+L)/g\}ka \]

\[ a = g(s_2 - s)/k \]

where \( (s_2 - s) \) is expressed in kgf/tonne or grade in mm/metre.

Therefore it can be seen that the curve in the Fig.2.3.2 represents acceleration to a certain other scale (the relationship being as indicated above). In fact this property of this curve is utilized in graphical determination of the speed-distance curve discussed in Annexure 2.3.1.
Performance of a 74 ton locomotive while hauling a 1150 ton goods train

**FIG. 2.3.2**
2.3.8 Total energy consumption and specific energy consumption:

From the speed-distance curves the curves of power at the pantograph against time can be drawn knowing the efficiency of the locomotive at various speeds. The power demand and the specific energy consumption can also be calculated for a typical run. The power demand curves of various trains can be added together to obtain the daily load curve of any sub-station. This computation can be done easily with Amsler’s machine or by suitably programming the same in a computer.

Specific energy consumption can also be calculated directly from the speed-distance curves as follows:

The total energy consumed during a run can be split up into four parts (assuming that there is no braking during the run or due to severe down gradients).

1. \( W_r \) The energy to overcome tractive resistance. For this purpose, the speed attained before braking, say, is \( v \) and the time of journey is say \( t \); average speed given is \( d/t = V_a \). The value of tractive resistance corresponding to this speed is taken as the average tractive resistance overcome during the run. But in practice, \( V_a \) is reduced by 10% to take into account corresponding extra allowance made in the time tables over the minimum time.

2. \( W_m \) The energy required to accelerate the train to the speed \( v \) (speed at which brakes are applied) including the rotary inertia. Here also the value is reduced by 10% for the reasons mentioned in (1) above.

3. \( W_m \) The energy required to take the train over the gradient. The difference in level between two successive points at which the energies are computed is taken as the average gradient encountered.

4. \( W_e \) The energy due to the equivalent grade effect of the curves.

The total of (1) + (2) + (3) + (4) is \( W = W_r + W_m + W_g + W_a \)

The total energy consumption at the rim is given by \( W \) and knowing the efficiency of the locomotive (without auxiliaries) the energy required is obtained. To this the energy consumption of auxiliaries is added to obtain the total energy consumption at the pantograph. Assuming an average efficiency of transmission of the overload equipment, the energy consumption at the substation is determined.

But in practice numerous down gradients are also met with during a run. The ideal driver will so adjust his speed on the summit before he takes the down gradient that he has only to
switch off the power and coast without brake application. Normally a driver should, as far as possible, avoid brake application on down gradients as it means a lot of wastage of power and he should try to maintain the speed carefully without resorting to braking. However, if the down gradients are very steep and continuous and the brake power on the train is not sufficient to make braking possible whenever required or to keep the train under control, brake application may be necessary. In such cases, the energy lost in braking has to be added to the total energy consumption.

There are several variations and simplifications of computing the energy consumption, but the principle is the same as stated above and in practice certain approximations are allowed. For instance, when there are different types of trains – fast passenger, slow passenger, fast goods and slow goods – it is usual to assume a type of train representing each category of trains for the purpose of calculating energy consumption.

Knowing the total energy consumption for a typical train on a particular section, the specific energy consumption can be easily computed.

2.3.9 Energy consumption vis-à-vis inter section running time:

It can easily be seen that a compromise is necessary between the energy consumption and the intersection running time. If the intersection running timings are to be minimum, energy consumption will be maximum, because in order to save time, the train has to be quickly accelerated and quickly braked. Alternatively if the intersection running time corresponding to minimum energy consumption is taken, then the line capacity will be considerably reduced. This is especially applicable to suburban services whether the locomotive hauling is used or EMUs are adopted. A careful investigation is necessary and optimum values are to be chosen consistent with the relative economies brought about by the increased services that are possible with reduced running time or the saving in energy consumption by adopting lower intersection running timings.

2.3.10 Determination of instantaneous and half hourly maximum demands:

Based on the inter section running timings obtained from the speed distance curves graphic train charts are drawn. The proposed tentative locations of traction substations and neutral sections are indicated on the train chart. An examination of the train chart on the route fed by the substation indicates the timings or periods when maximum number of trains draw power from the substation. Graded sections are also marked in the margin to facilitate picking up of loaded trains traversing such sections.
The time is picked up when the maximum load is considered to occur at the substation and from the location and currents of trains at that time (obtained from trailing loads, speeds and grades) the instantaneous maximum demand of the train is obtained from the empirical formula.

\[
\text{Power (in kW)} = \frac{\text{tractive effort (kgf) x speed in km/h}}{367}
\]

The instantaneous demand of all trains which are fed from the single substation are added algebraically to arrive at the maximum demand on the substation. This may be suitably increased to allow for the efficiency of locomotives and the transmission efficiency of the overhead equipment.

The second method is to obtain the instantaneous demand from the calculated half hourly demand. One such formula used is

\[
Z = Y + C \sqrt{Y}
\]

where \( Z \) is the maximum instantaneous demand, \( Y \) is the half hourly demand and \( C \) is a constant. The constant depends on traffic density, type of service EMU fast passenger or goods. For the mix of traffic obtained on trunk routes of Indian Railways this may vary between 40 to 60.

Around the instants of probable instantaneous maximum demand periods of half hourly duration can be chosen so as to include maximum tonne km. Knowing the specific energy consumption for each type of service as obtained from speed distance curves the total energy consumption for the half hour duration can be calculated and from which the half hourly demands can be arrived at.

2.3.11 Practical examples in the form of Annexures as detailed below are enclosed:

Annexure 2.3.1 Tracing the speed – distance curves

Annexure 2.3.2 Tractive Effort requirement calculation for starting & hauling BOXN loads

Annexure 2.3.3 Haulage capacity of WAG-7 loco

Annexure 2.3.4 Haulage capacity of WAG-9 loco

Annexure 2.3.5 Haulage capacity of WAG-5 loco
Annexure 2.3.1

Tracing the speed – distance curves

The method of plotting directly the speed-distance curve and graduating it in terms of time, is described. The principle of the method is based on the fact that knowing acceleration at any instant, the speed distance curve can be obtained by graphical integration.

Consider a point R (Fig.2.3.1A.1) on the speed-distance curve and suppose the speed-grade curve is placed in such a manner that the gradient axis is parallel to the distance axis of the speed-distance curve and such that OR = s where s is the grade corresponding to the point R. Let “R” be the projection of R over the distance axis and P be the point where the speed-grade curve meets that axis.
As we have seen earlier $R'P$ represents acceleration to a certain scale at that instant.

$$R'P = \frac{dv}{dt}$$

where $\frac{dv}{dt} = \frac{dD}{dv} \tan \angle PR'P = \frac{dv}{v} = dv/vdt = dv/dD$

The angle $PR'R'$ is the angle which the tangent of the curve makes with axis of $D$. If a line $RT$ is drawn perpendicular to $RP$ this will be a tangent to the curve at $R$. In order to determine the speed near $R$, it is sufficient to draw an arc at a circle with an angle theoretically infinitely small with $P$ as center. Thus $R'$, a point on the speed-distance curve, is obtained.

Now, starting from $R'$, the same procedure is followed step by step to obtain the speed-distance curve.

In actual practice, the characteristic speed-gradient is drawn on a transparent paper. The working angle “$\alpha$” is also drawn on this. The value of the working angle should be as small as practically possible and, therefore, depends to a certain extent on the scales adopted. However, 10 to 15 degrees will be a reasonable value of this angle without involving appreciable inaccuracy in the speed-distance curve.

**Tracing the curve for braking**

When the train has to stop or slow down, brakes are applied and it is necessary to know the rate of braking to obtain the braking curve. It is found from experience that the deceleration of a train is not uniform due to the variation of co-efficient of friction (between brake blocks and wheel tyres) with speed and also due to the variation of tractive resistance with speed. But for the purpose of tracing the speed-distance curve, this deceleration can be assumed as constant and the speed-distance characteristic which is a parabola can be obtained from the relation:

$$D = \frac{V^2}{2a}$$

This can be drawn on a thick transparent (or even opaque) paper and the sheet can be cut along the curve as indicated in Fig.2.3.A1.2. This can be graduated in time also so that the period of braking can be read out easily.

The following figures represent the average values of deceleration.

<table>
<thead>
<tr>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goods</td>
<td>...</td>
</tr>
<tr>
<td>Passenger</td>
<td>...</td>
</tr>
<tr>
<td>Electric train (suburban)</td>
<td>...</td>
</tr>
</tbody>
</table>
To determine the performance of a given locomotive with a given trailing load the following procedure is adopted:

From the speed tractive effort curve of the locomotive the tractive efforts for various speeds (say, at intervals of 10 km/h) are noted. From the formulae given earlier, the specific resistances for the trailing load (passenger or freight) for the corresponding speeds are worked out, and knowing the trailing loads, the values of total trailing resistance at different speeds are obtained. The locomotive resistance at various speeds is determined from empirical formulae. Thus the tractive efforts of the locomotive and the total resistance values at different speeds are tabulated. Then the difference between the total tractive effort and the total resistance at any speed gives the accelerating effort at that particular speed. This accelerating effort at any speed divided by the total load gives the gradient over which the corresponding speed would be the equilibrium speed. Thus the equilibrium speeds on different gradients can be obtained and a curve between the grades and speeds can be drawn as indicated in Fig.2.3.2. The scales chosen usually are speed 1 cm = 10 km/h and gradient 1° = 6 mm. This curve is drawn on a transparent plastic sheet. A working angle is chosen such that \( \tan \alpha/2 = 1/10 \) and this gives a fairly accurate speed-distance curve. This angle is also drawn on the transparent paper on which the speed-gradient curve is drawn.
The gradient diagram of the particular section on which the performance is to be studied is re-drawn to the suitable scale (1 km = 2 cm). The radii of curvature of different curves are to be noted and compensated gradients are arrived at. The gradient diagram has to be drawn carefully. The distance is represented on the X-axis and the speed on Y-axis. The maximum permissible speed on the section together with all the permanent speed restrictions and the lengths of sections affected thereof due to weak bridges, speed limits on facing points, speed limits on long down gradients, etc., are to be clearly represented on this diagram. Separate diagrams for Up and Down directions are to be drawn as the speed-distance curves are generally different.

Fig.2.3.A1.3 represents a typical example. Starting from `O' the section represented is a level section. The origin of the grade-speed curve representing zero gradient or level is made to coincide with the origin `O' and it is held thereby a pin and the transparent paper (on which the speed-grade curve is drawn) is rotated about this pivot such that line AB of the working angle is parallel to the X axis. In this position the speed-grade curve intersects the X-axis at the point P. Now the pin on point `O' is removed and pivoted on `P' and with `p' as center the transparent paper is rotated such that the line DC of the working angle is parallel to X-axis and the position of the origin which is at point V is pinned. Then OV which is a part of the speed-distance curve is joined by a straight line. The same procedure is adopted till the speed-distance curve meets a vertical line representing a change of the gradient. If a gradient is met with, then the same process is repeated with the only difference that the reference point in this case is not the origin of the speed-grade curve which represents level but the point on the Y-axis of the speed-grade curve corresponding to the particular gradient. If there is a speed restriction or if the train has to be stopped at a station or any other place, the speed-distance curve is obtained by assuming a uniform braking. The rates of braking assumed are different for different types of traffic as explained earlier.
FIG. 2.3.1A.3
It is also advantageous to draw the braking curves on transparent papers as indicated at Fig.2.3.A1.2 so that they can straight away be used. By repeating this process, the speed-distance curve for a given trailing load hauled by a given locomotive on the desired section can be obtained.

Having drawn the speed-distance curve, it is easy to obtain the inter-station running timings. In fact, the speed distance curve itself can be graduated in terms of the time taken in minutes. As is known

\[ V = \frac{\Delta s}{\Delta t} \quad \text{or} \quad \Delta t = \frac{\Delta s}{V} \]

If we consider two points M and N very close to each other (Fig.2.3.A1.5) the time taken for traversing the distance MN is measured by the angle MSN, the bisector of which is parallel to the Y axis or the distance axis.
This angle can be constructed and graduated in such a way that the base (or the opening) represents the distance traveled in one minute or in terms of fractions of a minute. The angle corresponding to one minute with the given scales in $\delta$ where $\tan \frac{\delta}{2} = \frac{1}{6}$ (i.e. at a speed of 60 km/h the distance traveled is 1 km). This angle can be drawn on a set square (Fig.2.3.1A.4) and it can be cut and graduated (in 10\textsuperscript{th} of a minute) in such a way that by merely moving the set square on the X-axis the speed distance curve can directly be calibrated in minutes.
From the above method, through running timings for non-stop trains and the intersection running timings for stopping trains are obtained. These are the minimum timings necessary and a certain extra allowance is allowed for operational facility. After obtaining the intersection timings for different trailing loads, the time tables can be drawn up by the operating department taking other operating conditions (like arrangements of crossings, halts, etc.) into account.

Mechanical methods of tracing the speed-distance curves

When the performance of various types of locomotives with different trailing loads and on different sections are to be studied or compared, it would be very tedious to plot the speed-distance curves manually. In such a case, especially in project studies, other mechanical means of tracing the curves are resorted to. One such apparatus is the Amsier’s machine used for tracing the speed-distance curves. This apparatus consists of two mechanical integrators.

The basic principle behind the working of the machine is the same as described before. The speed-grade curve and the gradient diagram that are used with the machine for tracing the speed-distance curve, are prepared exactly in the same manner as described earlier. The only difference is in the mechanical integration instead of graphical integration which is done manually. However, this machine can be used in conjunction with auxiliary apparatus for determining the energy consumption and the temperature of the traction motors.

This apparatus enables one to obtain quickly the speed-distance curve, intersection running timings, energy consumption, etc.

With the advent of computers, special programmes can be made to suit individual requirements and a lot of time can be saved besides reducing the tediousness. However all the basic data pertaining to locomotives, tractive resistance the gradient charts of the sections with all speed restrictions are to be fed as numerical data. Programmes like computer simulation of train working have been in vogue which can generate a time table of the trains actually run during simulation in graphic form akin to master chart in normal railway working where 75% of the paths can be actually used.
Annexure 2.3.2

Tractive Effort requirement calculation for starting & hauling BOXN loads

Sub : Tractive effort requirement calculation for starting and hauling BOXN loads.

From time to time RDSO have issued letters/reports to guidance of the Railways on the above subject. References have been received from Railway asking for clarifications. Through this circular, the basic methodology of calculations with the formulae, have been described for the information of the Railways. The method for calculation of tractive effect require for starting and hauling loads at particular speed, gradient an degree of curvature and also horse power, OHE current calculations is give in the following paragraphs. The methodology and the various formula adopted are also given.

I. Formulae to be used are :-

1. Tractive effort (TE) required for hauling a load “T” tonne on one in “G” grade and “S” degree is given by

   \[ TE \ (\text{kg}) = T_1 + T_2 + T_3 + T_4 \]

   Where
   
   - \( T_1 \) is train resistance in kg/t.
   - \( T_2 \) is locomotive resistance in kg/t.
   - \( T_3 \) is Grade Resistance for train and loco in kg/t.
   - \( T_4 \) is curvature resistance doe train & loco in kg/t.

2. Train resistance (T1) in kg/t as applicable to loaded BOXN wagons is given by

   \[ T_1 = 0.6438797 + 0.01047218 \times V + 0.00007323 \times V^2 \]

   (For details please refer Para II below).

3. Locomotive Resistance (T2) in kg/t is given by

   \[ T_2 = \frac{13.17}{W} + \frac{0.057}{WN} \times V + \frac{0.00933}{W} \times V^2 \]

   Where
   
   - \( N \) is Number of axles.
   - \( W \) is axle load of locomotive in tonnes
   - \( V \) is speed in kmph

4. Grade resistance (T3) in kg/t is given by

   \[ T_3 = \frac{1}{G} \times 1000 \times (\text{Train load is tonnes} + \text{loco wt. in tonnes}) \]

5. Curvature Resistance (T4) in kg/t is given by
T4 = 0.4 x S degree of curvature x (train load tonnes loco wt. in tonnes)

6. Starting Resistance of BOX ‘N’ and BOX wagon is taken as 4 kg/t and 5.0kg/t respectively including Acieration Reserve.

7. Starting Resistance of the locomotive to taken as 6 kg/t including acceleration reserve.

8. Rail Horse power ‘H’ is given by

\[
H = \frac{T.E.\ (kg) \times v\ (kmph)}{270}\]

Current ‘I’ drawn from OHE is given by

\[
I = \frac{H \times 735.5}{OHE\ voltage \times P.F \times n}\]

where n is the efficiency of the locomotive
P.F. if the power factor of the locomotive.
for conventional locomotive n is taken as 0.80 and
P.F. is taken as 0.84

Note: It is the practice in Railway to take into consideration ‘Compensated Gradient’ while deciding the ruling gradient in such a case T4 is to be excluded.

II

The rolling resistance of BOX ‘N’ / BOX wagons in kg/ t is represented by the formulae:-

i) \( R = 1.333973 + 0.021933 V + 0.000242 V^2 \) for empty BOX N wagons train

ii) \( R = 0.6438797 + 0.01047218 V + 0.00007323 V^2 \) for loaded BOX N wagons train.

iii) \( R = 1.517 + 0.01074 V + 0.000495 V^2 \) for empty BOX wagons train.

iv) \( R = 0.870 + 0.0103 V + 0.0103 V + 0.000056 V^2 \) loaded BOX wagons train.

When \( V = \) speed of the train in kmph
\( R = \) Rolling resistance in kg/t

From the above rolling resistance has been calculated and summarized below for ready reference
### ROLLING RESISTANCE (kg/t) AT VARIOUS SPEED

<table>
<thead>
<tr>
<th>Speed kmph</th>
<th>BOX N wagon Empty</th>
<th>loaded</th>
<th>BOXwagon Empty</th>
<th>loaded</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.5780</td>
<td>0.7559</td>
<td>1.674</td>
<td>0.978</td>
</tr>
<tr>
<td>20</td>
<td>1.8896</td>
<td>0.8826</td>
<td>1.930</td>
<td>1.098</td>
</tr>
<tr>
<td>30</td>
<td>2.2113</td>
<td>1.0239</td>
<td>2.285</td>
<td>1.229</td>
</tr>
<tr>
<td>40</td>
<td>2.6005</td>
<td>1.1799</td>
<td>2.738</td>
<td>1.372</td>
</tr>
<tr>
<td>50</td>
<td>3.0381</td>
<td>1.3505</td>
<td>3.292</td>
<td>1.525</td>
</tr>
<tr>
<td>60</td>
<td>3.5241</td>
<td>1.5360</td>
<td>3.947</td>
<td>1.630</td>
</tr>
<tr>
<td>70</td>
<td>4.0586</td>
<td>1.7360</td>
<td>4.700</td>
<td>1.865</td>
</tr>
<tr>
<td>80</td>
<td>4.6414</td>
<td>1.950</td>
<td>5.560</td>
<td>2.052</td>
</tr>
</tbody>
</table>

### III SAMPLE CALCULATION

Load -- 4700 t (BOX ‘N’)
Grade -- 1/200 (Un compensated)
Curvature -- 2. Degree
Speed -- 50 kmph
Locomotive -- WAG 7 of 123 t weight

1 TE required to start the load:

\[
TE = T_1 + T_2 + T_3 + T_4
\]

- \( T_1 \) = train load in tones & starting resistance of BOX ‘N’ wagon including acceleration reserve.
  
  \[
  T_1 = 4700 \times 4 = 18.800 \text{ kg}
  \]

- \( T_2 \) = Locomotive starting resistance including accelerating reserve locomotive weight in tonnes
  
  \[
  T_2 = 6 \times 125 = 750 \text{ kg.}
  \]

- \( T_3 \) = Grade resistance

\[
T_3 = \frac{1}{200} \times 1000 \times (4700 + 125)
\]

\[
T_3 = \frac{1}{200} \times 1000 \times (4700 + 125)
\]
= 24125 kg

T4 = Curvature resistance

= 0.4 x Curvature x (Train load in tonnes + locomotives weight in tonnes.)

= 0.4 x 2 x 4823

= 3858.4 kg.

TE = 18800 + 738 + 24115 + 3858.4

= 47511.4 kg = 47.51 t

Note :- 1.200 gradient on 2 deg curve is compensated gradient of 1:172.4

\[
\frac{1}{G} = \frac{1000}{X} + 0.4 \times G
\]

where G is grade

S in Degree of curvature

X in compensated grade

If the gradient is 1 in 200 and the curve is 2 degree then G = 200, S = 2 and then compensated grade is

\[
\frac{1}{200} = \frac{1000}{X} = 0.4 \times 2
\]

1000

\[
5 + 0.8 = \frac{1000}{X}
\]

1000

5.8 = \frac{1000}{X}

1000
Therefore X \[\frac{\text{--------}}{5.8}\] = 172.41

Therefore T. E. = T1 + T2 + T3

\[= 18800 + 738 + \frac{1}{172.41} \times 10000 \times 4823\]

\[= 18800 + 738 + 27974\]

\[= 47.512 \text{ t}\]

2. Running the load at 50 kmph

(i) T.E. required :-

\[\text{TE.} = \text{T1} + \text{T2} + \text{T3} + \text{T4}\]

\[\text{T1} = \text{BOX ‘N’ load in tonnes} \times \text{specific resistance in kg/t of BOX ‘N’ at 50 kmph}\]

\[= 4700 \times 1.3505 = 6347.35 \text{ kg.}\]

\[\text{T2} = \text{locomotive wt in tones a specific resistance in kg/ of load at 50 kmph}\]

\[= 123 \times 2.913 \times \text{X} = 358.3 \text{ kg}\]

\[\text{T3} = \text{Grade resistant}\]

\[= 24115 \text{ kg}\]

\[\text{T4} = \text{Curvature resistance}\]

\[= 3858.4 \text{ kg.}\]

\[\text{TE} = 6347.35 + 358.3 + 2411.5 + 3858.4\]

\[= 34679 \text{ kg}\]

\[= 34.679 \text{ t}\]

(ii) Rail Horse power at 50 kmph

\[H = 34679 \times \frac{50}{270} = 6422 \text{ hp}\]

(iii) OHE current at 50 kmph
I = (H X 735.5) / (OHE voltage X P.F. X n)

= (6422 X 735.5) / (22.500 X 0.84 X 0.8)

= 312.39 Amps

The above methodology is to be adopted for haulage & calculation of electric locomotive and supersedes all earlier instruction issued for RDSO on the subject
Annexure 2.3.3

Haulage capacity of WAG7 – loco
Sub: Haulage capacity of WAG7 – locomotive with 16.65 Gear Ratio in Run through conditions on different gradients with CC + 6 (5062t) and CC + 10 (5294t) loading of 58 BOXN.

The haulage of 4700t load with WAG7 locomotive with 16.65 gear ratio on different gradients have been issued by RDSO vide EL/3 1.39/1 dt 01-06-98 (Technical Circular No.22) Railway Board have permitted the loading of BOX N wagon with CC + 6 vide letter no. 2004 CE/IITS/2 dt. 4-5-2005 and CC+10 vide letter no. 2003/CE-II/Ts/5 Vol I dt 4-5-2005 58 Box ‘N’ train with CC+6 (5062t) and CC+10(5294 t ) cannot be started by single WAG7 locomotive on 1.200 up gradients. 1.150 up-gradients. on 1.100 up gradients However. such stretches can be negotiated in run through condition WAG7 locomotive can negotiate 1.200 up gradient with 5062 t. (CC+6) Box ‘N’ load in run through condition with speed more than 20 kmph for other gradients and loads the lengths of stretches which can be negotiated at various attacking speed, have been arrived at by computer and are given as under..

Table – 1
Negotiable Length on 1.150 Compensated up gradient in Run Through Condition
For load – 5062 t (CC + 6)

<table>
<thead>
<tr>
<th>Attacking Speed (kmph)</th>
<th>Max length of 1:150 section which can be negotiated (km)</th>
<th>Exit Speed (kmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1.00</td>
<td>16.0</td>
</tr>
<tr>
<td>30</td>
<td>1.25</td>
<td>22.5</td>
</tr>
<tr>
<td>40</td>
<td>2.00</td>
<td>27.0</td>
</tr>
<tr>
<td>50</td>
<td>3.00</td>
<td>31.0</td>
</tr>
<tr>
<td>60</td>
<td>4.00</td>
<td>33.5</td>
</tr>
<tr>
<td>70</td>
<td>5.00</td>
<td>35.0</td>
</tr>
</tbody>
</table>

Table – 2
Negotiable Length on 1.100 Compensated up gradient in Run Through Condition
For load – 5062 t (CC + 6)

<table>
<thead>
<tr>
<th>Attacking Speed (kmph)</th>
<th>Max length of 1:100 section which can be negotiated (km)</th>
<th>Exit Speed kmph</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Not recommended</td>
<td>---</td>
</tr>
<tr>
<td>30</td>
<td>0.5</td>
<td>18.50</td>
</tr>
<tr>
<td>40</td>
<td>0.75</td>
<td>27.00</td>
</tr>
<tr>
<td>50</td>
<td>1.25</td>
<td>30.00</td>
</tr>
</tbody>
</table>
Table – 3
Negotiable Length on 1.200 Compensated up gradient in Run Through Condition
For load – 5294 t ( CC + 10 )

<table>
<thead>
<tr>
<th>Attacking Speed (kmph)</th>
<th>Max length of 1:200 section which can be negotiated (km)</th>
<th>Exit Speed (kmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>Not recommended</td>
<td>16.0</td>
</tr>
<tr>
<td>30</td>
<td>3.0</td>
<td>24.0</td>
</tr>
<tr>
<td>40</td>
<td>4.5</td>
<td>28.5</td>
</tr>
<tr>
<td>50</td>
<td>5.5</td>
<td>36.0</td>
</tr>
<tr>
<td>60</td>
<td>8.0</td>
<td>37.5</td>
</tr>
<tr>
<td>70</td>
<td>8.5</td>
<td>40.0</td>
</tr>
</tbody>
</table>

Table – 4
Negotiable Length on 1.150 Compensated up gradient in Run Through Condition
For load -- 5294 ( CC + 10 )

<table>
<thead>
<tr>
<th>Attacking Speed (kmph)</th>
<th>Max length of 1:100 section which can be negotiated (km)</th>
<th>Exit Speed (kmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 30</td>
<td>Not recommended</td>
<td>-----</td>
</tr>
<tr>
<td>30</td>
<td>1.00</td>
<td>21.5</td>
</tr>
<tr>
<td>40</td>
<td>2.00</td>
<td>25.0</td>
</tr>
<tr>
<td>50</td>
<td>2.50</td>
<td>32.5</td>
</tr>
<tr>
<td>60</td>
<td>3.50</td>
<td>34.5</td>
</tr>
<tr>
<td>70</td>
<td>4.50</td>
<td>36.0</td>
</tr>
</tbody>
</table>

Table – 5
Negotiable Length on 1.150 Compensated up gradient in Run Through Condition
For load -- 5294 ( CC + 10 )

<table>
<thead>
<tr>
<th>Attacking Speed (kmph)</th>
<th>Max length of 1:100 section which can be negotiated (km)</th>
<th>Exit Speed (kmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 30</td>
<td>Not recommended</td>
<td>-----</td>
</tr>
<tr>
<td>30</td>
<td>0.50</td>
<td>17.5</td>
</tr>
<tr>
<td>40</td>
<td>0.75</td>
<td>26.0</td>
</tr>
<tr>
<td>50</td>
<td>1.25</td>
<td>28.5</td>
</tr>
<tr>
<td>60</td>
<td>1.75</td>
<td>32.0</td>
</tr>
<tr>
<td>70</td>
<td>2.00</td>
<td>40.0</td>
</tr>
</tbody>
</table>
2. Railway are requested to conduct field on the above guidelines in different sections. Based on such trains, they may issue guidelines to Drivers to enable them negotiate such stretches successfully without causing stalling and overloading of electrical equipments. RDSO may be apprised the developments.
Annexure 2.3.4

Haulage capacity of WAG-9 loco

Sub: Haulage Capacity of WAG 9 locomotive with 6 FRA 6068 Traction in Run Through condition on different gradients with CC + 6 (5062 t) and CC + 10 (5294 t) lading of 58 Box N.

The haulage of 4700 t Box ‘N’ load with WAG 9 locomotive on different gradients have been issued by RDSO vide EL/3.1.39/1 dt 24-7-98 (technical Circular no. 24) Railway Board have permitted the loading of Box ‘N’ wagon with CC +6 vide letter no 2004/CE-II/TS/2 dt 4-5-2005 and CC+10 vide letter no 2003/CE-II/TS/5 vol. I dt 4-5-2005.

WAG9 loco can start and haul CC + 6 (5062 t) load 58 Box ‘N’ train 1:200 up gradient whereas CC+10 (5294 t) load 58 Box ‘N’ train cannot be started in 1:200 up gradient WAG9 locomotive can negotiate 1:200 up gradient with 5294 t (CC + 10) Box ‘N’ load in run through condition with speed more then25 kmph.

58 Box ‘N’ train with CC+6 (5062 t) and CC+10 (5294t) cannot be started by single WAG9 locomotive on 1:150 up – gradients or 1:100 up – gradients. However, such stretches can be negotiated in run through condition. The lengths of scratches which can be negotiated at various attacking speed have been arrived at by computer simulation and are given as under-

Table – 1

<table>
<thead>
<tr>
<th>Attacking Speed (kmph)</th>
<th>Max length of 1:150 section which can be negotiated (km)</th>
<th>Exit Speed kmph</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1.5</td>
<td>15.0</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>18.0</td>
</tr>
<tr>
<td>40</td>
<td>4.0</td>
<td>23.0</td>
</tr>
<tr>
<td>50</td>
<td>5.5</td>
<td>29.0</td>
</tr>
<tr>
<td>60</td>
<td>6.0</td>
<td>32.0</td>
</tr>
<tr>
<td>70</td>
<td>7.5</td>
<td>32.5</td>
</tr>
<tr>
<td>80</td>
<td>8.5</td>
<td>34.5</td>
</tr>
</tbody>
</table>
**Table – 2**  
Negotiable Length on 1.100 Compensated up gradient in Run Through Condition  
For load -- 5294 ( CC + 6 )

<table>
<thead>
<tr>
<th>Attacking Speed ( kmph )</th>
<th>Max length of 1:100 section which can be negotiated (km)</th>
<th>Exit Speed kmph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 25</td>
<td>Not recommended</td>
<td>20.0</td>
</tr>
<tr>
<td>30</td>
<td>0.5</td>
<td>20.0</td>
</tr>
<tr>
<td>40</td>
<td>1.0</td>
<td>23.0</td>
</tr>
<tr>
<td>50</td>
<td>1.5</td>
<td>33.0</td>
</tr>
<tr>
<td>60</td>
<td>2.0</td>
<td>34.0</td>
</tr>
<tr>
<td>70</td>
<td>2.5</td>
<td>38.5</td>
</tr>
</tbody>
</table>

**Table – 3**  
Negotiable Length on 1.150 Compensated up gradient in Run Through Condition  
For load -- 5294 ( CC + 10 )

<table>
<thead>
<tr>
<th>Attacking Speed ( kmph )</th>
<th>Max length of 1:150 section which can be negotiated (km)</th>
<th>Exit Speed kmph</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1.25</td>
<td>15.0</td>
</tr>
<tr>
<td>30</td>
<td>1.50</td>
<td>19.5</td>
</tr>
<tr>
<td>40</td>
<td>3.00</td>
<td>24.5</td>
</tr>
<tr>
<td>50</td>
<td>4.50</td>
<td>29.0</td>
</tr>
<tr>
<td>60</td>
<td>5.50</td>
<td>30.5</td>
</tr>
<tr>
<td>70</td>
<td>6.50</td>
<td>33.0</td>
</tr>
<tr>
<td>80</td>
<td>7.50</td>
<td>35.5</td>
</tr>
</tbody>
</table>

**Table – 4**  
Negotiable Length on 1.100 Compensated up gradient in Run Through Condition  
For load -- 5294 ( CC + 10 )

<table>
<thead>
<tr>
<th>Attacking Speed ( kmph )</th>
<th>Max length of 1:100 section which can be negotiated (km)</th>
<th>Exit Speed kmph</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Not recommended</td>
<td>----</td>
</tr>
<tr>
<td>30</td>
<td>0.5</td>
<td>19.0</td>
</tr>
<tr>
<td>40</td>
<td>0.75</td>
<td>28.0</td>
</tr>
<tr>
<td>50</td>
<td>1.25</td>
<td>31.5</td>
</tr>
<tr>
<td>60</td>
<td>2.00</td>
<td>32.0</td>
</tr>
<tr>
<td>70</td>
<td>2.50</td>
<td>37.0</td>
</tr>
</tbody>
</table>
2. Railway are requested to conduct field on the above guidelines in different sections. Based on such trains, they may issue guidelines to Drivers to enable them negotiate such stretches successfully without causing stalling and overloading of electrical equipments. RDSO may be apprised the developments.
Annexure 2.3.5

Haulage capacity of WAG-5 loco

Sub: Haulage capacity of WAG-5 locomotive with Hitachi Traction motor 18:64 gear Ratio in Run Through condition on different gradients with CC + 6 (5062 t) and CC + 10 (5294 t) loading of 58 Box ‘N’.

The haulage capacity of WAG5 Locomotive fitted with Hitachi traction on different gradients have been issued by RDSO vide EL/3.1.39/1 dt 20-7-98 (Technical Circulars No. 26) Railway Board have permitted the loading of BOX ‘N’ wagon with CC+6 vide letter no 2004/CE-II/TS/2 dt 4-5-2005 and CC+10 vide letter no 2003/CE-II/TS/5 Vol. I dt 4-5-2005.

Single WAG5 locomotive cannot start and haul 58 BOX ‘N’ train loaded with CC+6 and CC+10 on up gradients steeper than 1:200, 1:150 and 1:100 For gradient sections twin WAG5 locomotives are required for starting and hauling 5.8 Box ‘N’ trains.

However, computer simulation have been done with single WAG5 loco I fitted with Hitachi traction motor) to arrive at the lengths of stretches which can be negotiated in Run through conditions at various attacking speeds for 58 BOX ‘N’ load results are as under.

Table – 1

<table>
<thead>
<tr>
<th>Attacking Speed (kmph)</th>
<th>Max length of 1:100 section which can be negotiated (km)</th>
<th>Exit Speed (kmph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.5</td>
<td>14.0</td>
</tr>
<tr>
<td>30</td>
<td>1.5</td>
<td>15.0</td>
</tr>
<tr>
<td>40</td>
<td>2.5</td>
<td>20.0</td>
</tr>
<tr>
<td>50</td>
<td>3.5</td>
<td>26.0</td>
</tr>
<tr>
<td>60</td>
<td>4.0</td>
<td>34.0</td>
</tr>
<tr>
<td>70</td>
<td>5.0</td>
<td>37.5</td>
</tr>
<tr>
<td>Attacking Speed (kmph)</td>
<td>Max length of 1:150 section which can be negotiated (km)</td>
<td>Exit Speed kmph</td>
</tr>
<tr>
<td>------------------------</td>
<td>----------------------------------------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Up to 20</td>
<td>Not recommended</td>
<td>---</td>
</tr>
<tr>
<td>30</td>
<td>0.5</td>
<td>22.0</td>
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<tr>
<td>40</td>
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<tr>
<td>50</td>
<td>2.0</td>
<td>26.0</td>
</tr>
<tr>
<td>60</td>
<td>2.5</td>
<td>33.0</td>
</tr>
<tr>
<td>70</td>
<td>3.0</td>
<td>29.0</td>
</tr>
</tbody>
</table>

Table – 3
Negotiable Length on 1.100 Compensated up gradient in Run Through Condition
For load -- 5062 ( CC + 6 )

<table>
<thead>
<tr>
<th>Attacking Speed (kmph)</th>
<th>Max length of 1:100 section which can be negotiated (km)</th>
<th>Exit Speed kmph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 30</td>
<td>Not recommended</td>
<td>------</td>
</tr>
<tr>
<td>40</td>
<td>0.75</td>
<td>19.0</td>
</tr>
<tr>
<td>50</td>
<td>1.00</td>
<td>28.0</td>
</tr>
<tr>
<td>60</td>
<td>1.50</td>
<td>30.5</td>
</tr>
<tr>
<td>70</td>
<td>1.75</td>
<td>29.5</td>
</tr>
</tbody>
</table>

Table – 4
Negotiable Length on 1.200 Compensated up gradient in Run Through Condition
For load -- 5294 ( CC + 10 )

<table>
<thead>
<tr>
<th>Attacking Speed (kmph)</th>
<th>Max length of 1:100 section which can be negotiated (km)</th>
<th>Exit Speed kmph</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.5</td>
<td>13.5</td>
</tr>
<tr>
<td>30</td>
<td>1.25</td>
<td>17.0</td>
</tr>
<tr>
<td>40</td>
<td>2.00</td>
<td>23.5</td>
</tr>
<tr>
<td>50</td>
<td>3.00</td>
<td>28.5</td>
</tr>
<tr>
<td>60</td>
<td>4.00</td>
<td>32.0</td>
</tr>
<tr>
<td>70</td>
<td>5.00</td>
<td>35.5</td>
</tr>
</tbody>
</table>
Table – 5
Negotiable Length on 1.150 Compensated up gradient in Run Through Condition
For load – 5062 ( CC + 10 )

<table>
<thead>
<tr>
<th>Attacking Speed ( kmph )</th>
<th>Max length of 1:150 section which can be negotiated (km)</th>
<th>Exit Speed ( kmph )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 25</td>
<td>Not recommended</td>
<td>---</td>
</tr>
<tr>
<td>30</td>
<td>0.5</td>
<td>21.0</td>
</tr>
<tr>
<td>40</td>
<td>1.25</td>
<td>21.5</td>
</tr>
<tr>
<td>50</td>
<td>2.0</td>
<td>24.5</td>
</tr>
<tr>
<td>60</td>
<td>2.5</td>
<td>31.5</td>
</tr>
<tr>
<td>70</td>
<td>3.0</td>
<td>34.0</td>
</tr>
</tbody>
</table>

Table – 6
Negotiable Length on 1.100 Compensated up gradient in Run Through Condition
For load – 5062 ( CC + 10 )

<table>
<thead>
<tr>
<th>Attacking Speed ( kmph )</th>
<th>Max length of 1:150 section which can be negotiated (km)</th>
<th>Exit Speed ( kmph )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to 30</td>
<td>Not recommended</td>
<td>---</td>
</tr>
<tr>
<td>40</td>
<td>0.5</td>
<td>28.0</td>
</tr>
<tr>
<td>50</td>
<td>1.00</td>
<td>27.5</td>
</tr>
<tr>
<td>60</td>
<td>1.50</td>
<td>29.5</td>
</tr>
<tr>
<td>70</td>
<td>1.5</td>
<td>36.0</td>
</tr>
</tbody>
</table>

2. Railway are requested to conduct field on the above guidelines in different sections. based on such trials. they may issue guidelines to Drivers to enable them negotiate such stretches successfully without causing stalling and overloading of electrical equipment RDSO may be apprised of the developments.

References

2. La Determination des – raires des trains de Voyageurs sur la Region Du Sud – Est M.Aramnd, M.Garin
3. Apparellde la S.N.C.F. pour le Trace des Horaires des Trains M.G.Bohi
Chapter-4

TRACTION SUBSTATIONS AND SWITCHING STATIONS

2.4.1 General considerations

The substation is the interconnecting link between the power station and the consumer. Substations are necessary because it is economical to transmit electrical power over appreciable distances at high voltages where it can only be economically utilized at comparatively low voltages. The same considerations hold good for traction distribution as well.

2.4.1.1 Principles of design

a) Equipment should be of sound design and construction so that risk of failure is minimized.

b) Automatic protective devices should rapidly remove faulty apparatus and sections from the system without interference to healthy section.

c) Wiring and methods of laying – in cables should be as simple as possible.

d) Suitable means of access and handling of the equipment should be provided.

e) All openings in control mechanisms should be dust and vermin proof and be so arranged as to prevent ingress of moisture by providing suitable heating elements as necessary.

f) Maintenance and repairs to plant and buildings should be possible without affecting the service. Effective sub-division into units or sections is essential.

g) A reserve of plant should be maintained in readiness to meet any emergency conditions.

h) Space should be allowed for a reasonable expansion to meet future demands.

i) Earthing conductors should be of adequate current carrying capacity throughout – especially at joints and be suitable for carrying maximum fault current for short durations.

The first step in designing a sub-station is to prepare a single line diagram of main electrical connections which should show the bus-bar arrangements, circuit breakers, isolators and may gradually be added to include protective apparatus, instruments and voltage and current transformers. Next step is to decide the arrangement of switchgear considering reliability, safety, flexibility, simplicity, space and cost.
Duplicate bus-bars are preferred to facilitate cleaning, repairs, modification and extensions without interruption of supply and for testing repaired breakers etc. before putting into commission.

2.4.1.2 Choice and location of site

The choice and location of sub-station sites are of prime importance. A far-sighted policy is essential in the selection of sub-station sites. The site selected should permit bringing in and taking out the feeders, both incoming HT and outgoing 25 kV.

Adequate access from a public road is desirable for traction sub-stations to facilitate handling of plant. A Railway siding will be an advantage if it can be conveniently provided. The site for substations must be free from water logging, should preferably be a site which requires less or no filling for leveling. It is further desirable to locate the site near overlaps, if OHE already exists. Though teeing-off method is simple and cheap it does not afford the facilities necessary on an important higher voltage network.

Where outdoor switchgear is installed, it is necessary to provide a room for the control equipment, protective relays, instruments and testing equipment. This building should have a room set apart for the maintenance personnel who will be required to work under varying conditions in an emergency.

2.4.1.3 Standardization

Standardization saves time in design, construction and procurement of materials. Stocking of standard spares help considerably. Much drawing office work is saved and the construction staff become familiar with details and arrangements.

2.4.1.4 Structures

Structures should be designed to carry the transmission lines, conductors, insulators, isolating switches, and other fittings under the specified conditions of loading and factors of safety. The rigidity of the structures should be such that the alignment of the equipment which they carry shall not be disturbed by the loads to which they are subjected. In calculations of factor of safety the strength of compression members is usually based on the crippling loads as given by approved formulae, the strength of tension members being based on the elastic limit.

2.4.2 Layout of Traction sub-station

The main considerations in planning the physical layouts of traction substations are reliability of supply, simplicity of equipment and connections, ease in the operation and maintenance and safety of personnel. The appearance of a traction substation is simple, deceptive but the design, construction, operation and maintenance are quite complex and hence are likely to be over-rated.
The equipment of the traction sub-station comprises:

- HV switchgear controlling the incoming supply.
- Step down transformers
- Switchgear controlling the outgoing 25 kV supply
- Auxiliary apparatus including protective system and cables

The schematic diagram of PT & CT connections in a sub-station is shown in fig. 2.4.1 below.
FIG. 2.4.1

For simplicity and economy single bus-bar arrangement; where each of the two circuits is provided with its own breaker is provided. The fact that reliability of traction supply is of primary importance almost always implies that provision of duplicate HV feeders is necessary. The sub-station comprises two transformer bays each with HV isolators, HV circuit breakers, single phase step down
transformers from HV to 25 kV and the associated 25 kV switchgear. Only one of the two transformers meets the load while the other is kept as standby. The primary windings of the power transformers are connected across two phases of the three phase system. One secondary terminal of the transformer on the 25 kV side is solidly earthed and the other terminal is connected to the catenary system through the 25 kV feeders.

The HV isolators are of the rotating center pillar type and the two switches in both the phases are operated simultaneously. The HV breakers consist of two single phase units interconnected mechanically and operated simultaneously. Each of the two transformers and its associated breakers on the primary and secondary are considered as one unit and protective system has been designed accordingly. If any of the equipments in one unit is to be taken out for maintenance, the unit has to be shutdown keeping the other unit in service by opening the double pole isolators located before the HV circuit breaker and after the 25 kV breaker. The feeder circuit breaker is provided either with a double pole isolator as per earlier practice or with one single pole isolator on either side so as to permit its cleaning and maintenance to be carried without having to shutdown the transformer of that bay.

A bus coupler interrupter is provided. If either of the two outgoing 25 kV feeder circuit breaker develops a fault and is required to be isolated, this can be done by opening the associated isolators. To permit continuance of supply through the other feeder circuit breaker, the bus coupler interrupter may be closed by remote control. Necessary interlocking arrangements are provided for all the isolators to prevent their operation on load. HV double pole isolators are mechanically interlocked with the associated HV circuit breakers. 25 kV single pole isolators after the transformer breakers are interlocked with respective 25 kV transformer breakers.

The layout of the sub-station is made fairly compact leaving enough working space around each equipment with additional space for adding one more transformer bay. While transformers are installed on concrete plinths at ground level, other equipments are usually installed on steel structures. The movement of equipment and access to equipment for maintenance purposes has to be taken care of. The sub-station building has to provide enough space for control room, battery room and a tool room.

### 2.4.3 Bus-bar layout

The bay widths are standardized for each primary voltage i.e. 66 kV, 110kV, 132 kV and 220 kV. The most generally used system voltage is 132 kV and bay widths for 132 kV are standardized as 14.0 m for HV bay and 6.0 m for 25 kV bay. The stung bus on the HV side stung at a height of 9.35 m from ground level comprises of 54/3.18 mm (28.62 mm dia) ACSR conductor (Zebra) with a gross area of aluminium of 428 mm². On the 25 kV side 50 mm outside dia aluminium tubular bus bar is provided at a height of 3.8 m. Tension of stung bus is specified as 450 kgf and the earth screen wires as 200 kgf. at 4°C without wind. The maximum span from the last tower to sub-station gantry is generally limited to around 75 m. If the distance of the incoming HV transmission line from the grid sub-station is more than 4 km, lightning arrestors are provided on the incoming lines, at the traction sub-station.
The deflections of bus-bars supported on post insulators should not exceed half the diameter of the bus bars or span/1440 whichever is less. The maximum current density in copper bus-bars and connections in direct contact with air should be such that the maximum permissible temperature of 70°C is not exceeded (maximum hot spot temperature not exceeding 75°C). The current density generally adopted for outdoor copper bus-bars is 2 A/mm². For aluminium bus bars, current density of 75% of that of copper is permitted. The maximum permissible current density under short circuit conditions should not normally exceed 100 times the permissible density.

The insulators, bus bars and connections should not be stressed to more than 1/4 of the breaking load or 1/3 of their elastic limit whichever is lower.

**Clearances**

The minimum clearances in air for live equipment shall be as under:

<table>
<thead>
<tr>
<th>Clearances</th>
<th>Clearance in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25 kV</td>
</tr>
<tr>
<td>1 Between phases</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>[ since single phase]</td>
</tr>
<tr>
<td>2 Between one phase and earth for rigid connection</td>
<td>500</td>
</tr>
<tr>
<td>3 Between any point where man may be required to stand to the nearest</td>
<td></td>
</tr>
<tr>
<td>a) unsecured conductor in air</td>
<td>3000</td>
</tr>
<tr>
<td>b) secured conductors in air</td>
<td>2000</td>
</tr>
<tr>
<td>4 Minimum height of bus bar</td>
<td>3800</td>
</tr>
</tbody>
</table>
2.4.4 Characteristics of Traction transformers

To cater for the peaks in the demands, the transformers are capable of withstanding non-recurring over-loads of 50% for 15 minutes and 100% for 5 minutes after the transformer has reached steady temperature on continuous operation at full load. OIP condenser type bushings with built in current transformers are provided on the primary/secondary sides. To reduce the short circuit currents higher percentage impedance i.e. $12 + 0.5\%$ is specified. Off load tap changing from $+10\%$ to $-15\%$ in steps of 5% is provided on the low voltage side. The maximum efficiency is specified at about 50% of full load.

The temperature rise over an ambient of 50°C for 100% over load for 5 minutes or 50% over load for 15 minutes after continuous full load operation is specified not to exceed 50°C for winding (resistance measurement) and 40°C for oil by thermometer.

In the traction application, the ability of transformers to withstand short circuits is very important. As many as 200 short circuits/earth faults with fault currents varying between 40% and 100% of the dead short circuit value, can occur in a month. At short circuits, the life of the windings is threatened by two phenomena i.e. the violently increased thermal and mechanical stresses. While the effect of heating can be reasonably predicted the effect of mechanical stresses cannot be evaluated. Unfortunately, all the existing transformer standards are unsatisfactory in this respect. Further even if some standards for short circuit tests are specified, the possibility of obtaining power for carrying such tests in the manufacturer’s work is remote. Hence, different manufacturers take different attitudes towards this problem and as such their makes are not strictly comparable. For this reason, in the specification, a general stipulation has been made that the transformers would be subjected to frequent short circuits during normal operation.

The transformers of ratings of 21.6 MVA are specified as ONAN cooled and so designed that with ONAF cooling at a later date the capacity is capable of being increased by 40% more by provision of forced cooling (ONAF).

Buchholz Protection

Incipient faults such as short circuited core laminations, broken down core bolt insulation, overheating of the winding, bad tap switch contacts, faulty joints etc. result in the slow production of gas. In case of more serious faults such as an internal short between the turns, earth faults, puncture of bushing insulators inside the tank etc., the evolution of gas is rapid.

Buchholz relay provides complete internal protection against such conditions. The relay basically comprises of a cast housing which contains two pivoted aluminium buckets, each bucket being counter balanced by a nickel-plated brass weight. Each assembly carries a mercury switch, the leads from which are taken to the terminal block.
In both the alarm and surge element assemblies, the respective weights of the bucket and the balance weight are so distributed that the balance weight predominates, thus tilting the assembly to 'switch open' position.

When a slight or incipient fault occurs in the transformer, small bubbles of gas will be generated and these, attempting to pass from the tank to the conservator will be trapped in the relay housing. As the gas accumulates the oil level in the relay will fall, leaving the top bucket full of oil. As the bucket will not now be fully immersed, the extra weight due to the contained oil will overcome the balance weight and cause the whole assembly to tilt thereby closing the mercury switch and completing the alarm circuit.

With a serious internal fault, however, the gas generation is rapid, causing the displaced oil to surge through the relay, the oil flow will impinge on the plate and cause the bottom bucket to tilt, closing the mercury switch and complete the trip circuit to the circuit breaker.

If the transformer suffers loss of oil, causing the oil level to drop below the level of the relay, the bucket of the two elements will be left full of oil and first the alarm and then the surge element will operate to close their respective circuits.

**Winding and oil temperature protection**

The life of the transformer depends upon the state of its insulation, whose rate of deterioration is accelerated at excessively high temperatures. Therefore, the transformers have been provided with winding and oil temperature alarm and tripping device which operate through mercury contacts. The settings adopted for the above are respectively 100°, 105°, 85°, and 90°C.

**Inter tripping of 132 kV CB and 25 kV transformer CB**

Operation of the following relays result in inter tripping of the transformer circuit breakers on primary as well as on the secondary sides.

a) Differential relay  
b) Restricted earth fault relay on primary or secondary  
c) Buchholz relay  
d) Winding temperature trip  
e) Oil temperature trip  
f) Pressure relief device tripping

Large size transformers are usually delivered to site on a special truck and are either jacked and lowered or lifted direct from the truck. They are then pulled into the outdoor bay by means of block and tackle attached to a substantial hook. Transformers are fitted either with skids or rollers to facilitate handling.
Transformers are fitted with pressure relief device of self reset type to afford protection against tank failures. The principal design factors in reducing the noise level are a reduction of the flux density and a substantial and well designed core. A further precaution is the inclusion of anti-vibration pads between the transformer and its foundations.

2.4.5 Characteristics of switchgear and other equipments

The choice of switchgear is governed by the maximum short circuit MVA which it is called upon to deal with and also in some degree upon its relation to the system of which it forms a part. The exact value of rupturing capacity of the switchgear is rather difficult to estimate because of complicated nature of the systems. Magnitude of possible fault currents depends on many factors which may vary from hour to hour on large interconnected system. Two extreme conditions are:

a) severe short circuit at times of heavy load and lagging power factor and

b) a mild short circuit during times of light load and leading power factor. The worst possible condition will govern the selection of switchgear.

2.4.6 Insulation levels for the equipments and the insulation co-ordination

The reliability of the sub-station depends very much on the proper co-ordination of the insulation levels of lines and equipments and the surge diverting equipment. The insulation level of any apparatus is characterized by the two test voltages which the apparatus can withstand i.e. the crest value of impulse voltage and the rms value of one minute, power frequency withstand voltage. These withstand voltages characterize the strength of the apparatus as to their capability of withstanding dielectric stresses.

Insulation co-ordination consists of the steps taken to prevent damage to electrical equipment due to over voltages and to localize flashovers when they cannot be economically prevented to points where they will cause least damage. This is achieved by the necessary correlation between the insulation strength of the electrical apparatus and the characteristics of the protective devices such as non-linear lightning arrestors against over voltages, which may be of atmospheric origin or generated within the system itself. Thus insulation co-ordination involves the design not only of the individual equipments but of the complete system.

The equipment three phase voltage for the 25 kV single phase system would be 44 kV and the corresponding system highest voltage will be 10% more i.e. 48.4 kV. This corresponds to the IEC standard system highest voltage of 52 kV. The basic insulation level for this system highest voltage is

- 250 kV impulse withstand
- 95 kV power frequency withstand
An essential requirement in the selection of insulation levels for the transmission lines is that the line insulation under adverse conditions should withstand a power frequency voltage of 3 to 4 times the nominal phase to earth operating voltage. This condition generally ensures that the impulse withstand voltage is about the same as or exceeds the IEC standard insulation level. As the pollution of insulators of the catenary system due to industrial pollutants, salt laden breeze in coastal areas etc., is unavoidable higher insulation level is specified to avoid failures on the overhead equipment. The impulse withstand values of solid core insulators of the traction overhead equipment have been specified as 260 kVp (negative wave), higher than the system insulation level. The test values in some cases are more than 300 kV.

As the flash over voltage of bushings should not be higher than the flash over voltage of the windings to prevent internal damages to windings due to surges, bushings are fitted with arcing horns. The amplitude of incoming surges are kept as low as possible by protecting the incoming lines with arrestors and gaps or by adequately screening the incoming feeders by earth wires.

The insulation levels specified in IEC are determined with a view to obtaining co-relation with protection level of the over voltage protective devices. A protective device is characterized by its impulse protection level which appears at its terminals. The major difference in rating of lightning arrestors and other equipments is on account of the fact that for arrestors, the voltage across individual arrestors is most important and not the phase to phase voltage. The rated voltage of lightning arrestor is taken as 80% of system highest voltage for effectively earthed systems or the system highest voltage itself for non-effectively earthed systems.

### 2.4.7 Supply and sectioning arrangements of OHE

#### 2.4.7.1 Need for sectioning of overhead equipment

In the traction distribution system, without booster transformer, the substations are located normally 50 to 80 km apart. Between adjacent substations neutral sections are provided. One feeder circuit breaker controls the feed for both up and down tracks on either side of the traction substation. The return current reaches the substation by way of rail/earth circuit. For any fault on the OHE the feeder circuit breaker has to trip cutting off the supply to the entire section (both up and down tracks) from the substation to neutral section thereby affecting the entire traffic on the section. It should be desirable to isolate a small faulty section (so that whole system does not get paralyzed simultaneously) and to restore the supply to other healthy sections. For this purpose the OHE has to be divided into sections and provided with switches. Sectioning is the method of dividing the OHE into electrically isolated sections by provision of interrupters/isolators at overlaps and with section insulators at turnouts.

#### 2.4.7.2 Overlaps in overhead equipment

The catenary and the contact wire of the OHE are given a constant tension of 1000kg each so that the variation in temperature does not cause sag or hog. This is achieved by providing auto-tensioning equipment at either end and by fixing the OHE at the mid point, known as anti-creep. The normal
length of OHE is about 1500 m between two tensioning equipments. A three span overlap maintains the mechanical and electrical continuity and permit smooth passage of pantograph from one tension length to the other. In the anchoring span the contact wire of ‘out of run’ OHE is raised and the catenary wire lowered so that it does not interfere with the ‘in run’ OHE. If two insulators are provided in either OHE at the overlap it becomes an insulated overlap and the OHE of two sides becomes electrically separated. In un-insulated overlaps separation of parallel OHEs is 200 mm and in insulated overlaps it is 500 mm. Thus an overlap provides a convenient point for sectioning of OHE into different sections. Another method of achieving this is to provide a section insulator in the OHE but this arrangement necessitates speed restrictions. Modern versions of short lengths of glass fibre insulation cut into the contact and catenary wires with a ceramic covering to resist abrasion, are replacing the provision of insulated overlaps and section insulator assemblies.

2.4.7.3 Sectioning Arrangement

OHE is divided into electrically isolated sections by provision of non-automatic circuit breakers called interrupters, which do not open out automatically on fault, or isolators at overlaps and with section insulators at turnouts. Sectioning is provided to permit isolation of OHE in small sections for maintenance or to isolate faulty or damaged OHE in case of breakdown or accident and to permit diversion of trains from up line to down line and vice-versa. Sectioning should however be kept to the minimum consistent with operational requirements. The section of overhead equipment, supply to which is controlled by one automatic circuit breaker located at the traction substation/feeding post is called a sector. A sub sector is the length of OHE of one track between two consecutive remote controlled interrupters i.e., between two switching stations. An elementary section is the smallest section of OHE, which can be isolated from the rest of the section by either removing the jumper or by the operation of switches i.e., circuit breakers, interrupters, isolators etc. An elementary section may cover more than one track and is bounded by an insulated/un-insulated overlap, dead-end anchor or a section insulator. Any such boundary of an elementary section may be bridged either by an interrupter or isolator.

2.4.7.4 Supply and sectioning of OHE

The 25 kV supply from the feeder circuit breakers of the traction substation is terminated on a gantry at the feeding post. The feeding post may either form part of the traction substation or may be situated at a separate location close to the track connected by 25 kV feeders from the feeder circuit breakers, if there is considerable distance between traction substation and feeding post. One feeder circuit breaker feeds the sector from substation to neutral section through two interrupters controlling the supply to each track on either side.

At the neutral section midway between two substations the up and down tracks are paralleled to reduce the voltage drop. Bridging interrupters are provided at the neutral sections to enable extension of the feed from one substation to the overhead equipment normally fed by the other substation in emergencies or when the latter is out of use. The bridging interrupter is normally kept open. Two such bridging interrupters are provided one for each track. The bridging interrupter is provided with an
under voltage relay which automatically opens the bridging interrupter when the voltage falls below a preset value (normally 19 kV) in case of extended feeding condition so as to maintain the supply to the normal section after disconnecting the extended zone.

In certain cases it may be desirable to provide an arrangement through an isolator (motor operated preferably or manually operated by the loco driver) by which the dead section can be fed from the OHE ahead to help any stalled locomotive. Potential transformers (to indicate the condition of OHE) and lightning arrestors are provided. A trip circuit battery and a remote control battery are housed in the cubicle at each switching station. An auxiliary transformer tapped off from the OHE provides supply for charging the batteries which provide the trip supply to the interrupters.

Between a feeding post and the sectioning post, sub-sectioning and paralleling posts are provided to enable switching off supply for smaller sections of OHE. A paralleling interrupter is provided to facilitate feeding of the tracks ahead from either of the live OHEs and also to reduce the voltage drop.

Circuit breakers and interrupters are all remote controlled from the remote control center. If a fault occurs on the section the circuit breaker trips and is indicated at the remote control center. Traction power controller isolates the faulty section and restores the supply to all the other healthy sections.

The distance between two switching stations (15-20 km) is large enough in cases of fault repairs and maintenance of longer durations. Hence sectioning is required at each station so that when long duration isolation of a section is required single line working can be resorted to between the affected stations. The sectioning is achieved by means of insulated overlaps bridged by isolators, which can be manually operated locally at no load. With the help of the traction power controller the faulty section or sections, which has to be maintained is isolated.

All sectioning is done by providing insulated overlaps and section insulators and the OHE design aims at location of these insulators and insulated overlaps at places which provide maximum operating facility consistent with economy.

2.4.8 Switching stations

Switching stations are provided at intervals of 15-20 km all along the electrified track. These switching stations house interrupters (load switches), which do not open out automatically on faults. These interrupters control the supply to different sections of the overhead equipment. The switching stations are unattended and the interrupters are operated by remote control from the supervisory remote control center. They can break load currents or can close on short circuit currents. Each interrupter is provided with a manually operated double pole isolator to facilitate its maintenance. As the isolators cannot make or break load currents they are interlocked with their associated interrupters, so as to ensure their operation only when the interrupter is open.

The interrupters are mounted on steel structures above ground level in a row. In front of the interrupters a gantry about 4.5 m high is provided where the corresponding isolators are mounted.
The connections from isolators to OHE are provided through jumpers and cross feeders anchored to a high gantry which is about 10 m from rail level, which also supports the isolator gantry.

Switching stations comprise of feeding posts (FP at traction substations), sectioning and paralleling posts at neutral sections (SP), sub-sectioning and paralleling posts (SSP), (numbering two or more depending on the distance between feeding post and the sectioning post), yard supply posts (YSP) to feed major yards and occasionally sub-sectioning posts (SS) which are similar to SSPs but without any paralleling.

Paralleling interrupters are provided at SP and SSP to parallel the up and down tracks of OHE, in order to reduce the voltage drop and to facilitate movement of traffic in case one sub-sector or one or more elementary sections are either faulty or taken up for maintenance.

At all switching stations the ancillary equipment comprises of:

i) Lightning arrestors to protect the equipments against surge voltages.

ii) Potential transformers (25 kV/110 V) connected to the OHE of each sub-sector to provide indication to remote control center about the availability of 25 kV supply to each sub-sector.

iii) Auxiliary transformer 10 kVA tapped off the OHE supply to supply 240 V ac for battery charging of remote control equipment, signaling and telecommunication facilities, control battery for trip supply and lighting etc. The auxiliary transformer is provided with off-circuit tap-changer on the secondary winding to allow for variation in voltage in the OHE.
A small masonry cubicle is provided to accommodate remote control equipment, telephone, batteries and battery chargers required for the trip supply and remote control of interrupters etc.
2.4.9 Neutral sections and location of sectioning posts

2.4.9.1 Need for the Neutral sections

For 25 kV single phase traction, power is tapped from the different phases of the HV grid at adjacent substations so as to reduce unbalance at the tapping point within permissible limits and to achieve a certain degree of balance on the grid by geographically connecting different substations on different phases. A neutral section essentially consists of a small length of overhead equipment provided midway between two traction substations which is electrically isolated from either of the substations but which provides mechanical continuity to permit smooth passage of pantograph from one section to the other. Neutral sections are also provided at traction substations having Scott connected or open delta connected transformers as the two sides are out of phase by 90° and 60° (or 120°) respectively.

Neutral sections are also provided sometimes in front of traction substations to prevent shorting between phases in case of a shut down of the substation and extension of feed from adjacent substations in emergencies as otherwise the pantograph will have to be lowered to prevent bridging of wrong phases.

2.4.9.2 Location of Neutral section

As the neutral section is negotiated by the loco/EMU with power off under its own momentum it should be ensured that the loco/EMU acquires the necessary momentum while negotiating the neutral section and that under no circumstances the loco/EMU should stop under a neutral section which tantamount to a failure and consequent blocking of the line. To prevent this, neutral sections should be provided far away from stopping signals, level crossing etc. The neutral section should not be on an up gradient or on sharp curve. The neutral section is ideally located in midsection between two block stations, away from stopping signals and on a down gradient if available or on tangent track or in a tough between two graded sections.

2.4.9.3 Length of Neutral section

The length of the neutral section is determined with reference to the extreme position of raised pantographs either of a multiple headed loco hauled train or EMU stock. A neutral section of 41 m has been adopted to cater for double heading of locomotives. When the pantographs of extreme ends of multiple headed trains are raised they are about 40 m apart and the air gaps will not be simultaneously bridged by the pantographs. General arrangements of neutral sections are indicated at Fig.2.4.3.

The standard neutral section is a five span arrangement providing two air gaps between the OHEs, the central section functioning as neutral OHE. As in the case of insulated overlap spans, the horizontal separation between the two OHEs is maintained at 500 mm with a minimum of 320 mm electrical clearance at any point. In suburban sections where adoption of overlap type neutral section, is not feasible short section, 5m long, comprising of section insulators can be adopted. With this arrangement speed is restricted to 100 km/h if the runners of section insulators are in trailing direction.
or 70 km/h otherwise. If adoption of short neutral sections is unavoidable on main lines, short neutral section at ceramic beaded resin boned glass fiber rod insulators can be provided up to 130 km/h.

The indication boards to indicate the approaching neutral section are provided.

2.4.10 Auxiliary power supplies at traction substations and switching stations

At traction substation, auxiliary LT supply is required for the following purposes

a) to charge the substation batteries which provide supply to control the various switchgear, control panels, remote control equipment, oil testing equipment etc.

b) to provide substation general switchyard lighting and to enable operation of hand tools etc. including repairs involving welding.

c) to provide power for operation of oil filtering plants.

Two 10 kVA auxiliary transformers one fed from each bay are installed to meet the requirements of (a) and (b) and partly (c) and to facilitate use of portable filtering plants.

During construction and commissioning a temporary three phase LT supply is taken from the local authorities to meet the main requirement of power for drying out the power transformers before commissioning. A filtering plant of 2500 litre per hour capacity with power requirement of 70 to 80 kW is used for purifying and drying of insulating oil. Though this arrangement was adequate for installation the need for use of high capacity filtering plant is felt. It is seen that 90% of power requirements of oil filtering plant is required by heaters and 10% for the motors and two pumps. It is feasible to work the plant on single phase system by redesigning the three phase motors, for operation on single phase system. To cater to this requirement substations may be provided with one 100 kVA single phase auxiliary transformer and one 10 kVA transformer.

240 V ac supply for operation of remote control equipment, signaling and telecommunication equipment, battery charging etc. is required at each switching stations. If a local reliable supply is available from the Electricity Board it is provided. Otherwise this supply is derived by installing 25 kV/240 V single phase out door type auxiliary transformers fed from the OHE. One terminal is connected to OHE and the other brought out and earthed through a link. The auxiliary transformers are pole mounted.

The batteries provided for trip supply of interrupters, remote control equipment, signaling and telecom installations are usually of stationary lead acid type with 10 hour rating. Nickel cadmium batteries can also be used to reduce maintenance.

The transformers are protected by a 25 kV, 1 A drop out fuse on primary side and 63 A fuse on secondary side. On the 240 V side of the transformer a single pole iron clad switch with fuses is
provided inside the remote control cubicle. A lightning arrestor is provided to protect the high tension winding of the transformer.

Fig.2.4.4, 2.4.5 and 2.4.6 indicate the schematics of FP, SSP and SP respectively.

2.4.11 AT system of feeding

With the conventional 25 kV ac traction system the substation spacing varies from 40 to 70 km depending on the traffic obtained on the electrified sections and the extent of provision of booster transformers with return conductors to limit the inductive interference in the neighboring
communication lines. Traction transformers of 10 to 12.5 MVA which were provided initially are replaced by 20 MVA transformers after twenty to thirty years to cater for the increased demands while keeping the voltage drop within permissible limits. Further increase in traffic (especially on certain mineral and trunk routes) with the attendant increase in line losses due to boosters and return conductors calls for reduction in existing substation spacing which might ultimately result in actual doubling of the number of traction substations as compared to their initial number at the time of electrification. The capacity of booster transformers also would be stretched to their limiting conditions.

Hence, in cases of unprecedented traffic growth on the existing electrified sections and on heavy mineral routes which might necessitate provision of boosters and return conductors (to reduce inductive interference) which in turn calls for closer substation spacing, it might be desirable and perhaps economical to go in 2 x 25 kV Auto Transformer feeding system (AT feeding system).
In AT, the feeding voltage from the traction substation is twice the conventional system voltage. Power received from the grid of the State Electricity Boards at 132/220 kV is stepped down and transmitted at the
high voltage of 50 kV from the traction substation through the contact system and a feeder wire (strung close to catenary on the same mast) is stepped down by auto-transformers to the catenary voltage of 25 kV required for the locomotives and EMUs. These auto transformers are located along the track at intervals of about 10 to 15 km depending upon the traffic density. The midpoints of the substation transformers and auto-transformers are connected to the traction rails. The auto-transformers ensure the flow of return current along the feeder wire except in cases of train-in-section where the return current flows in rails in that auto transformer cell.

The fundamental principle of working of an AT system is illustrated in Fig.2.4.7. If $V_1$ and $V_2$ are the terminal voltages of the primary and secondary windings of auto-transformers (with turns ratio of series winding and common winding of $n_1$ and $n_2$ respectively) and the induced emf’s are $e_1$ and $e_2$ with currents $i_1$ and $i_2$ then

$$\frac{V_1}{V_2} = \frac{e_1 + e_2}{e_2} = \frac{n_1 + n_2}{n_2}$$

(1)

If the load current is $I_2$ in secondary, current in primary $I_1$ would be such that (neglecting magnetization current)

$$\frac{I_1}{I_2} = \frac{n_2}{n_1 + n_2}$$

(2)

But $i_1 = I_1$ and $i_2 = I_1 - I_2$

(3)

In case of auto-transformers used in 2 x 25 kV AT feeding system $n_1 = n_2$.

$$\frac{I_1}{I_2} = \frac{1}{2} \text{ and } i_1 = I_1 \text{ and } i_2 = -I_1$$

(4)

It is seen that current in the series winding is equal and opposite to the current in the common winding. Hence under ideal conditions no current flows in the track rails of the section where no train runs and is called the ‘booster effect’ of the auto transformer (See Fig.2.4.6). The leakage impedance and saturation characteristics of auto transformers however cause flow of rail/earth currents causing minor induction problems in adjacent communication circuits. (See Fig.2.4.9).

In a conventional system with/without boosters the length of feeding section is limited by voltage drop considerations, whereas with AT system it can be twice as much due to 50 kV supply voltage at which power is transmitted. Every BT overlap is a point of electrical and mechanical weakness of the contact wire especially at high speed, AT system is more suitable for high speeds. Induced voltages are much less in AT system in both load conditions and short circuit conditions.

Fig.2.4.10, 2.4.11 and 2.4.12 indicate the schematic layouts of traction substations with AT system of feeding, with single phase transformers, V-connected transformers and Scott-connected transformers respectively.
PRINCIPLE OF WORKING OF AT SYSTEM

**FIG. 2.4.7**

CURRENT DISTRIBUTION IN 'AT' SYSTEM IN AN IDEAL STATE

**FIG. 2.4.8**

ACTUAL CURRENT DISTRIBUTION IN AT SYSTEM

**FIG. 2.4.9**
SCHEMATIC DIAGRAM - TSS

(WITH SINGLE PHASE TRANSFORMERS FOR FEEDING IN ONE DIRECTION)

FIG. 2.4.10
SCHEMATIC DIAGRAM - TSS
(WITH V - CONNECTED SINGLE PHASE TRANSFORMERS)
FIG. 2.4.11

132 kV T.P. ISOLATOR WITH EARTHING HEEL

132 kV D.P. ISOLATOR
400-200/5A, 30VA, 132 kV C.T. FOR TRANSFORMER PROTECTION
133 kV, D.P.C.B.
120 kV L.A.
BUSHING C.T. 330/5A
21.6 MVA, 132/2X27kV POWER TRANSFORMER
BUSHING C.T. 800/5A
42 kV L.A.

25 kV D.P. ISOLATOR

25 kV C.T.
1000-500/5A, 60VA

CBF-1       CBF-3
27.5 kv/110V, P.T, 100 VA (TYPE-III)
25 kV C.T,
1000-500/5A, 60VA
CBF-2
SHUNT CAPACITOR
SERIES REACTOR

54 kv/27 kv
8 MVA AUTO TRANSFORMER
SCHEMATIC DIAGRAM - TSS
(WITH SCOTT CONNECTED TRANSFORMERS)

FIG. 2.4.12

220 KV INCOMING SUPPLY

- 220 kv T.P. ISOLATOR WITH EARTHING HEEL

- 220 kv T.P. ISOLATOR

- 220 kv CT 200-100/5A, 30VA

- 220 kv, T.P.C.B.

- 132 kv L.A.

- BUSHING C.T. 330/5A

- SCOTT CONNECTED 2X27 MVA TRACTION POWER TRANSFORMER

- BUSHING C.T. 1000/5A

- 25kv DP ISOLATOR

- 25kv D.P. C.B.

- AUTO TRANSFORMER

- 27.5kv/100V, PT (TYPE-III)

- 54kv/27kv, 8MVA

- TRANSFORMER PROTECTION

- 100kVA, 25kv/240V, L.T. SUPPLY TRANSFORMER

- 10kVA, 25kv/240V, L.T. SUPPLY TRANSFORMER

- 132KV L.A.

- 220KV L.A.

- 198kv L.A.

- 220kv T.P. ISOLATOR

- 220kv T.P. ISOLATOR

- 220kv C.T. 200-100/5A, 30VA

- 220kv T.P.C.B.

- 132kv L.A.

- BUSHING C.T. 330/5A

- SCOTT CONNECTED 2X27 MVA TRACTION POWER TRANSFORMER

- BUSHING C.T. 1000/5A

- 25kv DP ISOLATOR

- 25kv D.P. C.B.

- AUTO TRANSFORMER

- 27.5kv/100V, PT (TYPE-III)

- 54kv/27kv, 8MVA

- TRANSFORMER PROTECTION

- 100kVA, 25kv/240V, L.T. SUPPLY TRANSFORMER

- 10kVA, 25kv/240V, L.T. SUPPLY TRANSFORMER

- 132KV L.A.

- 220KV L.A.

- 198kv L.A.

- 220kv T.P. ISOLATOR WITH EARTHING HEEL

- 220kv T.P. ISOLATOR

- 220kv C.T. 200-100/5A, 30VA

- 220kv T.P.C.B.

- 132kv L.A.

- BUSHING C.T. 330/5A

- SCOTT CONNECTED 2X27 MVA TRACTION POWER TRANSFORMER

- BUSHING C.T. 1000/5A

- 25kv DP ISOLATOR

- 25kv D.P. C.B.

- AUTO TRANSFORMER

- 27.5kv/100V, PT (TYPE-III)

- 54kv/27kv, 8MVA

- TRANSFORMER PROTECTION

- 100kVA, 25kv/240V, L.T. SUPPLY TRANSFORMER

- 10kVA, 25kv/240V, L.T. SUPPLY TRANSFORMER

- 132KV L.A.

- 220KV L.A.

- 198kv L.A.

- 220kv T.P. ISOLATOR WITH EARTHING HEEL

- 220kv T.P. ISOLATOR

- 220kv C.T. 200-100/5A, 30VA

- 220kv T.P.C.B.

- 132kv L.A.

- BUSHING C.T. 330/5A

- SCOTT CONNECTED 2X27 MVA TRACTION POWER TRANSFORMER

- BUSHING C.T. 1000/5A

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- 10kVA, 25kv/240V, L.T. SUPPLY TRANSFORMER

- 132KV L.A.

- 220KV L.A.

- 198kv L.A.
References


2.5.1 Introduction

The protection scheme adopted for single-phase traction though based on the principles of protection adopted for ac power transmission systems, differs from the same in certain respects. In a three-phase power transmission system a phase to earth fault can be detected easily by the flow of zero phase sequence current and a three-phase short circuit fault by the flow of large currents. But in the normal operation of the traction network one phase is always solidly earthed, a condition corresponding to an earth fault on a single-phase transmission system. As such the protective system should discriminate an earth fault current from the load current.

The schematic diagram of typical traction substation is shown in Fig.2.5.1

Relay is the most important component of any protection system. During a fault or an abnormal condition one or more of the basic electrical quantities such as current, voltage, phase angle, direction, frequency or rate of rise of current associated with the circuit of the relay changes. The relay compares one electrical quantity with another or a component of it in phase, magnitude or both by obtaining two forces or torques proportional to the two quantities. Basically all relays are phase or amplitude comparators. A number of relays measure derived quantities like impedance, admittance, current ratio etc.

Relays can be classified into electro magnetic relays, static relays, numerical relays and other special purpose types like Buchholz, thermal relays etc.

During the earlier stage of electrification electro magnetic type relays were used to protect the OHE. The main drawbacks of these types of relays were less accuracy, less reliability, more maintenance and changes in relay characteristics with time etc. To overcome these problems in electro magnetic type relays, static/numeric relays have been introduced in new projects since 1990 and existing electro magnetic type relays are gradually being replaced by static/numeric relays.

2.5.2 General considerations

A protective system is called upon to prevent damage due to overloads, to isolate a faulty section, thereby permitting the rest of the system to continue to function. As such the protective system shall be able to detect all fault conditions and isolate the faulty equipment from the system as quickly as possible.

The protective scheme should have the essential features like reliability and selectivity. The desirable features are sensitivity, high speed of operation and absence of blind spots.

Reliability is the ability to operate without fail when a fault occurs, while remaining in active under normal operating conditions. Besides proper design and installation, regular testing and proper maintenance of equipment improves reliability. Selectivity is achieved by proper application of the protective scheme.
High speed of operation ensures quick isolation of faulty sections with least damage to other healthy units. The protection zones should be so arranged as to overlap on both sides of circuit breaker by the proper location of current transformers. The protection system should be so designed that each part is covered by at least one protection ensuring absence of blind spots.
2.5.3 **Principle types of protective system**

There are two classes into which protective systems may be divided

a) Restricted or unit class (e.g. circulating current protection)

b) Unrestricted class (e.g. over current protection)

A unit or differential system of protection operates only for faults occurring in a clearly defined region i.e. between two sets of current transformers at either end of cable. Their essence is a comparison of some quantity (current or voltage) at the two (or more) ends of the protective zone. The unit scheme must have pilot connections between the points of measurement.

The performance of a unit system is measured as the ratio of the maximum through-fault current for which the equipment will remain stable to the minimum operating current under an internal fault condition. This factor is termed as the stability ratio.

In contrast to unit or restricted systems the zone operation for unrestricted protection extends over a power system without clearly defined limits e.g. over current protection and distance protection. Over current protection is frequently found as a back up protection. The over current relay is generally of the inverse definite minimum time type, allowing four or five circuits to be graded discriminatively in series.

Neglecting the fault impedance, for a solid fault on the catenary, the current in the fault loop and the voltage across it at the end of the line will be related by the impedance of the intervening line. Assuming the line impedance is constant, the position of the fault can be determined by measuring the impedance between the fault and the relaying point and this can be used to determine whether the fault is internal to the section being protected or a through condition for which no operation is required.

A simple relay consists of an element in which fault current produces an operating force and the voltages across the fault loop produces a restraining force. At a critical value of impedance the two forces balance. For any greater impedance the relay remains inoperative and for any lesser impedance it operates. This arrangement is a definite distance relay in which zone of protection extend from the relaying position upto the ‘balance’ points. The relay is stable for all faults beyond this point.

Other relays can be arranged to have a time of operation proportional to the distance of the fault from the relaying point so that discrimination between successive circuit breakers is achieved by virtue of a time interval between the operating times of the relays. Such an arrangement is termed time distance/time scheme. The quantity selected for measurement need not necessarily be impedance. It can be designed to respond to any desired component of the complete impedance vector depending upon the particular requirements of the network to be protected.
2.5.4 Primary and secondary system of protection

Efficient protection with the characteristics of discrimination and speed of operation is provided by a primary system of protection applied to various circuit breakers. A secondary system of protection associated with the same circuit breaker usually serves as back up protection in the event of failure of the primary protective gear, or when it is out of service or on test. The secondary system of protection when associated with another circuit breaker in series caters for failure in the opening mechanism of circuit breaker, which is supposed to clear the fault first.

Both primary relaying and back up secondary relaying is used for protection against short circuits. Primary relaying is the first line of defense and back up relaying function only in case of failure of action on the part of primary relays. Each of the protection relays is designed for a specified zone. Any failure occurring within the zone causes tripping of all circuit breakers in that zone only. A certain amount of overlap in the zones is inevitable and has to be tolerated as a lesser evil. Failures of primary relaying may be on account of failure of current or voltage supply, failure of relays, failure of ac tripping voltage supply, failure of tripping circuit or breaker mechanism or when the primary relaying is taken out for repair or maintenance. Back up relaying ensures protection in case of failure of primary relaying.

2.5.5 Component parts of protection system

It will be appreciated that although a protective system is quiescent for most of its life it must operate correctly when called upon. Such performance relies not only upon sound theoretical design and application but demands in addition a continuous program of maintenance. A complete protective system relies upon a number of components, the principle parts being:

a) The protective relay and associated equipment on the relay panel.
b) Current and voltage transformers.
c) Trip supply.
d) Interposing and tripping relays.
e) Wiring.

The electromechanical relays, which were in vogue till now, are gradually being replaced by static and numerical microprocessor based relays. The electromechanical relays essentially consist of a measuring element besides elements for ancillary functions such as tripping, timing, and operation indication and alarm purposes.

The simplest form of element is the instantaneous attracted – armature relay element, which can be wound for current or voltage and the setting, can be varied by spring adjustment or by a tapped coil and the contacts are designed for closing duty only. It has a inverse operating-time / current characteristic, to achieve good speed of operation (0.01 to 0.03 seconds) it must be operated at 2 to 5 times minimum operating value. It is used as an accurate measuring device in instantaneous over current or earth fault protection, and restricted earth fault protection for transformers.
The induction relay element produces a torque as a result of interaction of two ac fluxes, which are produced either from a single coil and a phase splitting copper, loop or by two coils suitably energized. A cup shaped rotor or a metal disc rotor can be used. The operating-time / current characteristic is inverse and may be varied (made long i.e. 10 – 20 s or short 0.015 to 0.04 s) by suitable choice of angular contact travel and applied operating quantities.

The moving coil relay element is the most versatile element and can be used in any protective scheme except those requiring a relatively long operating time. The element is normally operated from auxiliary transformers and rectifiers. Advantages are extremely high sensitivity coupled with good thermal rating and linearity of characteristic.

The potential transformer does not present unusual problems when applied in conjunction with protective equipment but the current transformer and the protective relay must be designed in close association. For a given CT, increase of the current level or the burden above the design limit can lead to serious ratio error.

In static relays, the relay action is performed by electronic /magnetic/optical or other means without mechanical motion. However additional electromagnetic relay units may be used in output stage as auxiliary relays. The analogue static relays use the printed circuit board (PCB) and single chip ICs. They are used for a wide range of application.

Digital static relays circuit use logic circuit and digital electronics. The relay may have PCB or IC having fixed circuits. Digital electronics circuit processes the information by processing discrete electrical signals in digital form. The digital electronic circuits can be used to hold and store discrete information by means of memory. The protective relaying functions require sequential operations depending upon information being processed.

2.5.6 **Protection for Power Transformers**
Transformers in traction substations are provided with the following protection.

a) Over current protection both for the primary and secondary.
b) Differential protection
c) Restricted earth fault protection both for the primary and secondary

2.5.7 **Over current protection**
Over current relays provided on the primary and secondary side of the transformers are set to operate for any currents above the permissible maximum.

2.5.8 **Differential protection**
Differential protection operates for faults occurring in clearly defined region i.e., between two sets of current transformers situated at either end of the equipment to be protected.

Figures 2.5.2(a) and (b) indicate the principle of operation of differential protection. The currents entering and leaving the equipment that is protected are compared and any inequalities cause the relay operation. The two current transformers secondary are so connected that there is no current in
the relay under normal conditions. If the currents at the two ends are unequal it is an indication of either an earth fault or fault between phases.

Differential protection must however, remain inoperative for maximum through fault currents and should operate even for small internal fault currents. For all through fault conditions the currents of the secondary of the current transformers must be exactly opposite in phase and equal in magnitude. This calls for high degree of perfection in design and high class of accuracy of the current transformers. Even small differences in the characteristics of the CT’s may produce out of balance current especially during heavy through fault conditions, resulting in mal-operation.

**PRINCIPLE OF DIFFERENTIAL PROTECTION**

![Diagram](Fig. 2.5.2(a) and 2.5.2(b))

Marginal differences in CT characteristics can be taken care of by using bias coil. A restraining or bias coil carries the circulating currents of both the current transformers is provided for this purpose. If the line currents are large, a large restraining force which cannot be overcome by any small differences in the current transformer characteristics is produced. The number of turns of the restraining coil are adjustable to get equal secondary currents.
The power transformers are fitted with off circuit tap-changer equipment. The CT ratios selected are based on the principle tap of the range. To compensate the effects of out of balance currents due to change of taps on the LV side (from the normal tap) which causes small differences in the ratios of the current transformers an auxiliary current transformer is included in the secondary circuit of the HV bushing current transformers. The difference in bushing CTs on account of change in the taps can be compensated by the appropriate tapping in the auxiliary CT. Whenever a power transformer is energized a short duration inrush current occurs, the magnitude of which depends on the point of the voltage wave at which the circuit breaker contacts are closed. This appears as an internal fault to the differential protection because it has no counterpart on the secondary side. This inrush current may result in mal-operation. To eliminate such mal-operation the relay is made insensitive for short durations. As the inrush magnetizing current comprises fundamental and high percentage of second harmonic, a positive torque for fundamental and high negative torque for the second harmonic are obtained by passing the out of balance current through a filter and the relay becomes insensitive for short duration and as the current is gradually damped the relay finally recovers its normal sensitivity. This does not prevent the operation of the relay if the transformer is switched on with an internal fault, as the percentage of fundamental is very predominant.

A percentage relay with 20%, 30% and 40% setting is employed and with 20% setting the operating current for 5 A, secondary current is 1 A. The purpose of the percent slope characteristic is to prevent undesired relay operation because of unbalances.

2.5.9 Restricted earth fault protection

This is provided as a back up protection to the differential protection for internal earth faults of transformer winding and also for earth faults in the restricted zone between the transformer breaker and the winding. High-speed earth leakage instantaneous relays of very low pickup current are connected to separately mount current transformers in the two phases separately for the primary and the secondary windings of the transformer. The relay also works on the principle of differential current in operating coil and a 10% setting of relay is used with an operating current of 0.5 A for 5 A secondary current. Time discrimination between the operation of differential relay and backup earth leakage relay is provided such that the former operates first.

2.5.10 Buchholz protection

Buchholz relay is used for detecting incipient faults which if allowed to persist can cause excessive damage. All types of faults occurring within oil filled transformers are accompanied by generation of gases, which the heat liberates, from oil. There are several types of incipient faults which produce gas though slowly i.e. short circuited core laminations, broken down core bolt insulation, local overheating of winding, bad switch contacts at tap changer, faulty joints etc.

The Buchholz relay usually consists of two floats, which carry contacts. The upper float indicates the presence of low accumulation of gas and gives an alarm. The lower float operates trip contact when
there is a sudden rush of gas indicating serious faults such as internal short circuit between phases and turns, earth faults etc., which require immediate isolation.

2.5.11 Other protective devices for traction transformers

In addition to the above types of protection other conventional protections for large power transformers i.e., excessive winding temperature, oil temperature indicator with alarm and trip contacts as well as low oil level alarm and pressure relief device are also provided.

2.5.12 Inter-tripping of transformer breakers

Inter-tripping is required in those special cases where an internal fault (fault between incoming and outgoing breaker) may be detected by the protection at only one end of the section. The local circuit breaker is thus tripped but the faulted line remains energized from the remote terminal. Operation of the following relays result in inter-tripping of both the transformer circuit breakers (on the primary and secondary), to ensure complete isolation of the fault.

- Restricted earth fault relay on either the primary or the secondary
- Instantaneous O/C relay and IDMT relay on primary
- Differential relay
- Buchholz relay (trip circuit)
- Excessive oil temperature (trip circuit)
- Excessive winding temperature (trip circuit)
- Pressure relief device in transformer

A hand reset feature is provided on the inter trip relay to minimize the likelihood of the transformers being reclosed inadvertently thereby subjecting the transformer to further damage unnecessarily.

The IDMT relay on the transformer secondary on operation trips the transformer circuit breaker on 25 kV side only.

2.5.13 Nature of faults on the catenary system

The faults on the overload equipment can be mainly of three types:

a) Earth faults
b) Overloads
c) Faults due to incorrect switching operations.

Earth faults can be due to overhead equipment insulator failures, bushing to earth faults of transformers and switchgear, flashover at arcing horns due to atmospheric over voltages, breakage of
overhead equipment, etc. Faults in the locomotives are cleared by the circuit breakers (air blast or vacuum circuit breaker) of locomotives. However, earth faults on the roof of locomotives ahead of its circuit breaker appear as earth faults on overhead equipment. Overloads can be due to abnormal traffic conditions resulting from bunching of trains or due to faults in the locomotives or electric multiple units, which are not cleared by their circuit breakers. Incorrect switching i.e. bridging of the neutral section, results in out-of-phase paralleling of adjacent substations, which are fed from different phases of the primary network.

Tracks on either side of the substation are fed through a single circuit breaker and individual tracks are fed through interrupters (non-automatic circuit breakers). The substation equipment are protected against over voltages by means of lightning arrestors/spark gaps or arcing horns and against short circuits and abnormal loads by feeder circuit breakers. The protective relays associated with each circuit breaker are called upon to fulfill the following functions:

- To detect all short circuits over the catenary system fed through the circuit breaker.
- To operate quickly resulting in minimum delay in opening the circuit breaker.
- To remain inoperative for the maximum working currents.

The normal zone of the fed of the substation extends only up to the neutral section midway between the adjacent substations. It will be necessary in case of emergencies to extend this feed up to the next substation by closing the bridging interrupter of the neutral section. The protection system should cater for this extended zone of feed.

The protection system comprises the following relays

a) In older system an admittance (Mho) relay to cover the entire zone of protection i.e. from the substation to the adjacent substation and to operate for any earth fault on the overhead equipment in this zone. A numeric based parallelogram characteristic distance protection relay has now been introduced in place of existing mho relays to protect the OHE from faults.

b) An admittance (Mho) relay for protection against wrong phase coupling due to phase-to-phase faults with 120° or 60° phase difference between two phases with a maximum torque angle of 125° to 145°. The relay is provided with forward ‘off set’ to prevent it from operating on phase to earth faults. In new generation microprocessor based numerical relay modules this is inbuilt.

c) An over current relay of instantaneous type which can clear faults between the substation and the neutral section with an adjustable current setting ranging from 200% to 800% with operating time not exceeding 10 ms. Some other protection relays now being provided are delta I relays and panto-flash over relays.
2.5.14 MHO relay protection

An ordinary over current relay cannot meet these requirements, as the short circuit current for a distant fault under unfavorable conditions is sometimes less than the maximum working current. Similarly, an ordinary impedance relay cannot be used because the working impedance is much less than the dead short impedance for a distant fault and, moreover, the magnitudes of these impedances may also be equal for a fault at a particular distance. Only the phase angle of the impedance would be different under such conditions and a relay, discriminating between the phase angles and having its maximum sensitivity for an impedance with a given phase angle, called the mho relay, is used. Phase angle discrimination is possible as the phase angle of the traction load varies between 30 and 40 degrees and under earth fault conditions, it will be between 60 to 70 degrees. The MHO relay derives its name from the fact that its characteristic is linear when plotted on an admittance diagram.

A numeric based parallelogram characteristic distance protection relay has been introduced in place of existing mho relay. It permits better discrimination between fault currents and load currents over the entire feeding section. Relay has a feature of independent setting of $R_F$, $R_B$, $X_F$, $X_B$, and characteristic angle. To avoid the mal-operation of the relay due to switching surges (arising due to simultaneous switching on of locos), second harmonic blocking feature has also been introduced in the relay.

2.5.15 Wrong phase coupling protection relay

In the event of outage of one traction substation, the 25 kV supply is extended up to the failed traction substation from the substations on either side by closing the bridging interrupters at neutral section. Under such emergency feeding conditions wrong phase coupling may be caused at the overlaps opposite the failed traction substation by the pantograph of a passing locomotive which is inadvertently not lowered (in spite of standing instructions in such cases) resulting in tripping of 25 kV feeder breaker at any one of the two substations through wrong phase coupling relay. The phase angle of the wrong phase relay is adjustable between 125° to 140°.

In place of existing WPC relay, numeric based WPC relay have been introduced at TSS. It operates on the principle of measured fault impedance and its angle; if impedance lies between 11 ohm to 38 ohms and its angle lies in second quadrant “between 90° to 150°” in R-X plane, then relay identifies a wrong phase coupling and initiates a trip command. The relay does not act for regenerative currents produced by locos/emus below a preset limit.

2.5.15 A Instantaneous over current relay:
An instantaneous type over current relay trips for current exceeding the set limit. The operating time of the relay is $20 \pm 2$ ms.

2.5.15 B Delta –I type high resistive fault selective relay:
The distance protection relay may fail to detect faults of high resistive nature. In order to detect these types of faults, Delta-I type relay have been introduced at traction sub-station. It works on the principle of vectorial difference between base & fault currents. If the vectorial difference seen by relay is more than the set current, it initiates the trip command.
Fault current comprises mostly fundamental components whereas the load current contains large harmonic component. This feature is used to discriminate between fault and load current in the Delta-I type fault selective relay. It is used as a back up to the distance protection relay.

2.5.15C Panto flash over protection relay:

Whenever the OHE at one end of IOL at TSS is dead due to faults in OHE or OHE is under maintenance and electric trains enter from the live to the dead section, there will be a heavy flash over when the Panto leaves the IOL.

The above problem can be taken care of by tripping the live side feeder CBs before the pantograph travels from live to dead side of OHE at IOL. For this purpose, suitable logics have been developed by continuously monitoring the status of feeder CBs, Interrupters, PTs provided at TSS. The relay generates a trip command if abnormal status is sensed.

2.5.16 Under voltage protection of neutral section

As the HV supply for the adjacent substations is tapped from different phases, a short dead section called a neutral section is provided on the overhead equipment between two such traction substations to maintain mechanical (but not the electrical) continuity of the overhead equipment.

When the zone of feed is extended beyond the neutral section (by closing the bridging interrupter) a low voltage relay provided at the neutral section acts and trips the bridging interrupter when the voltage falls below the normal set value of 17.5 kV (which can be set between 15 to 19 kV).

2.5.17 Capacitor trip device

Circuit breakers are provided with capacitor trip device through a no volt relay, to trip in case of failure of the control dc supply.

2.5.18 Auto-reclosing of Circuit Breakers

Operational experience has shown that most of faults occurring on the traction overhead equipment are of a transient nature and are likely to get cleared automatically if the line is de-energized for an interval long enough to permit the fault to be extinguished. The transient faults may be due to lightning discharges, or surface flashover on the overhead equipment insulators due to atmospheric pollution or due to deposits of carbon caused by diesel locomotives plying on electrified sections or salt deposits in coastal areas or due to any other industrial pollutants. Switching surges can also cause transient flashovers at times. All such flashovers occur with air as the conducting medium and are usually self-clearing once the fault current is interrupted by the first operation of the circuit breaker.

Therefore, if auto-reclosing of circuit breakers is adopted it reduces the outage of the affected sections. It is, of course, not possible to reclose the circuit breaker immediately after it trips as there are mechanical and other constraints in restoring the circuit breaker to be prepared to undertake a
reclosing operation. This dead time depends upon the type and design of the circuit breakers. In addition it is also desirable and necessary to allow a certain minimum time for the arc extinction at the fault location.

The practice adopted presently is to provide a single shot high speed auto reclosure of the breaker with a dead time of 0.5 second (adjustable between 0.1 to 1 second) and reclosure time after 30 second (adjustable between 6 to 60 seconds). If the fault persists the circuit breaker trips and gets locked out. The circuit breaker needs resetting for further operation. This autoreclosing scheme is inter connected with the remote control equipment for tele-signaling the ‘locked out’ condition of the autorecloser to Remote control centre and for resetting the same through telecommand from the RC centre.

2.5.19 Calculation of fault currents in traction system

The short circuit current depends upon the internal impedance of the supply (i.e. power stations, transmission lines and transformers) seen from the traction substation, and upon the impedance of the traction circuit up to the fault and the impedance of the fault. Fault impedance is usually neglected in order to find the maximum value of the fault current. In fault calculations it is customary to take into account only the reactances of apparatus and lines, resistance being neglected.

It is necessary to convert all reactance’s to the line voltage i.e. 25 kV and obtain a single reactance or impedance representing the system viewed from the fault. An impedance of $Z_1$ in part of the circuit at voltage $V_1$ seen from another part at voltage $V_2$ connected by means of transformers, becomes $Z_2 = Z_1 \left(\frac{V_2}{V_1}\right)^2$. Whereas the line reactance is given as Ohm/km the reactance of alternators, transformers and other apparatus is expressed as percentage reactance or per unit reactance. If $Z_P$ is the percentage reactance value $Z_P/100$ is the reactance value in per unit. The actual reactance of the alternator is given by

$$Z = \frac{(V / I)}* Z_P /100 = \frac{(V^2/P)}* Z_P /100 \text{ Ohm}$$

Where $P$ is the rated capacity of the alternator.

In the three phase system Z is always the impedance in Ohms per phase, whether in the equation the line to neutral voltage is used together with one third of the power or the line to line voltage together with full power. System calculations can be carried out with percent or per unit values in the same way as with Ohm values provided they all are based on the same reference capacity $P$. The value is proportional to the reference capacity so that an impedance of 6% referred to 10 MVA is 12% referred to 20 MVA. With Ohm values the same care has to be taken to ensure that all values used in one calculation are based on the same reference voltage. The Ohm values are proportional to the square of the reference voltage.

The impedance of a system as viewed from a certain point is given, generally, by its short circuit capacity $P_S$ in MVA. In this case the impedance is

$$Z = \frac{V^2}{P_S} \text{ in Ohms per phase referred to voltage V in kV}$$
and the impedance in percent is

\[ Z_P = \frac{P}{P_S} \times 100 \text{ referred to } P \text{ in MVA.} \]

Every earth fault of the traction overhead equipment gives rise to a short circuit as the catenary system generally gets connected to an earthed structure i.e. OHE mast, rail etc., the resistance of the fault being usually negligible.

The total impedance of the circuit from the generator to the point of fault on the catenary comprises of source impedance (determined by the three phase short circuit level), Transformer impedance, 25kV feeder line impedance and the impedance of overhead equipment up to the fault. If the three-phase short circuit power on the 132 kV bus is say 2500 MVA at the traction substation the impedance as seen on 132 kV

\[ j X_0 = \frac{132^2 \times 10^6}{2500 \times 10^6} = 6.97 \text{ Ohm} \]

The effective loop impedance is \( 2 \times j 6.97 = j 13.94 \text{ ohm.} \)

This impedance transferred to 25 kV side would become

\[ j 13.94 \times \left(\frac{25}{132}\right)^2 = 0.5 \text{ Ohm} \]

Main transformer reactance

\[ j X_T = \frac{E^2 \times Z\%}{100 \times P} \]

Where \( P \) is transformer capacity and \( Z\% \) is percentage impedance. When \( P = 13.5 \text{ MVA and } Z = 10\%. \)

\[ j X_T = \frac{25^2 \times 10^6 \times 10}{100 \times 13.5 \times 10^6} = 4.63 \]

The fault current is obtained by

\[ I = \frac{E}{\sum Z} = \frac{E}{j(X_0 + X_T) + Z_L} \]

Where \( Z_L \) is the impedance of the OHE from the traction substation to the point of fault and is obtained by knowing the distance and kilometric impedance of the traction overhead equipment.

2.5.20 Setting and adjustment of relays
RDSO had issued guidelines for setting of protective relays vide R.D.S.O report No. TI. 35 (7/95) on development of microprocessor based integrated feeder protection modules circulated to
zonal railways in July 1995. The same has been amended/ supplemented vide RDSO letter No. TI/PSI/PROTCT/STATIC/07 issued in April 2007. Guidelines and a sample calculations have been given at the end of the chapter however due to the continuous improvements taking place in the field of electronics, the OEM manuals should be referred for new features and data entry/setting procedures.

2.5.21 Protection for 2x25 kV AT system

1. Parallelogram characteristic distance protection relay

Distance relay of static type having a parallelogram protection characteristic is used for better discrimination between load and fault currents. The parallelogram protection characteristic permits same discrimination between fault currents and load currents over the entire feeding section. It has a fault detection time of less than 100 ms with an instantaneous operating characteristic, which operates, for large short circuit currents within 50 ms (See Fig.2.5.3).

This type of relay is used for feeder protection in the 2 x 25 kV AT feeding system. It is designed such that relay does not mal-function due to AT exciting inrush currents or for switching surges.

2. ∆I type fault selective relay

The distance relay can protect against short circuit faults in the catenary system. However, it cannot effectively function for high resistance ground faults. The incremental value of increasing fault current (∆I) differs from that of locomotive operation. Further fault current is mostly sine wave current whereas the load current contains much higher harmonic current. These features are used to discriminate between fault and load currents in the ∆I type fault selective relay used for feeder protection. This detects a fault by detecting the sharp change of a fault current (sine wave delta I current) and acts as a back-up relay for the distance relay. The characteristics of the relay are as follows: (See Fig.2.5.4)
a) Fundamental operation characteristic:
It operates by sine wave delta I current of same value as setting current (which can be altered from 1.5 to 5 A).

b) 3rd harmonic characteristic:
It operates at twice the setting current when delta I current include 15% of 3rd higher harmonic current.

c) Second higher harmonic operation lock characteristic:

When delta I current include more than 15% of 2nd harmonic current, the relay does not operate even if the delta I current is more than the setting value. This is to prevent mal-operation due to exciting inrush current of AT.

The operating time is 60 ms or less for 400% delta I current of set value, and 70 ms or less for 200% delta I current of set value.

2.5.22 Power supply diagram with AT system

The schematic power supply diagram for a double track section with AT feeding is given at Fig.2.5.5. Fig.2.5.6 gives the schematic of ATP (Auto transformer post) and Fig.2.5.7 and 8 give the schematic diagram of SSP and SP respectively.

2.5.23 Feeding circuit

In the AT feeding circuit with the AT winding ratio of 1 : 1 the current from substation at 50 kV is approximately equal to half of that actually flowing into the locomotive.

There are three kinds of impedances to be considered

a) 50 kV system impedance $Z_{50}$ which is the impedance seen from the load terminal at terminals at substation (T-F).

b) 25 kV system impedance $Z_{25}$ which is the impedance seen from the load terminal

$c)$ impedance $Z_{ry}$ of the relay system as seen from the secondary circuit of PT & CT

\[
Z_{50} = Z_{ry} \times \frac{PT\,\text{ratio}}{CT\,\text{ratio}} = 5 \, Z_{ry}
\]

$PT$ ratio is usually $27500 \times 2 / 110 = 500$ and $CT$ ratio is $500 / 5 = 100$.

With the above ratios

$Z_{50} : Z_{25} : Z_{ry} = 1 : 1/4 : 1/5 = 100 : 25 : 20$

The impedances considered for this purpose are

Impedance of OHE $Z_t = 0.1645 + j 0.6037$ ohm/km

Impedance of return feeder $Z_t = 0.1729 + j 0.7357$ ohm/km

Mutual Impedance $Z_{rf} = 0.0485 + j 0.386$ ohm/km
POWER SUPPLY DIAGRAM (2 X 25 KV SYSTEM)

FIG. 2.5.5

CIRCUIT BREAKER
INTERRUPTER
ISOLATOR
AUTO TRANSFORMER
TRACTION TRANSFORMER
CAPACITOR
LIGHTNING ARRESTER
TSS
SSP
ATP
SCHEMATIC DIAGRAM OF AUTO TRANSFORMER POST (ATP) (2x25kV SYSTEM)
SCHEMATIC DIAGRAM - SSP (2X25 kv SYSTEM)

FIG. 2.5.7

AT FEEDER
OHE
OHE
AT FEEDER
Impedance between T and F = \( Z_t + Z_f - 2Z_{tf} \)

(i.e. 50 kV system) = 0.2404 + j 0.5674

\[ 0.616 \angle 67^\circ \text{ ohm/km} \]

**Principle of distance relay setting**

The protection area is normally set at 120\% of single-track impedance of maximum feeding length under extended feed (i.e. distance from substation to the adjacent substation increased by 20\%). Assuming a substation spacing of 100 km the line impedance is

\[ Z_{50} = 24.04 + j 56.74 \text{ Ohm} \]

Adding an impedance of one AT

\[ Z_{50} = 24.04 + j (56.74 + 4 \times 0.45) = 24.04 + j 58.54 \]

An R-X chart is drawn with three scales 50 kV, 25 kV and relay system 100 : 25 : 20. See Fig.2.5.9. A straight line at 67\(^\circ\) from origin is drawn to represent line impedance. A point of SS with 24.04 + j 58.54 ohms at 50 kV base is plotted on this line. A 120\% point of SS2 impedance is also plotted on the line. Lines of power factor 0.7 (45.6 degree) and 0.8 (36.9 degree) are drawn. Circular arcs of load current impedance of 1000 A and 1500 A are drawn in between two power factor lines (of 0.7 and 0.8). The hatching area shows load characteristics. Impedance for load current is calculated as under.

\[ Z_{50} = \frac{V_{50}}{I^{1/2}} \]

for \( I = 1000 \text{ A}, \ Z_{50} = \frac{50000}{1000/2} = 100 \text{ Ohm} \)

Resistance component to be set is selected in relation with load characteristic. With a maximum load current of say 1500 A, 4 ohm setting of relay system impedance is appropriate which corresponds to 5 ohm of 25kV system impedance. This 5 ohm is the actual resistance value at fault point of 25 kV circuit.

**2.5.24 Protection scheme for AT feeding system with single phase or Scott connected transformers**

The protective relays for the receiving circuit i.e. incoming high voltage supply comprise of:

- Instantaneous over current relay
- Over current relay
- Earth fault relay

The protective relays for transformer comprise of:

- Over current relay (or phase failure relay)
- Back up over current relay
- Differential relay (for single phase transformer substation only)
The 25 kv catenary protection comprises of:

- Distance relay with a parallelogram protection characteristic.
- Instantaneous Over current relay.
- Delta I type fault selective relay.
- Under voltage relay to avoid wrong phase coupling.
2.5.25 Protection scheme of Mumbai suburban area for 25 KV, ac traction system.

The essential feature of the protection scheme of Mumbai suburban area is its capability to isolate minimum possible sub sector in case of fault in OHE. For this purpose CBs along with C&R panel is provided at TSSs, SSPs and SPs in place of interrupters as used in conventional traction system. This scheme is designed considering the need to maintain high availability and reliability of power supply in high traffic density routes. The protective relays used in Mumbai suburban area are the same as used in conventional system except distance protection relay and reverse power relay.

Distance protection relay for Mumbai suburban area:
Considering the requirement of the protection scheme in Mumbai suburban area, parallelogram characteristic time graded two-zone distance protection relays have been introduced at TSSs, SSPs & SPs. It acts instantaneously for near end faults (first zone) and with a time lag if fault persists in second zone. The second zone operating time is given by the following formula:
\[
T_o = \{ (X_m/R_{xm}) T_r \} + T_b
\]
Where
- \( T_o \): operating time of the relay
- \( T_r \): instantaneous operating time of the relay
- \( X_m \): Reactance measured by the relay
- \( R_{xm} \): set value of the reactance of the relay
- \( T_b \): \( T_r + \) operating time of the breaker (50 to 150 Millisecond settable in steps of 10 ms)

Reverse power relay for Mumbai suburban area:
In case of double-ended feed, it may so happen that the grid supply at one or more of the TSSs fails. In such cases, the power may start flowing from the energized TSS to the grid through the dead TSS. To prevent such incidents, a reverse power relay is provided at TSS. It senses the input from 25 kv side in case of reverse power flow and trips the concerned CB. This relay permits reverse power flow up to a set limit, to prevent the mal-operation for cases of regenerative currents produced by locos/EMUs.
A. Guidelines for Electromechanical Relays

The setting of various protective relays at traction substations and sectioning posts can be arrived at as follows:

1. OHE impedance

The following values of OHE impedances are used for calculating the relay settings:

- Single-track OHE without return conductor: $0.41 \angle 70^0$ ohm/km
- Double-track OHE without RC: $0.24 \angle 70^0$ ohm/km
- Single-track OHE with RC: $0.70 \angle 70^0$ ohm/km
- Double-track OHE with RC: $0.43 \angle 70^0$ ohm/km

On sections where booster transformers are provided, an impedance of 0.15 ohm per booster transformer may be added.

2. Feeder protection at traction substation

2.1 Distance protection using ‘Mho’ relay, Type YCG 14

At present, electromechanical type ‘Mho’ relays are also used for protection against catenary-to-earth faults. The maximum torque angle of this relay is $75^0$. The line impedance is increased by a factor of 1.25 to cater for CT and PT errors, variation in line impedance values due to changes in soil conductivity etc.

- For single line sections relay impedance setting

\[
Z_1 \times \frac{1.25}{\cos(\theta - \lambda)} \times \frac{\text{CT Ratio}}{\text{PT Ratio}}
\]

Where $Z_1$ = total impedance of OHE section to be protected i.e. impedance of OHE from the traction substation to the adjoining substation.

- Maximum torque angle of relay
- Angle of OHE impedances

ii) In the case of double line sections, the following procedure may be followed:
a) The single-line impedance of the OHE $Z_1$ from the traction substation to the adjoining substation is calculated. From the following relation the value of $X$ is arrived at

$$X = \frac{Z_1 X}{1.25 \frac{X}{\text{CT Ratio} \frac{\text{PT Ratio}}{\cos(\theta - \lambda)}}}$$

b) Assuming single-line operation from the traction substation up to the sectioning post (SP) and double-line operation from SP to the adjoining substation the OHE impedance $Z_2$ is calculated. From the following relation $Y$ is arrived at

$$Y = \frac{Z_1 X}{1.25 \frac{X}{\text{CT Ratio} \frac{\text{PT Ratio}}{\cos(\theta - \lambda)}}}$$

c) Assuming an overload of 50% of the traction transformer and that the entire current is fed through one feeder circuit breaker the critical impedance setting of the relay $Z$ (to allow line operation at maximum loads) is calculated from the following relation:

Critical impedance setting

$$Z = \frac{24000 \text{ V}}{1.5 \times \text{rated full load current of Transformer in Amp} \frac{X}{\text{CT Ratio} \frac{\text{PT Ratio}}{\cos(\theta - \lambda)}}}$$

Where $\theta$ = maximum torque angle of relay and $\phi$ = load angle, (taken as 40°)

For the relay not to operate under the said overload conditions, the impedance setting of the relay must be lower than $Z$.

d) The impedance setting of the Mho relay should be a minimum of $Y$ and a maximum of $X$. The setting should also not exceed $Z$ in other words, when the value of $Z$ lies between $X$ and $Y$, the relay may be set to $Z$. If $Z$ is higher than $X$, then the relay may be set to $X$. If $Z$ is less than $Y$, then the relay should be set to $Y$ and it should be understood that the assumed overload will not be permitted by
the relay. The values X, Y and Z are calculated along the maximum torque angle line of the relay:

iii) The relay settings may be calculated as indicated at i) or ii) above for the two sides of the traction substation separately. However, the distance protection relays of both the feeders should be set to higher of the two calculated values to ensure that when one feeder breaker is taken out for maintenance, the relay shall be able to protect either side of traction substation.

2.2 Instantaneous over-current protection

This relay provides primary protection to the catenary on earth faults in the vicinity of the traction substation. The current settings of the relay may correspond to about 200% of the continuous current rating of the traction transformer. Assuming that a factor of 1.25 will account for the CT and relay errors and relay transient overreach, the relay will allow loads of about 200/1.25 i.e. 160% of the rated current

2.3 Wrong phase coupling protection using off-set Mho type YCG-14 (English-Electric make)

The impedance setting of the English-Electric make YCG-14 relay is given by $K_1 \times K_2 \times (K_3 + K_4)$ where $K_1$ & $K_2$ are plug board settings and $K_3$ and $K_4$ are potentiometer settings.

The maximum torque angle of the relay is $125^\circ$ and forward offset is about 10% of $K_1 \times K_2$. The WPC relay at that substation where the 25kV voltage is lagging with respect to the voltage at the substation with which it has been wrongly coupled will operate.
The impedance setting of the WPC relays at TSS-1 may be determined graphically following the procedure given below (refer Fig. 2.5.2A.3 of Annexure 2.5.2)

a) Draw lines A’A, AB and BB’ as shown in Fig (A is the origin of R-X diagram), where
   A’A = Source impedance at TSS-1 as seen on the 25kV side. The impedance angle may be taken as 85 to cater for transformer and transmission line impedances:
   AB = Minimum OHE impedance between TSS-1 and TSS-2. the impedance angle may be taken as 70. (For a double-line section, this corresponds to the double-line impedance of the section, whereas for a single line section this corresponds to the single-line impedance of the section.)
   BB’ = Source impedance at TSS-2 as seen on the 25kV side. The impedance angle may be taken as 85 to cater for transformer and transmission line impedances.

b) Join A’ with B’. Construct a right-angle bisector to A’B’ and locate
points P & Q on the bisector line such that the angles subtended at these points by A'B' are 120 degrees and 60 degrees respectively. P and Q are the points for Case-I (refer to Fig. 2.5.2A.1 of Annexure 2.5.2A)

c) Draw lines AC and CC', where

AC = Maximum OHE impedance between TSS-1 and TSS-3. The impedance angle may be taken as 70° to cater for the single-line OHE impedance between TSS-1 and TSS-3 irrespective of single line/double line sections.

CC = Source impedance at TSS-3 as seen on the 25 kV side. The impedance angle may be taken as 85° to cater transformer and transmission line impedances.

d) Join A with C, Construct a right-angle bisector to the line A'C', Locate points R & S on the right-angle bisector such that the angles subtended by A'C' are 120 and 60 respectively. R and S are the WPC points for case-II (refer fig. 2.5.2A.2)

e) Draw line AO at an angle of 125° with the R axis. This line is the maximum torque angle line for the relay.

f) Draw a circle with centre on the maximum torque angle line such that the points P, Q, R and S are just enclosed by the circle. The circle cuts the maximum torque angle line at D and E. The off-set ‘AE’ will be equal to 0.1xK₁xK₂ xPT ratio/CT ratio. As K₁ & K₂ are not known exactly, guess may be made initially. The step (f) may be repeated after going through step (g).

g) Measure AB, say it is ‘Z₁’. Now, the desired impedance setting of the relay at TSS-1, say Z₂.

\[
\frac{Z_2}{Z_1} \times \frac{CT \text{ Ratio}}{PT \text{ Ratio}} \times 1.25
\]

The factor 1.25 used here is to cater for errors in the CT, PT and relay. Values of K₁, K₂, and K₃ & K₄ may be suitably selected to get the impedance setting Z₂. Forward off-set AE may be checked to be around 0.1x K₁x K₂xPT ratio/CT ratio. If the offset is different, the circle drawn at (f) may be re-drawn to satisfy this requirement.

h) The impedance settings of wrong phase coupling relay for two sides of the TSS-1 may be calculated individually following the above procedure. The higher of the two values may be adopted for both the WPC relays at TSS-1.
3.0 Traction substation: Transformer protection

3.1 Low voltage side (25 kV side)
   i) Restricted earth fault relay
      The current setting of this relay may correspond to 10% of the current of traction power transformer.
   ii) IDMT over current relay
      This relay acts as back-up protection to the feeder protection relays. The current setting of the relay may be selected to correspond to 150% of the rated current of the traction power transformer.
      The time-multiplier setting of the IDMT relay may be selected such that the relay operating time is 0.4 to 0.5 sec. for an earth fault on the 25 kV bus.

3.2 High Voltage side (220kV/132 kV/110 kV/66 kV side)
   Restricted earth fault relay
   The current setting of the relay may correspond to 10% of the rated current of traction power transformer.
   ii) IDMT over current relay with instantaneous over current element:
      The instantaneous element may be set to correspond to a current of 1.25 times the fault current, for an earth fault on the 25 kV bus at the traction. Sub-station. The purpose of such setting is to avoid operation of this relay for 25 kV bus faults at the traction substation.
      The current setting of the IDMT relay may be such that it has maximum reach but permits overloading of traction transformer. The setting may, therefore, be selected to correspond to 150% of the rated current of traction power transformer. To have time grading with the IDMT relay on the 25 kV side, the time multiplier setting may be selected such that the relay operating time is 0.8 to 0.9 for earth fault on the 25 kV bus at the traction substation.
   iii) Biased differential relay (Type DDT)
      The three settings of the relay may be selected as follows:
      a) The percentage bias setting should be so chosen that the relay remains inoperative on differential currents resulting from (1) tap changing on traction transformer, (2) mis-match in CT ratios and (3) difference in CT. Saturation levels under through-fault conditions. Percentage mismatches resulting from factors (1) and (2) may be calculated from actual data and an allowance of 7.5 to
15% may be made for factor (3).

b) The operating current setting may be taken as 40%. If mal operations of the relay are observed on through faults and magnetizing inrush (Switching-in of power transformer), a higher setting may be considered.

c) The time multiplier setting may be taken as 1. If mal operations of the relay are noted on magnetizing inrush but not on through faults, then the time multiplier setting may be increased.

B. Guidelines for setting of parallelogram type Distance protection

The procedure for calculating setting values for $X_F$, $R_F$, $X_B$ and $R_B$ is as follows:

The sketch above shows a typical characteristic of parallelogram type distance relay. The relay characteristic angle is taken as 70° which is same as the impedance angle of OHE and the load angle is considered as 36.9° corresponding to an average p.f. of 0.8. for calculating the settings:

i) Forward reactance ($X_F$) setting:

The following procedure may be followed to calculate the forward reactance setting for single, double or triple line.

   a) In order to ensure protection under all OHE configurations possible, calculate the single line impedance of the OHE from the feeding post/TSS to the adjoining feeding post/TSS. In other words consider the maximum OHE impedance under any possible configuration considering long yards, sidings and feeding lines.
A factor of 1.25 is to be multiplied to the total impedance to take account of the errors due to CT, PT and the relays say this is \( Z_L \). Where \( Z_L = 1.25 \times \) calculated impedance of single line OHE

b) Calculate the forward reactance by using following formula for setting on the relay. Say this is \( X_F \)

\[
X_F = Z_L \times \left( \frac{\text{CT ratio}}{\text{PT ratio}} \right) \times \sin \text{OHE impedance angle}
\]

c) The forward reactance setting may be calculated by following the procedure given at (a) and (b) above for the two sides of the feeding post/TSS separately. However the distance protection relays of the both feeder should be set to higher of the two calculated values. This is to ensure that when one feeder breaker is taken out for maintenance, the relay shall be able to see the faults on either side of feeding post/TSS.

ii) Forward resistance (\( R_F \)) setting:
This is computed based on peak load impedance (\( Z_{PL} \)) likely to occur in the system and to accommodate arc resistance, tolerances of CT, PT and relay.

\[
25000 \quad \frac{Z_{PL}}{1.5 \times \text{rated secondary current}} \times \frac{\text{PT ratio}}{\text{CT ratio}}
\]

In order to accommodate arc resistance & tolerances of CT, PT, and the relay, \( Z = 70\% \) of \( Z_{PL} \)--------------------------------------(1)

As seen from Figure 1,

\[
X = AB \tan 70^\circ
\]

And also \( X = Z \sin 36.9^\circ \)

Hence \( AB \tan 70 \text{ deg} = Z \times 36.9^\circ \)

\[ AB = \frac{Z \sin 36.9^\circ}{\tan 70^\circ} = 0.2185 Z \]

Also \( OB = Z \cos 36.9^\circ = 0.7997 Z \)

We see that \( R_F = OB - AB = 0.7997 Z - 2185 Z \)

\[
R_F = 0.5812 Z \quad \text{--------------------------------------(2)}
\]

Substituting the value of \( Z \) obtained from equation (1), in equation (2), we get.

\[
R_F = 0.5812 \times Z
\]

(iii) Reverse reactance (\( X_B \)) setting:
Backward reactance setting be calculated by the following method

\[
X_B = 25\% \quad \text{of forward reactance setting subject to minimum 6.0 Ohms.}
\]
iv) **Backward resistance (R_B) setting:**
   It is selected to be of same value as R_F.

V) The setting of distance element shall be calculated by following the above procedure for other side of the traction substation also and the larger of the two settings are selected.
Annexure 2.5.2

A. Sample calculation of setting of feeder protection module

The following assumptions are taken for sample calculation.

(i) OHE impedance.

The following values of OHE impedance for 107mm² contact and 65 mm² catenary wire may be used for the purpose of calculating relay settings.

i- Single-track OHE without return conductor: $0.41 \angle 70^0 \, \Omega/\text{Km}$

ii- Single-track OHE with return conductor: $0.70 \angle 70^0 \, \Omega/\text{Km}$

Add booster transformer impedance at the rate of $0.15 \, \Omega$ per booster transformer, where these are provided.

(ii) Traction power transformer.

No load voltage:

- Primary side = 132kV
- Secondary side = 27kV
- Secondary voltage at rated output = 25kV
- Rated output = $21.6 \, \text{MVA}$

\[
\text{Rated secondary current} = \frac{21.6 \, \text{MVA}}{27 \, \text{kV}} = 800 \, \text{Amp}
\]

CT ratio 25kV side = 750/5 Amp

PT ratio 25kV side = 25kV/110V

5.1 Parallelogram characteristic distance protection element.

The following OHE section details assumed here for calculation given below.
Calculate single line impedance from TSS A to TSS B

Single line with BT&RC = 30Km
Single line without BT&RC = 60Km

Total Line impedance = 30 x 0.70 + 60 x 0.41
= 21 + 24.6
= 45.6 Ω

∴ ZL = 1.25 x 45.6 = 57Ω

X_F Setting = \(\frac{57 \times 750}{5} \) X Sin 70
\(\frac{25000}{110V}\)
= 57 x 150
\(\frac{57 \times 150}{227.27}\)
X 0.939
= 35.35Ω

X_B setting = 35.35 x \(\frac{25}{100}\) = 8.83

R_F setting:
25000 \times \frac{750}{5}
ZPL   =  1.5 x 800 x 25000/110
      =  13.75

Z    =  70% of ZPL
      =  13.75 x 0.7
      =  9.63 Ω

R_F  =  0.5812 Z
      =  0.5812 x 9.63
      =  5.60 Ω

R_B setting:  
R_B  =  5.60 Ω

5.2 Over current setting

Rated secondary current  =  21.6 MVA
                         =  27 kV
                         =  800 x 2
                         =  750/5
                         =  10.66 Amp
                         =  10.66 x 100
                         =  213%

Note: according to availability of setting on the relay whether in amperes or percentage may set accordingly.

B. Setting guide lines and sample calculations of vectorial Delta – I relay (type AVDI 11-C and AIDI/IC of M/s ALIND and M/s ASHIDA make respectively)

(i) Delta-I current setting

Current setting of Delta-I relay is based on the assumption on number of locos entering or number of locos switched on simultaneously in the section causing sudden rise of load current to avoid the false tripping due to sudden rise of load current. The Delta-I current setting should be more than the sudden rise of load current.
Assuming 2 numbers loco entering or switched on simultaneously in the section and load current of one loco is 150 Amp.

Total load current = \(2 \times 150\)  
= 300Amp

\[
\text{Load current transferring to relay side} = \frac{\text{Load current}}{\text{CT ratio}} = \frac{300}{750/5} = 2 \text{ Amp}
\]
(Assuming CT ratio 750/5 Amp)

Hence Delta –I current setting = 2 Amp
Note: If relay gives more spurious tripping then next higher value may be selected.

(ii) X-BLINDER SETTING
This is the setting of reactance of OHE in ohms below which delta I relay shall pick up if other conditions like delta I, time delay are met.

a) First calculate the OHE impedance from feeding TSS to adjacent feeding TSS considering the lowest OHE configuration (Single line OHE)

b) Multiply a factor 1.25 to accommodate CT, PT & relay error.
Say \(Z_L\). \(Z_L = 1.25 \times \text{Calculated impedance of the single line OHE}\)

c) Calculate the reactance \((X)\) blinder setting on the relay side by following formula.

\[
X = Z_L \times \sin (\text{Impedance angle}) \times \frac{\text{CT ratio}}{\text{PT ratio}}
\]

Example:
Let the distance between adjacent TSS = 70 Km
Single line OHE impedance = 0.43 \(\angle 70^0\) Ω/Km
Total impedance = 70 \times 0.43 \(\angle 70^0\)  
= 30.1 \(\angle 70^0\) Ω

Effective impedance \(Z_L\) = 1.25 \times 30.1 \(\angle 70^0\)  
= 37.63 \(\angle 70^0\)  
\(\frac{750}{5}\)
.: Reactance blinder setting X =37.63 X Sin 70° X -------- 25000/110 (Assuming CT ratio 750/5 & PT ratio 25000/110)

= 23.34 Ω

(iii) Second & Third harmonic blocking feature setting

Generally manufacturer set these parameters internally during relay manufacture. However some relay manufacturers made provision to set these parameters externally through knob or keypad. If external setting available, it is to be set at 15%.

(iv) Additional time delay setting

Additional time delay setting is to be calculated by following method.

Additional time delay = DPR operating time + MTR operating time + CB operating time + tolerance

Assuming DPR time = 50 ms  
MTR time = 15 ms  
CB time = 50 ms  
Tolerance = 30 ms

Hence time delay setting = 50+15+50+30 = 145 ms

If exact value is not available on the relay then a setting close to higher side of 165 ms, is to be selected.

(v) DS (De-sensitivity for 3rd harmonic) and DT (Delta time) setting:

These parameter is settable only in M/s ASHIDA make relay,
The following value is recommended by manufacturer.

DS = 100 %

The relay monitors the current samples continuously, this delta time setting defines time duration between the two samples.

DT = 60 ms.
Chapter 6

POWER FACTOR IMPROVEMENT OF TRACTION SYSTEM

2.6.1 General

Most ac electric machines draw from the supply apparent power in terms of kilovolt-ampere (kVA) which is in excess of the useful power measured in kilowatts (kW) required by the machine. The ratio of these quantities i.e. useful power/apparent power (kW/kVA) is the power factor (Cos $\theta$) of the load and is dependent upon the type of machine. A large number of electric machinery used in industry have an inherently low power factor with the result the supply authorities have to generate much more current than is theoretically required. In addition the transmission lines, transformers have to carry this extra current. When the overall power factor of a generating system is low, the system is inefficient and the cost of electricity gets correspondingly high. To overcome this, the supply authorities insist upon a minimum average power factor by their consumers (usually around 0.85) and impose stiff penalties for low power factor. Reduction in power costs can be made by taking measures to improve the power factor. Even if there is no such penalty, the transmission equipments can be relieved of a considerable wattless current there-by reducing the system voltage drop and line losses and increasing the power transference limit.

2.6.2 Causes for low power factor on traction system

Usually equipments like induction motors, power transformers, thyristor installations are likely to have low power factors. The locomotive when working at less than the rated loads especially the auxiliaries tend to reduce the overall power factor. In actual practice because of the terrain the average load factor of the locomotive hardly exceeds 50%.

2.6.3 Methods of improving power factor

The method employed to achieve the power factor improvement is by introduction of reactive kVA into the system in phase opposition to the wattless or reactive current of the load. The apparent power (kV) in an ac circuit can be resolved into in-phase component which supplies the useful power (kW) and the wattless component (kVAr) which does no useful work. The phasor sum of the two is the KVA drawn from the supply. To improve the power factor, equipment drawing kVAr of approximately the same magnitude as load kVAr but in phase opposition (leading) is connected in parallel with the load. The resultant kVA is now smaller and the new power factor is increased. The power factor improvement can be varied by varying the leading kVAr.

The voltage and current relationships in ac circuits with pure capacitance and pure inductance as well as the power and energy curves for a capacitor circuit are shown in Fig.2.6.1 (a), (b) and (c). The method of power factor improvement is shown in Fig.2.6.2 (a) and (b).
FIG. 2.6.1
POWER AND ENERGY CURVES FOR A CAPACITOR CIRCUIT

(a) CAPACITIVE CIRCUIT
(b) INDUCTIVE CIRCUIT

VOLTAGE AND CURRENT RELATIONSHIPS IN AC CIRCUITS

(a) CAPACITIVE CIRCUIT   (b) INDUCTIVE CIRCUIT

POWER AND ENERGY CURVES FOR A CAPACITOR CIRCUIT

FIG. 2.6.2

POWER FACTOR CORRECTION BY ADDING LEADING P.F.

FIG 26.1

FIG 26.2
The capacitors can be connected either in series with the load or in parallel (as shunt) to the load. The application of shunt capacitors alters the load characteristics by improving the power factor, while the application of series capacitors alters the circuit parameters with the load remaining virtually unaltered.

If the load at the Traction substation fluctuates considerably and there are prolonged periods of light load, the fixed shunt capacitor bank may be ineffective in providing desired improvement in power factor. In such cases, Dynamic Reactive power compensation equipment can be used to improve the p.f.

(a) Dynamic Reactive power compensation through thyristor switching:

In this scheme, required capacity of capacitor bank is divided in steps; each step is controlled by thyristors connected in anti-parallel so that capacitor banks are in circuit during both positive and negative half cycles. This scheme connects at LV side of a step-down transformer (25 kv/430-430v) (General scheme is given as Annexure-I). All switching on takes place when the voltage across the thyristors is zero, to obtain almost transient free switching. As the capacitor, while switching off is left with a trapped charge, the voltage across thyristors will alternate between zero and twice the peak phase voltage. Besides since the capacitors will start discharging when switched off, a transient free switching will therefore require two conditions to be met:

1. The thyristors must be gated at a positive or negative crest of supply voltage and,
2. The capacitors must be pre-charged or topped up for the loss of charge with the same polarity.

\[
\text{Pre-charged voltage} = n^2 \cdot v_p, \\
\text{where } n = \sqrt[2]{\frac{x_c}{x_L}}, \\
v_p = \text{peak phase voltage} \\
x_c = \text{capacitor reactance and} \\
x_L = \text{Reactance of damping reactor used for keeping } \frac{di}{dt} \text{ within capability of thyristor}.
\]

Appropriate circuitry to pre-charge the discharged capacitor has also to be provided to avoid large switching transients and premature failure of capacitors.

(b) Dynamic Reactive power compensation through IGBT switching:

In this scheme, voltage source converter (VSC) based static VAR compensator comprising of switching device IGBT is provided for required capacity of compensation (General scheme is given as Annexure-II). The pulse width modulation mode in this IGBT scheme, provides a step-less variable KVAR for maintaining p.f. close to unity by generation or absorption of reactive power.

In this scheme, half of the required capacity of reactive power compensation is provided by STATCON (IGBT based voltage source converter) at LV side of 25 kv/430v step-down transformer &
rest half capacity is provided by fixed shunt capacitors at 25 kv bus. Thus the working range of compensation of reactive power is from zero to total required reactive power.

For more details RDSO Specification No. TI/SPC/PSI/DRPC/0050 and Instruction No. TI/IN/0014 may please be referred.

2.6.4 Advantages of Shunt Capacitors

a) The current on the supply side is reduced resulting in lower $I^2R$ losses and lower IR and IX drops.

b) The power-factor on the supply side is improved and the power angle (angle between sending end and receiving end voltages) is decreased.

c) The receiving end voltage as well as the line regulation is very much improved.

d) The reactive power drawn from the supplying end machines is reduced, thereby the kVA loading of all the equipment between the capacitors and the supply source is reduced.

e) Shunt capacitors offer relatively quick solutions to peak load bottlenecks thereby postponing the necessity of reinforcement or augmentation of substation capacity.

2.6.5 Difficulties in the use of Shunt Capacitors:

a) In order to derive maximum benefit the shunt capacitors must be applied as near to the load as possible which is difficult to achieve at times. As the capacitor draws constant current, the supplying end power-factor may become leading under light load conditions which increases power loss and kVA loading of the plant. It may have to be switched off under light load conditions.

b) Switching in and out of shunt capacitor banks give rise to current transients in the system which some times are quite serious.

c) The switchgear required for controlling capacitor bank must be capable of handling high RRRV (Rate of Rise of Re-striking Voltage).

d) Harmonics present in the system find the condenser bank a path of low impedance and thereby cause overloading and over voltage of the banks.
e) The residual voltage of shunt capacitor bank after being switched off may be considerably high and, therefore, it is necessary to discharge the same for safety.

2.6.6 Advantages of series capacitors

a) It can be located in general anywhere in the system and not necessarily near the load.

b) The voltage improvement is precise and spontaneous with widely fluctuating loads. It is, therefore, not necessary to disconnect series capacitors under light load conditions.

c) The voltage improvement in case of series bank is much more as compared to the shunt capacitor bank for the same kVar rating.

d) Since the series capacitors not only reduce the power angle but also the circuit reactance, the system stability as well as the power transference limit is considerably increased.

e) The series capacitor banks normally remain in circuit and only under system fault condition they are required to be short circuited. The switchgear employed for the purpose, therefore, has to close and apply a short across the bank with the result that the duty on the switchgear is very much lighter compared to the duty it has to perform in controlling the shunt banks.

2.6.7 Difficulties in the use of Series Capacitors:

a) There is no reduction in the line current, power losses and reactive power loading of generating machines. The improvement in power factor on the supply side is very small.

b) The starting current of large motors may contain substantial sub-harmonic components and resonance may set in between the series capacitor and the motors. In such a case the motor accelerates from rest up to the sub-synchronous speed corresponding to the resonance frequency and continues to rotate at this reduced speed. Excessive vibration and large currents may result with possible damage to the machine.

c) When the magnetization characteristic of a transformer swings into regions of saturation, when its reactance gets considerably reduced. It may resonate with the reactance of the series capacitor. This phenomenon called “Ferro-resonance” can occur when a transformer is energized with no load on secondary or when the primary voltage is substantially boosted. Under these conditions high voltages can occur across capacitor and suitable steps must be taken to prevent occurrence of such conditions.
d) The synchronous machines operating in parallel may hunt when subjected to sudden load variations or periodic torque variations, more so in systems with low (X/R) ratio.

e) The system fault currents are higher with use of series capacitors. Distance protection schemes cannot be directly applied on lines with series capacitors.

f) The capacitor banks being in series are to be fully insulated from the ground. It is the short time current rather than the working current which dictates the design of the capacitor. Further, the protective equipment required to be provided is quite elaborate and expensive as the capacitor banks are not only subjected to system fault currents but also to surges.

2.6.8 Choice of type and location of p.f compensation equipment:

It is seen that for traction application, where the objective is to improve the system power factor (and not so much for voltage regulation under load conditions) capacitors connected in parallel are considered more suitable. Shunt capacitor as well as Dynamic Reactive power compensation equipment should be ideally as close to the load as possible but if larger installations are considered they are better located at traction substation.

In any particular location where the capacitor bank or DRPC equipment is to be installed, it is necessary to know the minimum and maximum reactive power requirements. The size of the capacitor bank should not be more than maximum kVAr requirement of the load. Power factor will be leading under light load conditions, which is undesirable. From the minimum kVAr requirement of the load, rating of the capacitor which can be left permanently connected can be determined. If the maximum and minimum kVAr requirements of the load are widely different, it may be necessary to install DRPC equipment, which will be switched On or Off depending upon the load conditions.

2.6.9 Choice of rated voltage of shunt capacitor or DRPC:

The rated voltage should be equal to the highest voltage of the network to which the capacitor is to be connected, account being taken of the influence of the presence of the capacitor itself. This is a matter of considerable importance for capacitors since their performance and life may be adversely affected by an undue increase in the stress in the capacitor dielectric. Where series reactors are connected in series with the capacitor, to limit in rush currents due to switching over voltages and harmonics the resultant increase of the voltage at the capacitor terminals above the actual voltage of the network will necessitate an equivalent increase in the rated voltage of the capacitor.

When determining the voltage to be expected on the capacitor terminals the following considerations are to be taken into account:

a) Capacitors cause a voltage rise at the point at which they are located. This voltage rise may be even greater for any harmonics that may be present. Capacitors are therefore liable to operate at a higher voltage than that measured before connecting the capacitor.
b) The voltage of the capacitor terminals may be particularly high at times of light load.

As the DRPC equipment is connected at LV side of a step-down 25 kv/430v transformer, the rated voltage should be equal to the highest voltage at LV side due to highest voltage of the network to which it is to be connected.

2.6.10 Transients

1. Switching in transient

At the time of energization of single bank the transient current is maximum when the switch is closed at the instant the voltage wave is passing through its peak value. At the time of switching in, the capacitor momentarily offers very low impedance with the result a large current flows into the capacitor at higher frequencies. As the capacitor gets charged the current reaches its steady state value. The initial current flowing during switching in is called the inrush current a transient current. The transient current is more when one or more banks are in service and the next one is switched in, as all the banks in service discharge into the bank being switched in. The transient current can also be more when a capacitor is energized before it is fully discharged. Hence fast re-closures on circuit breakers controlling capacitor banks are not advisable.

The peak value of inrush current is given by

\[ I_{\text{max}} = 1.15 I_0 (1 + \frac{\text{short circuit kVA}}{\text{capacitor kVAR}}) \]

where \( I_0 \) is the peak value of nominal capacitor power frequency current. The frequency of the inrush current is given by

\[ f_c = f' \frac{\sqrt{\text{short circuit kVA}}}{\sqrt{\text{capacitor kVAR}}} \]

where \( f \) is the power frequency.

In normal cases the inrush current is around 20 times the normal full load current and the frequency of oscillations up-to 1 kHz. To limit the inrush current during parallel switching in, it is desirable to provide a series reactor.

2. Switching out Transient

Re-striking may occur at the time of switching off due to rapid rate of rise of voltage across the contacts of the circuit breaker controlling capacitor banks. Repeated re-striking can produce dangerous over voltages and under adverse conditions, the voltage across contacts may be as high as 3 to 4 times the amplitude of the normal voltage wave. It is thus important to ensure the
suitability of a particular circuit breaker for the switching duty. Semiconductor devices are very much prone to damage. When they are used near capacitors they must be adequately protected against voltage transients. It is advisable to use bar type current transformers for capacitor control and protection and keep the power factor of the current transformer load as near unity as possible. In the case of cables, it is necessary to earth the sheath at both ends.

2.6.11 Effect of Harmonics

The reactance of a capacitor is inversely proportional to the frequency. Hence if the applied voltage includes harmonics the current will be greater than that would be produced by the same voltage at the fundamental frequency.

Comparatively small components of the higher harmonics can produce current components comparable in magnitude to the normal capacitor current when fed from a pure sinusoidal supply. Harmonic currents cause an appreciable increase in the total capacitor current and corresponding increase in the kVAR loading.

The actual current taken by a capacitor when harmonics are present is the square root of the sum of the squares of the various current components including the fundamental.

In practice the higher frequency components are almost invariably the higher odd number harmonics of the fundamental supply frequency, such as 3rd, 5th and 7th etc.

If the various harmonic voltages across the capacitor $h_3$, $h_5$, $h_7$ are expressed as a percentage of the fundamental voltage, the rms value of the resultant voltage wave is given by

\[ V = 0.01V_1 \sqrt{100^2 + h_3^2 + h_5^2 + h_7^2 + \ldots} \]

The total capacitor current is given by the expression

\[ I = 0.01 I_1 \sqrt{100^2 + 9h_3^2 + 25h_5^2 + 49h_7^2 + \ldots} \]

Where

- $V$ = rms voltage
- $V_1$ = rms value of voltage at the fundamental frequency
- $I$ = the rms capacitor current due to $V_1$
- $h_3$, $h_5$, $h_7$ = rms value of 3rd, 5th, 7th etc. harmonic expressed as percentage of $V_1$.

In practice the of 3rd, 5th, 7th etc. harmonics only need be considered. Percentage increase in reactive output due to the existence of harmonic voltages is given approximately by

\[ \Delta \text{kVAR} = 0.01(3h_3^2 + 5h_5^2 + 7h_7^2 + \ldots) \]
The peak voltage of the wave may amount to the sum of the fundamental and all the individual harmonic peak voltages.

The typical percentages of current harmonics present in the traction system with silicon diode rectifier locomotives are as under:

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>Frequency</th>
<th>Percentage at 142 A</th>
<th>Percentage at 480 A</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd harmonic</td>
<td>150 Hz</td>
<td>38.50</td>
<td>11.50</td>
</tr>
<tr>
<td>5th harmonic</td>
<td>250 Hz</td>
<td>14.35</td>
<td>5.48</td>
</tr>
<tr>
<td>7th harmonic</td>
<td>350 Hz</td>
<td>16.00</td>
<td>2.01</td>
</tr>
</tbody>
</table>

The harmonics percentages are generally higher at lower loads and lower at higher loads and they may be still higher with thyristor locomotives.

### 2.6.12 Rating of capacitors for power factor correction

Assuming the load P (kW) has a power factor of \( \cos \theta \) and it is desired to raise the power factor to \( \cos \theta \) the kVAR compensation required is (see Fig.2.6.3)

\[
\text{Capacitor kVAR} = kW \left( \tan \phi_1 - \tan \phi_2 \right)
\]
Capacitor $kVAr = kW (\tan\phi_1 - \tan\phi_2)$

where $\phi_1 =$ uncorrected angle of lag

$\phi_2 =$ corrected angle of lag

RATING OF SHUNT CAPACITOR

Depending upon the system voltage, typical ratings may be chosen. The average power factor is obtained from the ratio of monthly consumption of kWh and kWAh.

Capacitors are normally designed to withstand 1.1 times rated voltage. For traction service the voltage rating of the capacitor should cater for the voltage rise under light or zero load condition.

The capacitor units are suitable for continuous operation at 1.3 times rated power frequency current to take care of the combined effect of harmonics and over voltages.

With installation of shunt capacitor banks at a traction substation, under no load conditions the 25 kV bus voltages may increase due to Ferranti effect and this condition may overstress the capacitor.
Systems on load or inductance in association with the p.f compensation equipment can form circuits, which are in series or parallel resonance at some harmonic frequency. Out of the two resonant conditions, the parallel resonance is more serious. The harmonic resonance may have the adverse effects such as excessive currents, over voltage torque disturbances and radio and telephone interference.

2.6.13 Series reactor

Any reactor connected in series to a capacitor will have resonance with the capacitor bank at a particular frequency. The reactor as well as the capacitor bank should be designed to handle the system harmonics. The reactor should be rated not only for the maximum current that could flow through the capacitor bank but also for the overload conditions which could appear.

The condition for series resonance of the capacitor-reactor at n\textsuperscript{th} harmonic is

\[ nX = X_C/n \text{ or } X_L/X_C = 1/n^2 \]

For third harmonic resonance \( X/X_C = 1/9 = 0.111(11.1\%) \) and for 5\textsuperscript{th} harmonic resonance \( X/X_C = 1/25 = 0.04 (4\%) \) and for resonance at 7\textsuperscript{th} harmonic \( X/X_C = 1/49 0.02 (2\%) \).

To avoid any resonance at all odd harmonics, the rating of the series reactor should be such that the series resonance frequency of the capacitor reactor is below that of lowest odd harmonic present in the traction load. If \( X/X_C > 11.1\% \) condition for resonance of capacitor bank with series reactor at all odd harmonics present in the system is eliminated. Generally a 13 to 15\% reactor is recommended.

The series reactor must be capable of withstanding transient overvoltages or for voltage rise at light loads without getting saturated.

2.6.14 Fuse protection of shunt capacitor banks

The weak point in condensers is its insulation or dielectric, which can fail due for over-heating and over-voltage. The overheating is caused by excessive current and is a function of time. The over-current can be caused by over-voltage, harmonics, series resonance, and inrush current at the time of switching on and switching off operations.

The over-voltage, apart from causing thermal failure due to over-current can also cause dielectric failure due to puncturing of the insulation especially when over-voltage is of a very peaky nature. Such over-voltage can be due to restriking in the controlling circuit breaker, system faults, parallel resonance and failure of capacitors in a bank containing some unit in series.

Fuses are an essential part of high-voltage capacitor bank design to provide protection against the effects of unit dielectric failure. This protection must operate in such a way as to enable the remainder
of the capacitor bank to continue to operate satisfactorily with the minimum disturbance to the system. The high voltage capacitor fusing may be achieved by either internal or external methods.

2.6.15 Internal fuse operation

The tin/copper fuse link must be capable of withstanding the transient inrush currents experienced by capacitors at switching-in without deterioration and it must also operate positively when an element suffers dielectric breakdown. This condition depends upon an adequate number of elements being connected in parallel with the faulty element so that the additional discharge current from the healthy elements ensures positive operation of the faulty element fuse.

It is desirable that the number of elements in parallel (n) should be as large as is practicable; and indeed there is restriction on the minimum number of elements in parallel which relates to the increase in voltage occurring across a parallel group of elements when one element fuse has failed. The reactance of the group is increased by the ratio n/n-1 and assuming a constant current supply the voltage across the element group rises in the same proportion, though in practice it is somewhat less due to other factors.

Advantages of Internal fusing

a) Enables a capacitor unit to continue in service after the first dielectric breakdown. In externally fused bank dielectric failure can result in loss of complete bank.

b) With mixed dielectric (plastics/paper) HV capacitor units upto 250 kVAr (as against 100 kVAr with paper dielectric units) are made which are more economical and internal fusing make it possible to use a smaller number of larger units for banks.

Disadvantages of Internal fusing

a) Internal fusing does not provide protection for faults between element pack and unit case. Unless HRC fuse protection is provided in the main connection to capacitor, case rupture of the capacitor unit could result.

b) Internally fused capacitors give no indication of fuse operation. The only method of detecting premature fuse operation is by individual capacitance measurement of each unit which is time-consuming maintenance programme.

c) Fast transients may cause high transient currents in a capacitor bank resulting in operation of fuses without any dielectric failure occurring in capacitor units. External fuses could be replaced but with internal fuses many or all units need replacement.
2.6.16 Current-limiting HRC fuses

With external fusing, breakdown of an element causes over-stressing of the remainder of the elements in the series group which result in progressive breakdown unit final dielectric failure causes operation of the external fuse without case rupture, HRC fuse failure is indicated by the striker pin indication.

2.6.17 Detection of fuse operation

Operation of a fuse either external or internal in series – connected groups of capacitor units, results in an increased voltage being imposed on the remaining units or elements connected in parallel with the fuse which has operated. This is due to the increase in reactance of the group. Hence it is important to the life of the capacitor units of elements that the fuse operation is detected as soon as possible before many fuses operated in a parallel group as to cause a voltage rise in the group so high that cascade breakdowns occur.

There are two basic methods by which fuse operation and hence local voltage increase may be detected. One method is by measurement of out-of-balance current and the other by out-of-balance voltage protection.

2.6.18 Out-of-balance current protection

A typical diagram of connection is shown at Fig.2.6.4. For balanced conditions i.e. with all fuses intact no current will flow between the two points A and B. Operation of a unit fuse in one or the other of the parallel assemblies will cause a voltage to appear between the two points A and B and a current will flow in the current transformer primary.

A current-sensitive relay can be made to operate on the secondary. Because of the low magnitude of the out of balance current a standard CT would be unsuitable. The CT should meet the insulation level of the system. Normally loss of one unit due to fuse operation will not increase the voltage across the remaining units by more than 10% of nominal design voltage. Hence most out-of-balance current relays provide two stage operation i.e. initial alarm which means that the bank can continue in service until balance can be restored, or second-stage trip in the event of a second unit fuse operation in the same group.
Calibration of the relays should be available to cater for marginal design differences in capacitor groups. Further to prevent spurious operation under transient conditions the instrument includes a time delay feature.

2.6.19 Out-of-balance voltage protection

A typical diagram of connection is shown at Fig.5. Specially designed voltage transformers called residual voltage transformers (RVT) are connected across a parallel group of capacitors.
For balanced conditions no voltage will appear across the RVT but operation of a unit fuse will cause an unbalance and a voltage will appear across the secondary winding of RVT. Operation of a single unit fuse will impose a voltage of less than 1.1 times nominal design voltage across the remaining parallel units and hence a voltage relay will provide an initial alarm function followed by a trip operation if any further fuses in the same group operate.

As with the current out-of-balance system the voltage relay should incorporate a time delay feature and will be connected into the control circuits of the capacitor circuit breaker.

In either method of unbalance detection i.e. current or voltage it has been assumed that under balanced condition no voltage will appear across, or current flow through the protective relay. But in practice perfect balance cannot exist. Hence both the voltage and current relays are designed to take into account residual out-of-balance condition. The capacitance unbalance detection methods may be used for either externally-fused or internally-fused capacitor units, although with the latter design more sensitive detection equipment is required. As a compromise unbalance detection system for externally fused capacitors are usually designed to alarm for the effective loss of one capacitor unit in a group.

2.6.20 Line Protection
The line current of a capacitor bank may be increased above its nominal value by increases in line voltage, permitted capacitance tolerances, increase in fundamental frequency and the effect of
harmonic currents flowing in the system to which the capacitor presents a low impedance path. Because of the increase of the use of thyristor convertors in the past few years the incidence of harmonic currents flowing in any high voltage power system is much greater. Electric traction with rectifier and thyristor locomotives aggravates this problem further.

The margin of 1.3 times nominal line current which is the maximum permitted by IS and international specifications takes into account particularly the effect of harmonic currents.

2.6.21 Overvoltage Protection

Capacitors are designed to accept over voltages upto 1.1 times the nominal voltage. However under conditions of harmonic current overloading caused by fifth and seventh harmonics which may occur at light load periods, the capacitor bank may be subjected to over voltages in excess of 10% before the maximum permissible current overloading of the capacitor has been reached.

High over-voltage may be encountered when capacitors are disconnected by switching devices which allow re-striking. Switching devices, which operate without causing excessive over voltage due to re-striking and re-ignition, should be used with capacitors.

To cater for these and other special circumstances such as sudden loss of load which might cause a voltage rise on the system, over voltage relays should operate when the voltage exceeds 10% for prolonged periods. Alarm and trip features with suitable time delays should be incorporated. The relay should be peak voltage sensitive and operate from a PT in the capacitor circuit breaker circuit.

Capacitors, which are liable to be subjected to high over-voltages by lightning should be protected by lightning arrestors located as near to capacitors as possible.

2.6.22 Protective measures for capacitor banks

The protective system comprises of the following:

a) Internal element fuses against element short circuits with or without external HRC fuses. (rated about 2.5 times the rated current for each unit).

b) A neutral displacement relay or a neutral current-relay in conjunction with Residual voltage transformers/Neutral current transformers for detection of unbalance voltage/currents.

c) An over current relay with suitable time setting.

d) An under voltage relay for switching off the bank during failure of supply.

e) An over voltage relay with suitable time setting.
f) A time delay lock up relay to prevent immediate closing of the capacitor CB in the event of its tripping and to allow 5 minute time gap for complete discharge of the units before recharge.

g) A 42 kV station class lightning arrester located close to capacitors to protect against lightning surges.

h) A series reactor of suitable rating to limit in rush currents due to switching over voltages and harmonics.

i) A ‘Re-strike free’ circuit breaker.

Apart from the above protection, suitable device to discharge the capacitor after being switched off within a specified period (5 minutes above 600 V) should be provided. In some cases suitable resistors are built inside the capacitor bank for this purpose.

Typical shunt capacitor installation at a traction substation is given at Fig.2.6.6.
25kV BUS

- S.P. ISOLATOR, 25kV, 800A
- 25kV/110V P.T., 30VA
- CT, 1000-50A, 10VA
- VCB, 25kV, 1250A
- LA, 42kv, 10kA
- RVTS (7.5kv/132V)
- HRC FIVE (12kV/40 AMP)
- CAPACITOR

864 VAR AT 7.52kV

SERIES REACTOR 103kvar, 30kv (6%)

1200 KVAR CAPACITOR INSTALLATION (WITH 5 PARALLEL STRING WITH 4 UNITS IN SERIES)

FIG 266
2.6.22 A Protective measures for DRPC equipment

The protective system for DRPC equipment comprises of the following:

(a) External HRC fuse (rated about 2.5 times of the rated current for each branch/unit).
(b) Over current relay (instantaneous & IDMT) with suitable time setting.
(c) An under voltage relay for switching off the bank/equipment when Supply voltage goes below a set limit.
(d) An over voltage relay with suitable time setting.
(e) A 42 kv station class lightning arrester located at primary of 25 kv/430v transformer to protect against lightning surges.
(f) A series reactor of suitable rating to limit the inrush currents due to switching over voltage and harmonics.
(g) earth fault protection of the bank/equipment.
(h) A suitable over temperature protection to protect the switching devices (IGBT/Thyristor).

2.6.23 Capacitor banks at switching stations

It is seen that in big marshalling yards, electric loco sheds where several locos will be idling with power-on and with auxiliaries working, the power factors tend to be poor i.e. of the order of 0.7. **Hence if shunt capacitors/DRPC equipment are installed in the vicinity of sheds the improvement will be much more.** Capacitor banks installed at switching stations with single HRC fuse protection on each string have proved to be workable propositions, providing much needed improvement in power factor. It might indeed be desirable to provide only HRC fuse protection for capacitor bank at the switching station. Provision of shunt capacitors at switching stations has, however, the disadvantage of additional line losses due to capacitors during periods of light load and the possibility of over voltages at such times. The major installation will, therefore, be at the traction substation.

2.6.24 Capacitor mounted on locomotives

As the source of the poor power factor is primarily the locomotive, it is ideal if the power factor correction equipment together with harmonic filters are located in the locomotive itself. The capacitor that can be installed is dictated by the space and weight considerations of the locomotive.
Annexure 2.6.1

DESIGN OF SHUNT CAPACITOR INSTALLATION WITH SERIES REACTOR

1. **Basic data (assumed)**

   i) Average maximum demand 7300 kVA
   
   ii) Normal system voltage 25 kV
   
   iii) Initial average power factor \(\cos \phi_1\) 0.74 (lagging)
   
   iv) Desired average power factor \(\cos \phi_2\) 0.90 (lagging)
   
   v) System short circuit level on 132 kV bus at traction substation 2000 MVA

2. Rating of shunt capacitor bank : see Fig 1 of Annexure 2.6.1 below.

\[
\text{Average MD in kVA} = \frac{\text{Annual kWh consumed}}{365 \times 24 \times \text{power factor (average)}}
\]

kVAr rating of shunt capacitor bank at 25 kV:

\[
= \text{Average MD} \times \text{Initial PF} \times (\tan \phi_1 - \tan \phi_2)
= 7300 \times 0.74 \times (0.9089 - 0.4843) = 5402 \times 0.4246 = 2293.69 \text{ kVAr}
\]

Allowing 10% extra for future growth, kVAr capacity of the capacitor bank is increased by 10% i.e. to 1.1 \times 2293.69 = 2523 kVAr.

\[
\text{Capacitive reactance, } X_C = \frac{(kV)^2 \times 1000}{\text{kVAr}} = \frac{25^2 \times 1000}{2523}
\]

\[
= 247.72 \text{ Ohms}
\]

3. Determination of the series reactor rating.

Condition for series resonance of the capacitor-reactor at the \(n\)th harmonic is

\[
nX_L = \frac{X_C}{n}
\]

where,
\[ X_C = \text{capacitive reactance of the capacitor bank.} \]

\[ X_L = \text{inductive reactance of series reactor} \]

or \[ \frac{X_L}{X_C} = \frac{1}{n^2} \]

For resonance at 3\(^{rd}\) harmonic \( X_L / X_C = 1/3^2 = 0.111(11.1\%) \)

\[ \ldots \ldots \text{5\(^{th}\) harmonic } \quad \ldots \ldots = 1/5^2 = 0.04(4\%) \]

\[ \ldots \ldots \text{7\(^{th}\) harmonic } \quad \ldots \ldots = 1/7^2 = 0.02(2\%) \]

In order to avoid resonance at all odd harmonics the rating of the series reactor should be such that the series resonant frequency of the capacitor – reactor is below that of the lowest odd harmonic current present in the traction load.

Thus the value of \( X_L / X_C \) should be greater than 11.1\% to avoid resonance of the capacitor bank with any harmonic in the system. A value of 13\% reactance is usually adopted for the series reactor.

To maintain the effective capacitive reactance at 247.72 Ohm, the capacitive reactance of the capacitor bank should be increased by the same amount as the reactance of series reactor.

Hence the value of reactance of series reactor

\[ X_L = 0.13(X_C + X_L); \quad X_L = \frac{0.13 X_C}{1 - 0.13} \]

\[ = 0.13 \times 247.72/(1-0.13) = 37.02 \text{ Ohm} \]

4. **Actual Rating of capacitor bank with series reactor**

Modified capacitive reactance of the capacitor bank,

\[ X_C' = X_C + X_L = 247.72 + 37.02 = 284.74 \text{ Ohm}. \]

Considering the no load voltage of 27.5 kV of the transformer and the anticipated voltage rise of the incoming HT supply at low loads due to capacitor itself, the rated voltage of the capacitor is specified as 30 kV. Corresponding kVAR rating at 30 kV = \( 1000*\text{kVAR}/X_C \).
= 1000 * (30)^2/284.74
= 3161 kVAr

5. Harmonic current distribution

Current drawn by capacitor – series reactor circuit at fundamental frequency

\[ I_{cr} = \frac{30000}{X_C - X_L} = \frac{30000}{284.74 - 37.02} = 121.1 \text{ A} \]

:see Fig 1 of Annexure 2.6.1 below.

The average current harmonic level in traction supply is found to be 20% for third harmonic, 12% for fifth harmonic and 8% for 7th harmonic. Allowing 15% safety margin, for the load current of 292 A (7.3 MVA), the corresponding harmonic currents are \( I_{C3} = 67.2 \text{ A}, I_{C5} = 40.3 \text{ A}, I_{C7} = 26.9 \text{ A} \).

These harmonic currents in the line get distributed in the two parallel branches i.e. source and the traction transformer circuit and the capacitor series reactor circuit. The actual distribution of various harmonics depends on the circuit constants. For the equivalent circuit of traction power supply, discussed below the distribution has been worked out and given in Table 2.6.1A.1 below. Considering the distribution factor for the 3rd, 5th and 7th harmonic as 0.6, 0.21 and 0.2 respectively, the corresponding harmonic current through the capacitor bank would be

\[ I_{C3} = 0.6 \times 67.2 = 40.32 \text{ A} \]
\[ I_{C5} = 0.21 \times 40.3 = 8.46 \text{ A} \]
\[ I_{C7} = 0.20 \times 26.9 = 5.4 \text{ A} \]

\[ I_{cmax} = \sqrt{I_{c1}^2 + I_{c3}^2 + I_{c5}^2 + I_{c7}^2 + \ldots} \]

\[ = \sqrt{121.1^2 + 40.32^2 + 8.46^2 + 5.4^2} \quad = 128.03 \text{ A}, \text{ say} \]
\[ = 130 \text{ A} \]

6. Voltage rise due to harmonic currents

a) 3rd harmonic voltage across the capacitor bank

\[ V_{c3} = \frac{X_C}{3} x I_{c3} = \frac{284.74}{3} \times 40.32 = 3827 \text{ V} \]
b) 5th harmonic voltage across the capacitor bank

\[ V_{c5} = \frac{X_C}{5} \cdot I_{c5} = \frac{284.74}{5} \times 8.46 = 482 \text{ V} \]

c) 7th harmonic voltage across the capacitor bank

\[ V_{c7} = \frac{X_C}{7} \cdot I_{c7} = \frac{284.74}{7} \times 5.4 = 220 \text{ V} \]

Total harmonic voltage across the capacitor bank,

\[ = \sqrt{V_{c3}^2 + V_{c5}^2 + V_{c7}^2 + \ldots} \]
\[ = \sqrt{3827^2 + 482^2 + 220^2 + \ldots} \]
\[ = 3864 \text{ V} \]

Final voltage across the capacitor bank,

\[ V_{cr} + V_{char} = 34.482 + 3.864 = 38.346 \text{ V}, \text{ say } 40 \text{ kV}. \]

KVAR capacity of the capacitor bank at 40 kV

\[ = \frac{kV^2 \times 1000}{X_c} = \frac{(40)^2 \times 1000}{284.72} = 5620 \text{ kVAR} \]

7. Rating of Series reactor

Voltage across the series reactor,

\[ V_{\max} = X_L \sqrt{l_c^2 + 9l_{c3}^2 + 25l_{c5}^2 + 49l_{c7}^2} \]
\[ = 37.02 \times \sqrt{(121.1)^2 + 9(40.32)^2 + 25(8.46)^2 + 49(5.4)^2} \]
\[ = 37.02 \times 180.32 = 6675.5 \text{ V}. \]

kVAR rating of the series reactor = \( V_{\max} \times I_{c_{\max}} \times 10^{-3} \)
\[
\frac{72x681}{6675.5 \times 128.03 = 855 \text{ kVar}}
\]

Inductance of the series reactor, \( L = \frac{X_L}{2\pi f} \times 10^3 \text{ mH} \)

= \frac{37.02}{100\pi} \times 1000 \text{ mH}

= 117.84 \text{ mH}

8. Resonant frequency

a) Source reactance (\(X_S\))

Assuming 3 phase fault level on 132 kV side of substation as 2000 MVA.

Source reactance on 132 kV side = \( \frac{(132)^2}{2000} \) = 8.71 Ohm.

Loop reactance on 132 kV side = 2*8.71 Ohm = 17.42 Ohm.

Reflected reactance on 25 kV side, \(X_S = 17.42 \times (27/132)^2 \)

= 0.729 Ohm

b) Transformer Impedance

132/27 kV, 13.5 MVA transformer with 12% impedance has a reactance value:

\[ X = \frac{12}{100} \times \frac{(27)^2}{13.5} = 6.48 \text{ Ohm} \]

c) Equivalent circuit of traction power supply circuit
Fig 1 of Annexure 2.6.1

Where

\[ I_n \quad \text{-- Harmonic current at nth harmonic} \]
\[ X_S \quad \text{-- Source reactance} \]
\[ X_T \quad \text{-- Transformer reactance} \]
\[ X_C \quad \text{-- Capacitive reactance} \]
\[ X_L \quad \text{-- Series reactor reactance} \]
\[ I_{cn} \quad \text{-- Capacitor current at the nth harmonic} \]
\[ I_{sn} \quad \text{-- Supply current at the nth harmonic} \]
HARMONIC ORDER DISTRIBUTION FACTOR VS HARMONIC ORDER

fo = 128 Hz

HARMONIC CURRENT DISTRIBUTION FACTOR
$P_S, P_C$ – Distribution factors.

\[ I_n = I_{cn} + I_{sn} \quad \ldots \ldots (1) \]

\[ I_{cn} = \frac{(X_S + X_T)}{(X_S + X_T + X_L) - X_C / n^2} I_n = P_c I_n \quad \ldots \ldots (2) \]

\[ I_{sn} = \frac{X_L - X_C / n^2}{(X_S + X_T + X_L) - X_C / n^2} I_n = P_s I_n \quad \ldots \ldots (3) \]

Capacitor bank will have two types of resonances:

I) Parallel bank will occur at

\[ (X_S + X_T + X_L) - X_C / n^2 = 0 \]

i.e. \( n = \left( \frac{X_C}{X_S + X_T + X_L} \right)^{1/2} \)

\[ = \left( \frac{284.74}{0.729 + 6.48 + 37.02} \right)^{1/2} = 2.54 \]

\[ f_C = 2.54 * 50 = 127 \text{ Hz} \]

II) Series resonance will occur at:

\[ X_L - X_C / n^2 = 0.1 \text{ i.e. } n = (X_C/X_L)^{1/2} \]

\[ =(284.74/37.02)^{1/2} = 2.77 \]

\[ f_C = 2.77 * 50 = 138.50 \text{ Hz} \]

From the above equations (1), (2), (3) it is seen that:

\[ \frac{P_C}{P_S} = I_{cn} / I_{sn} = \frac{X_S + X_T}{X_L - X_C / n^2} \text{ and } P_C + P_S = 1 \]
From these relationships the harmonic current distribution between supply and capacitor bank for various harmonics is calculated and tabulated below:

Table 2.6.1A.1

<table>
<thead>
<tr>
<th>n</th>
<th>( P_S )</th>
<th>( P_C )</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td>0.185</td>
</tr>
<tr>
<td>8</td>
<td>0.821</td>
<td>0.179</td>
</tr>
<tr>
<td>9</td>
<td>0.827</td>
<td>0.173</td>
</tr>
</tbody>
</table>

The above values are indicated in the graph.

It is seen from the graph of harmonic current distribution to supply circuit and capacitor bank circuit versus frequency, that when harmonic current distribution factor \( P_S \) is less than 1, higher harmonic current is decreased by current is amplified with the shunt capacitor bank.

Therefore, the resonant frequency of the capacitor bank with the system should be in the range between 50 Hz and 140 Hz to avoid amplification of harmonic current at 3rd and other higher harmonics.

Use of 13 to 15% reactor in series with capacitor bank will make the capacitor reactor bank inductive in the frequency range above the 3rd harmonic.

Whenever a capacitor unit gets defective, it is advisable to cut off the whole capacitor bank from the circuit instead of allowing the capacitor bank work with reduced capacity. This is to avoid the resonant frequency getting increased which will cause the amplification of high harmonic current.
GENERAL SCHEME OF THYRISTOR SWITCHED CAPACITOR EQUIPMENT
GENERAL SCHEME OF IGBT Based
DYNAMIC REACTIVE POWER COMPENSATION
references


5. Series Capacitors for distribution networks – Asea 7582 E.

Chapter 7

INTERFERENCE PROBLEMS WITH 25 kV AC TRACTION

2.7.1 Introduction

The objective of this chapter is to give theoretical exposure to possible interference problems in 25 kV AC traction. However it is pointed right in the beginning that communication engineers have adopted optical fiber technology and other measures, which have reduced the effect of electrostatic and electromagnetic interferences of 25 kV traction power lines on their equipment. As a consequence, on most of the Railways the BT and Return conductors have been removed.

Interference to line-side cables from an adjacent ac traction system is a particular case of the more general problem of interference between power and telecommunication lines. This interference may arise either from the electric field or from the magnetic field. To appreciate how even with considerable separation between power lines and telecommunication lines i.e. with very weak coupling between the circuits. Interference occurs, one has to realize the power used in the two systems.

Power used in transmission lines and telecommunication lines.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 kV</td>
<td>$10^9$ W</td>
</tr>
<tr>
<td>132 kV lines</td>
<td>$10^8$ W</td>
</tr>
<tr>
<td>33 kV lines</td>
<td>$5 \times 10^6$ W</td>
</tr>
<tr>
<td>11 kV</td>
<td>$10^6$ W</td>
</tr>
<tr>
<td>400/240 V mains</td>
<td>$10^4$ W</td>
</tr>
</tbody>
</table>

Telephone line
- Sending End   $10^{-3}$ W
- Receiving End $10^{-5}$ W

In a power system, which transmits a kind of raw material i.e. electric energy, the efficiency must be high but purity of waveform is not of primary importance. The telecom line transmits a finished product, a message concealed in a complicated wave form, therefore, the waveform must not get distorted; power losses in telecom line are not important. Additional or suppressed impulse in a telegram may falsify a letter and then the meaning of a message. Harmonics may reduce or destroy the intelligibility of the speech or distort music transmitted by landline for radio. The more perfect the transmission the more sensitive does it become to disturbance.

Power interference may thus manifest at very different power levels – as hardly perceptible noise or as grave disturbance of the service, as dangerous acoustic shock or even as over
voltage endangering life or installations. Hence a distinction is generally made between
disturbance and danger. Normal operation of telecommunication system is possible if danger
is non-existent and disturbance is sufficiently low under normal operating conditions in the
neighboring power installations. During a fault of short duration in the power system the
disturbance in a telephone system is usually tolerable. The question arises as to what should
be the tolerable limit of danger.

To combat interference, coordinated action is called for from power and telephone engineers
because both installations have to serve the same people who have to pay for the protective
measures. Hence technically and economically best remedies are to be adopted even when
the two installations are under the control of separate administrations. General rules are laid
down for all new installations so as to exclude the possibility of interference.

2.7.2 CCITT- ITU-T K-53 and K-33 directives

The international Telegraph and Telephone consultative committee has recommended the
limits of permissible induced voltage under different conditions of operation.

2.7.2.1 Permissible Voltage Levels in the Case of Normal Operation of the Inducing Line

To avoid danger, it is recommended that the permissible continuous induced voltages be limited to 60
volts rms. This applies to screened or unscreened cables or open wire lines to which access is
required for work operations by staff.

Under conditions of particular-difficulty, the permissible voltage limit may be raised to 150 volts rms.
induced on conductors of a cable or an open wire line, provided special precautions are taken. These
special precautions may include:

- The issue of special instructions to personnel likely to have access to circuits exposed to
  voltage in excess of 60 volts rms so that special work measures can be applied;

- The marking of accessible parts of the installations or equipment with warnings.

2.7.2.2 Permissible Voltage Levels in the Case of a Fault on the inducing Line

Except for the cases described in the following paragraphs of this section, it is recommended that the
permissible voltage induced on cable conductors or open wire telecommunication lines be limited to:

a) 430 volts rms during a fault on a nearby inducing line that is constructed to usually accepted
technical standards;

b) 650 volts rms during a fault on a nearby high-reliability power line.
c) 1000 volts peak during a contact to earth of one wire of a nearby dc power or electrified railway line.

The permissible induced voltage may be increased for conductors in cables with earthed metallic sheath or screen and that are terminated in isolating transformers at both ends, or at one end with the other end connected through a low resistance to earth or, to a metallic cable sheath or screen, or if all the cable conductors are fitted with lightning protectors at their ends. In such cases, the permissible values are:

i) For cables tested for breakdown strength between conductors and sheath or screen after installation: an rms. value equal to 60% of the test voltage if tested with dc or, 85% of the test voltage if tested with ac.

ii) For cables where the above tests are not made: an rms. value equal to 60% of the lowest dc voltage or 85% of the lowest ac voltage used in factory tests to ensure the breakdown strength, between conductors and sheath or screen unless there is reason to fear that the laying and jointing operations have caused any appreciable reduction in the breakdown point. In such cases, special studies should be made to select the method for determining the permissible limit.

Where only some of the cable pairs are terminated satisfying the above conditions, the voltage limit indicated in i) or ii) is permitted on such cable pairs provided that the dielectric strength from other pairs in the cable is sufficient to avoid breakdown.

The isolating transformers and other line apparatus should have a dielectric strength equivalent to or greater than available on the cable conductors, unless lightning protectors are used.

Experience shows that dangerous levels of induced voltage are unlikely on cable conductors where the above conditions are met and where faults on medium voltage inducing lines are involved and where protective devices are used. Where the permissible induced voltage on cable conductors is increased above the permissible levels for open wire lines, it is desirable to consider safety precautions when work is carried out on these cables and to ensure that equipment connected to the line can withstand the resultant common mode voltages and currents.

Allowance may need to be made when considering permitted induced voltages induced into cables carrying significant telecommunication voltages (e.g. power feeding systems.)

2.7.2.3 Permissible Capacitive – Coupled Current

In cases of capacitive coupling, a resulting current through a contact between a conductor and earth or other metallic structure, up to 10 mA is permissible.

2.7.3 Coupling between circuits
The coupling between two circuits may be conductive or alternately due to electric or the magnetic field. These are distinguished as conduction, electrostatic induction and electromagnetic induction. Even when all the three kinds of couplings occur simultaneously, usually one of them will only be strong.

### 2.7.4 Conductive coupling

Conductive coupling is present when two circuits I and II have a common branch (see Fig.2.7.1). If the common branch is sufficiently well defined the distribution of the current and the effect produced in II may be calculated. If a common resistance ‘r’ couples them, the parasitic current ‘I’ in the circuit II is given by

$$I = \frac{Er}{RW + Rr + Wr}$$

![Diagram of conductive coupling](FIG. 2.7.1)

Generally $W >> R >> r$, because I is a power circuit and II a telecommunication circuit. It is approximately equal to $I = \frac{Er}{RW}$. The effect in II is same as if a parasitic voltage $e = \frac{Er}{R}$ were induced i.e. the voltage produced on $r$ without the circuit II. This means that reaction produced in I by II is negligible.

Conductive coupling occurs often between two circuits, using to some extent, the earth as conductor. Very weak couplings of this kind exist, obviously, between all circuits because of imperfect insulation. In practice, conductive coupling exists when electrified railways use rails as a return conductor. In telephony, coupling of this kind may arise in all circuits in which earth is used as an auxiliary or third conductor, especially all circuits using common batteries. In all such cases disturbances may occur if the earth connection of a telecommunication circuit is near enough to an earthing point on the power system.

In practice, interference by conductive coupling between lines can be neglected. Conducive coupling is present if the interference can be suppressed by resetting the earth connections or by replacing the
earth return by a metallic return conductor well away from the existing one. Electric or magnetic coupling is present if the interference can be suppressed by a displacement of the line well away from the inducing line without any alteration of the earthing connections.

### 2.7.5 Electrostatic Induction

Electric induction occurs due to capacitive coupling. The electrostatic induction is practically eliminated by using underground cables with metal sheaths. Discussion hereunder is confined to the systems of lines, which are long in relation to all dimensions perpendicular to the length (distance, diameter); the lines are assumed to be parallel with the surface of the earth and with each other.

Consider line 1 at voltage $U_1$ with the frequency $f$. Line 4 is insulated (see Fig. 2.7.2). The mutual capacitance $K_{14}$ and the earth capacitance $K_{40}$ are in series. The voltage $U_1$ produces a charging current.

\[
U_1 \ jw \times \frac{K_{14}K_{40}}{K_{14} + K_{40}} = U_1 \ jw \ K_{14} \text{ as } K_{40} \gg K_{14}
\]

\[\text{FIG. 2.7.2}\]

Voltage on line 4 is $U_4 = U_1 \ \frac{K_{14}}{K_{14} + K_{40}} = U_1 \ K_{14} / K_{40}$

If line 4 is earthed the charging current from 1 to 4 and hence to earth is given by $U_1 \ jw \ K_{14}$. This is proportional to the frequency and like $K_{14}$ to the length of parallelism. Thus the voltage electrostatically induced in an insulated line does not depend on frequency and length of exposure whereas the current to earth from an earthed line is proportional both to frequency and length.

The earth and mutual capacitance are calculated from the dimensions of the lines and the relations between voltage and charge of conductors established. The effect of earth is taken into account by
means of Kelvin’s method of electrostatic images. The image of each conductor in the earth’s surface has the same charge as the actual conductor but with opposite sign.

The induced voltage on overhead bare conductors running parallel to a 25 kV contact wire and insulated throughout can be calculated by the formula

\[ V = \frac{E}{4} \frac{bc}{a + b + c} \]

where

- \( V \) = induced voltage to earth
- \( E \) = contact wire voltage i.e. 25 kV
- \( a \) = horizontal spacing between the contact wire and the overhead conductor
- \( b \) = height of inducing line above ground
- \( c \) = height of overhead conductor

For the usual heights of contact wire and the overhead communication lines, the approximate induced voltages in the latter for different spacing are indicated below.

<table>
<thead>
<tr>
<th>Separation (m)</th>
<th>Induced voltage with 25 kV system</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>4600</td>
</tr>
<tr>
<td>6</td>
<td>2600</td>
</tr>
<tr>
<td>10</td>
<td>1440</td>
</tr>
</tbody>
</table>

It is seen that even if the lines are within 10 meter of contact wire they are subjected to induced voltages exceeding 1000. This would lead to a continuous discharge across the spark gaps with which telephone circuits are normally equipped and which have a nominal break down voltage of about 300 V dc.

When such bare conductors situated in the electric field are earthed through a person’s body the resulting discharge current is proportional to the inducing voltage and the capacitance or length of parallelism. If the parallelism reaches around 10 km the current could reach dangerous proportions. Hence it is not possible to contemplate normal operation of circuits with bare overhead conductors over any significant length alongside an ac-electrified railway.

Electrostatic effects decrease very rapidly when the separation between the inducing line and the line receiving induced emf is increased. If separation is increased to 40 m the voltage in conductors placed parallel to 25 kV contact wire hardly exceeds 150 V rms and the drawback of continuous discharge across the spark gaps is immediately removed.
The CCITT gives the following formula (which is more conservative than the one cited above) to arrive at the minimum separation between contact wire and the communication line to limit the induced voltage to 300 Volts. The minimum spacing is given by
\[ A = \frac{1}{3} \sqrt{E}. \]
where \( E \) is the contact wire voltage. For 25 kV system this works out to 53 m. In order to calculate electric induction due to an oblique exposure the distance \( d \) is reposed by the geometrical mean \( \sqrt{a_1 a_2} \) between the distances at the ends in the formula.

The calculation takes into account ideal conditions i.e. lines parallel to earth’s surface, and mostly to one another, free from additional capacitances and pure sinusoidal alternating current. In practice these conditions are never fulfilled. Line sags reduce average height and additional capacitances occur between wires and poles including capacitance of insulators. Further, roughness of earth’s surface, vegetation, buildings etc. result in reducing the effective height of conductors. The combined effect of all these is to increase capacitances to earth by 20% and mutual capacitances between conductors get reduced. Hence measured values of specific induced open circuit voltages are usually smaller than the calculated values, however high harmonics, even with small amplitude may increase considerably the electric induced short circuit current.

### 2.7.6 Electromagnetic induction

The emf ‘\( e \)’ induced in an overhead line or a cable running parallel to an electrified railway is given by the formula:

\[ E = 2 \pi MLI K_e K_c K_m f \]

Where
- \( f \) = supply frequency
- \( M \) = Mutual inductance per unit length
- \( L \) = Length of parallelism
- \( I \) = Catenary current

\[ K_e = \] a reduction factor which takes into account the presence of a current flowing in the rails the effects of which partly compensate for those due to current flowing in the contact system

\[ K_c = \] a reduction factor when the line in which currents are induced is in a metal sheathed cable.

\[ K_m = \] a reduction factor which takes into account the existence near the railway or in the vicinity of the line receiving induced currents, earthed metallic pipework carrying an appreciable induced current.
It is seen that an appreciable reduction in interference is obtained from the screening effect of earthed conductors such as cable sheaths, metal pipes, earth wires and finally the rails themselves. These reduction factors are also known as screening factors.

The mutual inductance $M$ per unit length is a complex factor, which depends on the separation of the inducing and induced line (a) and the soil conductivity and the frequency of inducing current. The function $M$ is in the form

$$M = f(a, \sqrt{\sigma f})$$

Fig.2.7.3 contains a family of curves, for the mutual impedance $M$ per kilometer v/s distance of separation of the lines, for various values of parameter.

At a little distance from the track $K_r$ can be approximated to $I - I_t/I_c$, where $I_t$ is the total induced current flowing in the rails and $I_c$ the catenary current.
MUTUAL IMPEDANCE AT 50 Hz BETWEEN TWO LINES WITH EARTH RETURN AS A FUNCTION OF THEIR SEPARATION $a$; PARAMETER $s$. 

**Fig. 2.7.3**
Reduction factor $K_c$ represents the relationship of the emf developed between a cable conductor and its sheath to the emf, which appears between an insulated conductor and earth in the absence of sheath. This reduction factor depends on character and dimensions of sheath and armoring and magnetic properties of the metal used for armoring. This improves as the frequency of the inducing current increases.

For cables located at a little distance from the track $K_c$ is smaller under heavy inductive conditions like short circuits than under less severe conditions like normal operation.

Screening of cable sheaths can be improved by reducing the dc resistance of sheath and by increasing the mutual inductance between sheath and wires. Aluminum sheath has resistance of about $1/7^{th}$ of similar sized lead sheath. As against screening factor of 0.8 for lead sheathed cable, for Al sheathed cable it is 0.16. If the inductance is increased by steel tape armoring, screening factor gets reduced to 0.025 and 0.2 respectively.

The presence of metal work electrically connected to earth near the track, or the circuit subjected to induction exerts a reducing effect, which may be considerable especially when several cables are buried in same Trench as they shield each other to certain extent.

2.7.7 Rail currents

The rails form a conductor with rather uncommon qualities. The resistance is very small and the leakage very large. The attenuation is so large that the return current is diverted completely to earth after about few kilometers and with higher frequencies even sooner. If the distance between feeding and loading points is large enough and if the track is homogenous, the rail current divides equally in both directions at both points, without any preference for the ‘inside’ direction. Part of the current penetrates deep into the earth and some leaves the earth to find a path in cable sheaths, metal pipes and other similar conductors parallel to the track. Near the feeding point the whole of the current returns to the earthed end of the traction transformer winding through the rail/earth mat of the feeding post.

If the return current could be wholly retained in the rails the inducing effect on an adjacent telephone line would be that from a comparatively narrow loop formed by the overhead wires and rails and would be relatively small. In practice the load current rapidly leaves the rails for earth as shown in Fig.2.7.4 (3b) which is applicable to an electrically long section where the rails continue for some distance on either side of the section.

The rails will however themselves be subject to an induced voltage from the overhead wire which will cause a current to flow in the rails virtually in the opposite direction to the contact wire current as shown in Fig.2.7.4 (3c).
TYPICAL RAIL CURRENT DISTRIBUTION

**FIG. 2.7.4**

- **(a)** LOAD COMPONENT
- **(b)** CONTACT WIRE
- **(c)** INDUCED COMPONENT
- **(d)** TOTAL CURRENT (FULL LINE)
In the centre of a long section the value of this current will be uniform and is equal to the induced voltage divided by the series impedance of the rails. It is usually about 0.4 to 0.7 of the overhead line current. Combining this induced current with the load current in rail, the total distribution of current in rails is shown in Fig.2.7.4 (d).

The resistivity of steel rails is rather high but the cross section is so large that the resistance mainly depends upon the resistance of the joints between rails. The d.c. resistance of welded rails is about 0.03 ohm/km. The screening factor becomes less than 0.6 if the track is well maintained.

### 2.7.8 Protective measures

Protective measures can be applied either in the low current communication circuits affected or at source (in the traction supply) or in both systems. Protective measures in telecommunication circuits consist of insertion of isolating transformers at intervals to limit the longitudinal build up of emf, balancing of the circuits and equipment and increasing the signal to noise ratio. Additional protective devices such as discharge tubes, drainage coils are also used.

Moreover by use of cables the induced voltages can be reduced by the appropriate screening factors of different types of cables. A cable with a break down test voltage of 2000 volt should be able to withstand the voltage induced by a short circuit. All the ac circuits must be terminated by transformers. The terminating transformers only allow currents produced by differences of voltage (transverse voltage) to pass out to the external apparatus. As a result, in general the noise so produced is hardly noticeable and is not troublesome if the cable is only subjected to moderate induction and if there are not too many harmonics in the traction current.

Exchange and subscriber’s equipment not separated by transformers from the line conductors must be protected by fuses and voltage arrestors or protectors against induced voltages.

DC circuits should be replaced by ac or impulse circuits. Special measures are required for the protection of the operators, the main precaution being to avoid any possibility of a simultaneous contact with the apparatus and with earth.

Anti induction measures include periodic transposition of the positions of conductors in a circuit at their supports, to produce compensation along the length of the line between the emfs induced between the conductors themselves. Even under favourable conditions (almost perfect parallelism between the inducing circuit and the circuits subjected to induction and regular spacing of the supports at which transpositions are made) and even if the distances between transposing points are small (less than 1 km) perfect compensation is not obtained.

In an overhead line at a short distance from the track the effects of electrostatic induction from the contact wire are added to the inductive effects due to traction current. Even if a bare overhead line is located at 300 m from a railway with a parallelism of 4 to 5 km it is likely to be affected by noise which creates difficulties for conversation.
Cabling the overhead communication circuits is an effective means of reducing interference. The screening is improved by reducing the resistance of cable sheath i.e. by conductivity screening. This is achieved either by use of aluminium sheath or by addition of copper wires under the lead sheath. The cable sheath is also effectively earthed at intervals of about a km. Secondly the magnetic coupling between sheath and conductors is increased by provision of steel tape armouring over the conducting sheath. The screening factor with such cables coupled with that provided by the rails and buried metal pipes etc., can be around 0.06. Further improvement would be possible if the cable circuits are laid far away from the electrified sections. Moreover with the use of OFC the interference is virtually eliminated.

2.7.9 Suppression of interference at source

Though the above measures are generally adequate for protection of communication circuits there might be special cases where highly sensitive long distance communication circuits or dense urban communication networks exist either parallel to the track or in its vicinity. When such a railway line is taken up for electrification, the above remedial measures might prove either too expensive or inadequate. In such cases suppression of interference at source may have to be resorted to.

Reduction in the interference effects of electrified railways can be obtained by the use of booster transformers. These transformers have a 1:1 ratio with the primary winding connected in series with the contact wire and the secondary is connected either to the rails (as in Scandinavian countries) or to a return conductor as per general practice followed elsewhere. The return conductor arrangement is more favourable for reducing telephone interference.

2.7.10 Rail connected booster transformers

In this system the secondary winding is connected to the rails on either side of insulated rail joints and the current in the rails is thereby increased to an extent that for a booster transformer spacing of 2.66 km only less than 5% of return current flows in the earth. The effective area of the inducing loop is much reduced and the interference effects are correspondingly reduced.

The screening effect of this system depends on the spacing of the booster transformers and the propagation coefficient of rail-earth return circuit which in turn depends on frequency and on the insulation of rails to earth. With a spacing of 2.66 km the theoretical screening factor is taken as 0.05 at 50 Hz. As the rail screening factor without boosters would be 0.5, the improvement ratio due to the provision of boosters is 10:1. The reduction at higher frequencies is less.

The disadvantage of rail-connected booster system is that a considerable voltage can exist across the insulated rail joints, endangering the safety of maintenance personnel quite apart from the difficulty in proper maintenance of insulated joints. The screening factor for harmonic currents is lower than for fundamental current as the series impedance of rails is greater for harmonics than for fundamental and therefore larger proportion of harmonics escape into earth. Hence this method is not satisfactory for the elimination of noise due to harmonics.
2.7.11 **Booster transformers with return conductors**

In this system the secondary windings are connected in series with a return conductor which is connected to the rails midway between booster transformers. The return current flows almost entirely in the return conductor and very little in the earth or rails except in section where the load current is being taken. The return conductor is erected on the overhead masts carrying the catenary and the inducing loop formed by the traction and return currents is therefore of small width.
With return conductor system two effects need be considered. The first is induction from through currents, i.e. those currents taken by trains well beyond the parallelism and confined wholly to the contact wire and return conductor. The second is induction due to train in section effect i.e. where the train is in a BT cell within the parallelism and the current is flowing along the rails.

For telecommunication lines well removed from railways the first effect i.e., direct induction from the contact wire return conductor loop (which are nearly equidistant from the cable) can be ignored. However the rails are not and cannot be symmetrically disposed with respect to contact wire and return conductors and hence an induced current flows in rails which causes induction in telecom lines. Rail screening factor of remote cables would be about 0.025 and is independent of frequency. This represents an improvement of 20:1.

Considering the second effect, maximum induced voltage occurs when a train is close to a booster transformer in which case the length between the train and rail return conductor connection may be treated as being equivalent to a normal feeder section without booster transformer for which a screening factor of 0.5 at all frequencies would be appropriate provided the parallelism extends for about 3 km on either side of the equivalent section.

It is seen that the first effect i.e. induction from through currents is independent of booster spacing whereas the second effect is not. In practice if boosters are spaced at 2.66 km, the longest section for which a screening factor of 0.5 would be appropriate will be 1.33 km and this would apply only to the current drawn by the particular trains in the booster section.

2.7.12 Salient features of booster transformer system

As the primaries of boosters are connected in series with the contact system with voltages of 336 V (for 100 kVA boosters spaced at 2.66 km) they have to be designed to withstand 25 kV. Since they are in series with the OHE they must be capable of withstanding the mechanical and thermal stresses caused by system short circuits.

Magnetizing current is required to flow in the primary to induce secondary voltge to enable secondary current to flow in the loop. This magnetizing current which flows in primary and (not in secondary) is superimposed on the load current. To limit the uncompensated current in the OHE to the minimum the exciting current has to be kept as low as possible. The harmonic current of the exciting current is to be minimum as this uncompensated current would create noise in telecommunication lines. To reduce the harmonic component of excitation current, the flux density in the core has to be kept low so that it lies on the linear portion of BH curve for the maximum voltage that may develop across the primary/secondary winding of the BT at 700 A (assumed maximum catenary current). Cold rolled grain oriented steel is used with maximum flux density of 0.7 T to contain the exciting current to 0.2 to 3% of full load current and the harmonics at 10 to 15% of the exciting current.
A high exciting impedance at harmonic frequencies is required to obtain compensation of harmonic induced voltages by currents in the return conductor. The exciting impedance at 800 Hz should not be less than 450 Ohm.

Since several booster transformers are in series and they tend to add to the OHE impedance, the leakage impedance of boosters is to kept as low as possible.

2.7.13 Limitations of Booster Transformers

There is always a residual induced voltage in communication conductors due to proximity of other conductors including rails carrying induced currents etc. For a train in section only partial compensation is obtained. Whenever the booster primary is shorted by the pantograph of the locomotive while negotiating the BT overlap span, there will be no compensation in that cell even for through current for that duration, though it is very small. During system short circuits due to saturation of core, compensation tends to be less than normal. Both even and odd harmonics are induced in the exciting current flowing in the OHE.

2.7.14 Drawbacks of Booster Transformers

The initial cost of the system of booster transformers and return conductors is substantial. The impedance of the OHE is increased by more than 50% thereby increasing the voltage drop and decreasing the permissible loading of the section, necessitating closer spacing of substations. There will also be additional loss of energy due to additional impedance of the booster transformers and return conductors.

2.7.15 Instructions for provision of booster transformer:

A technical committee consisting of members from DOT and Railways was constituted in Dec 1992 to study the requirement of BT/RCs as well as payment to DOT for protective works due to Railway Electrification. The guidelines generated after the completion of protective works by DOT during Railway Electrification. And approved by the Telecom Commission are as under.

a. The voltage on DOT lines due to RE should not exceed 60 Volts longitudinal voltage and 5 V as transverse voltage under normal loading conditions and 430 V under fault conditions as per CCITT recommendations.

b. Railway Reduction/Screening Factor (RRF) for the new scheme can be taken as 0.28 where all the four rails are conducting on a double track section, under the following conditions.

   i. The Rails have been provided with bonded joints and not mechanical bonds.
   ii. After the RE work is completed, if on actual measurements, the RRF as observed is not more than .28.
   iii. In all other cases, RRF will be taken as 0.44.

2.7.15.1 DOT are required to modify and/or shift as necessary if existing telecom circuits fall within the zone of induction due to introduction of 25kV ac traction system. Railways
are also required to provide booster transformer and return conductor as necessary for limiting the induced voltage in DOT circuits to 60V.

2.7.15.2 A certificate is to be given by DOT in terms of modified Performa 10.09 of ACTM Vol.II (Pt.I) so as to enable railways to energise the OHE. In absence of completion certificate of the protective works in said Performa from DOT, the Railways/CORE/Construction Units will approach the Board along with the certain documents as described in RB letter no. 91/RE/141/5 New Delhi, dated 23.06.95 for considering grant of approval for energisation.

2.7.16 AT system

With increased system loading due to introduction of high speed passenger trains and heavy freight trains, the 2 x 25 kV AT system has certain advantages over the conventional system apart from suppression of induction at source. BT system will be found wanting due to problems like heavy arcing at overlaps and higher voltage drops due to heavier currents. In the 2 x 25 kV AT system electric power from traction substation at single phase 50 kV is transmitted along the track between the OHE and a separate feeder wire supported on suitable insulators. At intervals of about 10 to 15 km along the track, centre tapped single phase auto-transformers are installed and connected between the OHE and the feeder wire, with the midpoint of these ATs being connected to the rails. Both the OHE and feeder wire will be at 25 kV with respect to the rail but the actual voltage of transmission will be 50 kV. The current from the substations flows between the OHE and the feeder wire of the two ATs on either side of the load. These two ATs feed the current required for the load connected between the OHE and the rail. Due to equal and opposite currents flowing in the OHE and the feeder the magnetic fields produced will neutralize causing no interference except the AT cell effect. Voltage regulation on the traction system is also better with the AT system.
References


Chapter 8

SUPERVISORY REMOTE CONTROL AND DATA ACQUISITION SYSTEM

2.8.1 Need for Remote Control

In the protection schemes employed at present, for any fault on the overhead equipment between a substation and a neutral section the feeder circuit breaker at the substation is called upon to clear the fault, in order to clear the fault or to isolate the same, certain operations are to be carried out involving opening and closing of interruptors and breakers all along the line. This has to be done in the quickest possible time to restore supply to healthy sections.

Further it would be necessary to carry out frequent switching operations for maintenance and operational needs. Supervisory remote control of traction power supply installations is therefore resorted to. The alternate method of manning the switching stations with operators who carry out switching operations at the instance of telephone instructions from the control centre is attendant with abnormal delays for isolation of faults thereby adversely affecting train operations besides being prohibitively costly.

2.8.2 Type of Control Signaling and Transmission

Equipments situated at relatively small distances from the operator can be remotely controlled with dc signals or power frequency ac signals. As the distances increase and the equipments spread out along the track at various places, which are several kilometers apart, remote control of all the equipments by these methods involves large number of physical circuits for transmission. This number could be reduced by coding the signals that would be of direct current (dc) or alternately using one or more current pulses with equal or unequal pauses. Signal distortion sets the limitation for transmission of dc or low frequency ac signals. Further they cause interference and cross talk in adjacent circuits requiring independent cables for the remote control. Amplification of signals, which is inescapable with long distance transmission, is difficult with dc and low frequency ac signals.

Hence carrier systems like OFC which permit several channels on a single physical circuit are used to carry the signals. Carrier systems also reduce the number of physical pairs required for remote control.

To avoid any cross talk in the adjacent communication circuits (in the same cable) due to the remote control signals the same voice frequency band is used for transmission of remote control signals.
The superimposition of the signal currents on the carrier frequencies is called modulation. The three types of modulation available are amplitude modulation, frequency modulation and phase modulation.

In amplitude modulation the amplitude of the current is varied by the modulating frequency, the carrier frequency remaining constant, whereas in frequency modulation the carrier frequency is varied by the modulating frequency, amplitude of the carrier wave remaining constant.

In phase modulation the amplitude of the modulated wave is constant and equal to that of an un-modulated carrier but there is an infinite series of modulation components alternately in phase and in quadrature with the carrier, and also an infinite series of side frequencies spaced from carrier frequency by amounts corresponding to harmonics of the modulated frequency.

Phase modulation is not normally used and is replaced by frequency modulation. An important advantage of frequency modulation as compared with amplitude modulation is that a reduction of the effect of noise or interfering currents in the transmission link can be secured. In amplitude modulation such currents have the effect of varying the amplitude of the transmitted wave and are thus reproduced together with the signal in the rectified output of the receiver. With frequency modulation although interfering currents still vary with the amplitude of the carrier their variation in amplitude can be eliminated by means of a limiting stage in the receiver prior to demodulation. This considerably improves signal to noise ratio.

In view of the above advantages frequency modulation, is employed for the remote control signal transmission.

Switching equipment with earlier system

This is either of uni-selector type or of all relay type. The rotary selector mechanism was an electromagnetic device operating on the step-by-step principle. It employs a ratchet and Paul, which actuates a set of wipers and moves it over a series of bank contacts, which are arranged circumferentially with respect to the operating spindle. The inherent limitations of the selectors are the need for metal contact surfaces between the wiper and bank contacts, the inconvenience of flexible wiper cords and collector brushes and the necessity for periodical lubrication and maintenance.

In the All-relay system all the switching operations are made through simple relays. These systems were slow in operation and needed considerable maintenance of moving parts besides heavy power consumption. Further special features like logging of events, telemetry etc. were also not possible with these systems.

2.8.3 SCADA System

With the advent of computers/microprocessors, data telecommunication, control systems and the developments in the associated hardware and software SCADA systems were developed to provide continuous vigil and supervision with high speed of functioning which suited the
intrinsic management philosophy of reliability with overall economy and the traction engineers were quick enough to exploit its potential in supervisory remote control of traction power supply installations.

SCADA stands for Supervisory Control and Data Acquisition. SCADA systems are employed for simultaneous acquisition of a large amount of data, real time processing, display and supervisory control. For the new electrification projects Railways have gone in for computer based SCADA systems for monitoring and controlling the traction power supply. SCADA enables the Traction Power Controller (TPC) to control from the Master station at the Remote Control Centre (RCC) the switching operations of the equipments at controlled stations i.e. traction substations and switching stations. It helps the TPC to achieve real time data acquisition, processing, display and control of data pertaining to the traction power supply to the 25 kV overhead traction systems over a geographical span of railway tracks extending over 400 to 600 km.

The main functions of Supervisory Control are:

- The remotely operate the bi-state devices which control the electric supply to the overhead equipment i.e. circuit breakers, interruptors etc.

- To remotely effect the release of locks-outs wherever necessary.

- To automatically carry out operation of circuit breakers and interruptors to localize any faults on the overhead equipment, segregate the faulty sub-section, and restore the 25 kV supply to the healthy sub-sections.

- To remotely operate any indicator lights, like (flashe lights at traction substation) etc., at the remote stations if required.

Supervisory Control should have all the safeguards built into it to avoid faulty operation of control commands. Check-back-verify, or select-before-operate kinds of safeguards are incorporated.

Data acquisition

The main Data Acquisition functions are as under:

- To acquire real time data regarding the status of all the circuit breakers, interruptors, transformer alarms and faults arising out of excessive transformer winding temperature, transformer Buchholz relay operation, transformer excessive oil temperature, pressure relief device operation etc.

- To acquire data regarding the abnormal and faulty conditions of various equipments.
- To acquire data regarding the power system measurands like current, voltage, power factor, maximum, demand etc.

- To perform, alarm functions on all the data acquired. Limit violations, abnormal states of status devices, rate-of change violations etc. shall be processed.

- To log and printout all commanded and uncommanded changes which take place in the system.

- To print out log sheets and summaries in the desired formats, with station address, item address and time.

- To compute, report and log “derived measurands” like maximum demand, status of overhead Equipment (energized/de-energized) etc.

2.8.4 Master Station Equipment

Hardware configuration

1. Master station equipment
   The basic hardware configuration consists of nine Pentium PCs connected on a 16 port soft switchable active Ethernet LAN Hub. Out of nine PCs, two PCs act as main and standby Masters/Host, two PCs act as main and standby Front End Processors and remaining five PCs are utilized for MMI (man-machine interface) at RCC. Each PC/server has its own color monitor, Keyboard, mouse, floppy and CD-ROM drives, multimedia kit complete with speakers and microphone. The PCs used in the SCADA system have minimum 256 MB RAM, 40GB hard disk and clock speed 1.8 GHz or better. Provisions are made in the software so that the telecommand operation can be carried out from any one of the MMI PCs provided at the operator's workstation. In case of failure of main computer, the switchover takes place through the software to the standby computer system automatically.

   Two data-logging printers are connected to the system, one on-line and other as standby. In case of failure of one printer, the other printer starts logging the data.

2. Communication with RTUs
   Standardized communication protocol is used between master and the remote station. Each LAN system is interfaced through FEP and modems with the RTUs (Remote terminal units). The modem provided for communication between the Front End Processor and RTUs works on 600/1200-baud speed on 4-wire communication in half duplex mode.

3. Modes of Operation
   The modes of operation include the supervisory mode, control mode, edit and programming mode.
4. **Security**

To ensure a high degree of system security and to prevent unauthorized operations, the following levels of access are provided.

a) **Operator’s level** – This is for interaction of the TPC with the computer for his day-to-day working.

b) **Supervisory level** – This is meant only for getting information from the computer. Control operation of electric switchgear shall not be possible from this level. This level can create more operators in the system.

c) **Engineer’s level** – This has total access to all the programmes stored in the system.

d) The operator’s console desk forms part of the SCADA equipment.

5. **Mimic diagram board (MDB)**

A mimic diagram board and its associated mimic driver were earlier provided at the RCC. The MDB depict the traction power supply diagram, indicating the energized / de-energized condition of sub-sectors of catenary, status of the interruptors and feeder circuit breakers at TSS & FP, SSP and SP. However, in the latest system of SCADA, the functions of MDB are being carried out on PC itself.

6. **Real-time display and control:**

Man Machine Interface (MMI) computers ensure graphic coloured displays of the full section indicating clearly the devices at TSSs, SPs and SSPs. Any three adjacent controlled stations are displayed for viewing to operator at any time; however other stations can be seen by scrolling through keyboard or mouse. The display includes both fixed and variable data, namely ON/OFF status of equipment/catenary (such as feeder CB trip, AC and DC fail/low, RTU fail/Remote station defective/ Communication fail & Machine down etc.) alarms, measurands and names of the controlled stations. Bridging interrupters and paralleling interrupters (to be controlled during feed extension) are displayed for extending feed in case of power supply failure. The condensed picture for full section is displayed so that status of full power supply diagram can be viewed on workstation.

2.8.5 **Function of Software**

The operating system is suitably designed for multi-user, multi-tasking, networking and real time applications. The latest window based operating software is used. Master station software is working on window 2000 Operating system or its latest versions. The protocol between master station and RTU has been standardized as SPORT (Standard Protocol for
Railway Traction) by RDSO and is given in SCADA specification TI/SPC/RCC/SCADA/0988 Vol-II. The protocol defines rules and regulation for various types of information exchanged between RCC computers and RTU. This protocol has been designed on basis of IEC-870-5-1. Above development has resulted into better control over SCADA system maintenance and augmentation apart from advantages of interchangeability of RTU’s.

VDU Displays: The software supports the following VDU displays.

a) Station diagrams:

Semi graphic, colored displays of any three adjacent controlled stations including both fixed and variable data, namely ON/OFF status of equipments, catenaries, alarms, measurands along with the names of the controlled stations which permit transmission of tele-commands to circuit breakers, interruptors and other equipments, by simple key-board operations by the operator. Facility for marking (manual input) is provided for any alarms, equipment status including manually operated isolators, measurands and limit-settings, by simple key-board operations by the operator.

b) Tabular displays: Tabular display of data of a controlled station includes equipment status, alarms and measurands.

c) Alarm list: Display of the alarm list in a chronological order starting from any given time.

d) Event list: Display of the event list, which includes commanded and uncommanded changes in equipment status, acknowledgement of alarms, markings, in a chronological order starting from any given time.

e) System alarms: The alarms generated by the SCADA equipment, and not by the traction power supply system, are displayed.

f) Trend diagrams: The time versus value plot of upto four measurands can be displayed in a trend diagram. Each measurand can be displayed in a separate colour. The trending includes both historical trending and dynamic trending of the current data.

g) Histograms: For both current and historical data the time versus value plot of any measurand by histogram can be provided.

h) Bargraphs: Display of the current values of upto four measurands by bargraphs – each bar having a different colour-can be provided.

i) Message pad: One page is provided for the operator to record important messages.
Calling any of the VDU displays shall be by simple keyboard operations by the operator. NEXT/PREVIOUS or PAGE UP/DOWN option is also available.

The software for the SCADA equipment is designed so as to cater for updating for adding or deleting controlled stations or individual parameters such as telecommand, telesignal or measurand at any of the existing controlled stations.

Facilities are provided for the operator, through simple keyboard commands to:

- Take out of scan and control (Process inhibit) any alarm point/control point/measurand or a complete RTU.

- Block/de-block a complete RTU as well as any control point (circuit breaker, interruptor and other equipments at the controlled stations) which disables/enables control operations from the RCC. The blocked condition of any equipment is suitably indicated on the VDU, for example by a change in colour of the corresponding equipment display.

- Inhibit any alarm point, which shall discontinue processing of the alarm point at the RCC.

2.8.6 Transmission and Coding system

The master station equipment normally scans continuously all the RTUs in a predefined cyclic sequence, to update the equipment status, alarms, events and measurands. Exchange of information between the master station and the RTUs is on interrogation by the master followed by the reply from the RTU. The communication technique is based on Digital Address Time Division Multiplexing. Each transmitted information contains sufficient parity check bits so as to allow an effective error detection code to detect different combination of transmission errors.

2.8.7 Operation of Power Block

a) Power block is generally given for maintenance of any equipment like transformer, circuit breaker, interruptor, section of OHE or any other equipment by de-energizing the equipment/section of OHE. Provision is made for entering into the computer necessary pass words to the operator at RCC in connection with the requisition for issue/cancellation of the power block and the time duration for which the power block is given. If a power block is not cancelled at the end of the permitted duration, a message “Power Block Time exceeded” appears on the VDU along with the equipment/section reference and time, with an audible alarm to attract the attention of the operator.

b) When equipment is under power block, it is not possible to operate that equipment unless the power block is first cancelled from the RCC. In case the telecommand for operating that
equipment is attempted, a message “Equipment under power block” appears on the VDU. Power block cancellation should be possible through Operator’s password only.

2.8.8 Other features of the system

2.8.9.1 Indication for complimentary faults

The status of any bi-state device like circuit breaker, interrupter is monitored through two auxiliary contacts of the device, the status (open/close) of the two contacts being normally complement (opposite) of each other in the ON/OFF condition of the device. However, when both the auxiliary contacts are either in open or in closed condition, such faults are detected and identified as complimentary faults. The event is logged and suitable indication appears on the VDU.

2.8.9.2 Alarm processing

Any and every change in the state of telesignals, uncommanded change in the status of equipments like circuit breaker, interrupters, and limit violation of tele-metered parameters (measurands) is processed as alarms. Each and every alarm attracts the attention of the operator by an audible hooter/prerecorded voice message and by a change in the display of the equipment status or change in colour of display of the telemetered parameter or change in colour of display of the alarm (telesignals) point as applicable, and the display shall start flashing. Upon acknowledgement by the operator, the audible alarm ceases and the display on VDU becomes steady.

2.8.9.3 Historical data storage

a) SCADA equipment at RCC is designed to cater for historical data storage of the traction power supply system data for a period of one year.

i) All alarms/events/measurands of the controlled stations and all system alarms.

ii) Day-wise storage of average feeder current and voltage during the day, maximum demand, maximum and minimum feeder voltages, total number of operations of feeder protective relays viz. OCR, DPR and WPC relays, and maximum and minimum OHE voltages at SP on both sides of the neutral section or phase break in 2 x 25 kV system. A sufficient memory capacity is provided for this purpose in the hard disk.

b) A facility is provided for accessing any data from the SCADA data-base from any other remote computer terminal/RCC or from a centralized computer located at the zonal railway headquarters.

2.8.10 Uninterruptible power system at RCC

Dual stand-alone UPS system of adequate capacity is provided for supplying stabilized 240 V ac, 50 Hz, single-phase supply to various equipments of the SCADA system at master station. Input supply to the UPSs is 415 V AC, 50 Hz, 3 phase with a permissible variation between
+10 and –15% for the voltage and +3 and –3% for the frequency. Both the UPSs work in parallel to share the load of the system. However, the capacity (VA rating) of each UPS is designed to meet with the entire load of the system in the eventuality of the failure of the other. The taking over the load by the healthy UPS is automatic without affecting the normal working of the system. The failed UPS disconnects itself from the circuit automatically. The UPSs provide for trickle/normal/boost/auto charging of the battery in addition to supplying normal load to the various equipments. Alarm and mimic facilities are provided on the facia of the UPS for ease of operation and maintenance. The acoustic noise level generated by UPS is kept as low as possible and shall not exceed 50 dB when working alone.

A single set of storage battery of low maintenance Lead Acid type is provided with both the UPSs. The battery has adequate Ah capacity to provide two hours of supply to various equipments in case of failure of input 415 V ac supply.

2.8.11 Data-logging

1. Data logging printers

Two alphanumeric desk jet printers are provided.

2. Alarm/Event logging

All events such as signals and alarms, commanded and uncommanded changes and limit violations of telemetered parameters are printed automatically by the data-logger with date (year, month and day) and time of occurrence (hours, minutes, seconds and milli-seconds) stamp.

3. Diagnostics

The system provides diagnostic checks for faults in the SCADA equipment at the RCC. These faults are printed out with details such as names of controlled station, card number with date and time stamp.

4. On-demand facility

The facility is provided for the operator to obtain reports on-demand through the keyboard. Such reports include current status of bi-state devices, signals and alarms at the remote stations, communication failures, telemetry printout and other information required.

5. Periodic printouts

The data-logger gives periodic printouts, whenever required by the operator, as under:
a) 15/30 minutes printout giving average values of all the analogue parameters at TSSs and SPs during the last 15/30-minute period.

b) 8 hourly printouts giving summary of all important events that occurred during the immediately proceeding 8 hours. Events that occurred during the periods when the data-logger is printing ‘periodic’ or ‘on demand’ reports are not to be lost but printed out thereafter with their time of occurrence stamp.

2.8.12 Remote Terminal Unit (RTU)

1. Hardware

The RTU is microprocessor based with its associated digital input/output modules, alarm input modules, analogue input modules, watchdog transducers, memory, modems, interposing contactors, summation current transformers, power supply units and surge arrestors and other items necessary for its proper functioning. A suitably designed circuit for giving initialization pulse to the CPU at pre-defined interval of time, which itself shall be user selectable, is provided in the RTU so that the CPU gets initialized automatically in case it halts due to any reason.

2. Reporting of events and alarms

All the changes in the status of the circuit breakers/interruptors/motor-operated isolators and alarms that may occur between consecutive polling shall be stored by the RTU unit they are reported to the master station along with their time of occurrence. No event is lost without being reported to the master station. The feature is essential in view of the fact that the normal polling may get suspended due to failure of communication channel or other reasons.

3. Power Supply Units

The RTU shall normally operate of 240 V ac, 50 Hz, single phase supply from the auxiliary transformer provided at the controlled station. This voltage may vary from 155 V to 290 V due to variation in the catenary voltage (25 kV). In case of failure of ac supply, the RTU shall operate of the 110 V DC battery supply. The load of the RTU is within 1 A at 110 V dc.

2.8.13 Telemetering functions

1. Parameters to be telemetered/computed (measurands)

The RTU are designed to telemeter two feeder currents and one OHE voltages and one P.F from each TSS, and two OHE voltages from each SP. The arrangement for telemetry is as under:
a) From TSS

i) Feeder currents: Two current transducers are provided one each for either side of the TSS, taking reference from the two feeder CTs of that side through a summation CT.

ii) Feeder voltages: Two voltage transducers are provided, one each for either side of the TSS, taking reference from the two OHE PTs of that side through a suitable change-over device. In the event of supply failure in any of the PTs, the change-over device shall automatically connect the live PT to the transducer.

iii) Power Factor: The power factor value is acquired by the RTU through p.f. Transducer and sent to the RCC.

b) From SP

Voltage of the OHEs on either side: Two voltage transducers are provided, taking reference either from the UP or DOWN line PT through a suitable changeover device. The other measurands such as Capacitor bank current and 132 kv/220 kV incoming voltage can be acquired if demanded by purchaser.

2. Limit settings of telemetered parameters for Alarm generation

Provision is made for ‘low’ and ‘high’ limits of voltages at TSS and SP, ‘high’ limit for currents. The voltage setting can be selectable continuously between 15 kV and 30 kV. The current setting can be selectable continuously between 300 A and 1000 A. The settings are software selectable.

3. Transducers

Transducers provided at the controlled stations (TSS and SP) are self powered or Auxiliary-powered and are of quick response type with a response time not greater than 1 second and have linear characteristic over the entire range giving an output proportional to the input from current transformers and potential transformers at the SP.

2.8.14 System alarms

The system alarms are provided in the event of partial or complete failure of the RTU to communicate with the master station due to failure of RTU, or on failure of individual I/O modules and other modules in the RTU. The nature of fault is indicated on the VDU.

Remote station defective: This alarm appears in the event of partial or complete failure of the RTU to communicate with the master station due to failure of RTU, or on failure of individual I/O modules and other modules in the RTU.

Master Station Defective: This alarm appears in the event of failure of any computer at master station.
2.8.15 System capacity and other salient operational features

1. The SCADA equipment is typically designed for the following capacity of telecommands, telesignals and telemetered parameters (measurands) for a typical TSS, SSP, SP and ATP of a double line section. Capacity may be increased based on actual requirement.

2. Typical telecommands, telesignals and measurands of different type of RTU are given as follows.

<table>
<thead>
<tr>
<th>SN</th>
<th>Controlled station</th>
<th>Telecommands</th>
<th>Telesignals</th>
<th>Measurands</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TSS</td>
<td>24</td>
<td>96 (48+48)</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>SP</td>
<td>8</td>
<td>28 (16+12)</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>SSP</td>
<td>8</td>
<td>28 (16+12)</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>ATP</td>
<td>-</td>
<td>8</td>
<td>-</td>
</tr>
</tbody>
</table>

When the number of parameters to be commissioned initially is less than the above, the balance-designed capacity shall be available for future use.

3. Speed of transmission and update time:

   The communication between the master station and the RTUs shall be at a suitable transmission speed 600 baud and above. Whenever the number of controlled stations is more than 30 and the RCC is located somewhere in the middle of the section, the controlled stations on one side of the RCC are polled simultaneously in parallel with the controlled stations on the other side of the RCC, so that the cyclic update time is kept to the barest minimum. The master station equipment configuration is designed for such simultaneous polling.

4. Priority of data exchange between master station and RTUs.

   While the master station is polling the RTUs cyclically, the telecommands receive the highest priority. The normal polling is interrupted for sending the telecommand and for receiving the telesignal from the RTU for change of status resulting from execution of telecommand before normal polling restarts.

2.8.16 Modems

a) The modems provided for communication between the master station and the RTUs utilize frequency shift keying (FSK) modulation and include send, receive and timing functions. The send and receive functions are independently programmed. The modem is capable of satisfactorily
working up to an input signal level of –45 dbm. It also performs a watch dog role and turns the
transmitter off in the event of any fault occurring within the equipment.

b) The modem also incorporates necessary amplifiers with a gain of 30 db to compensate for
any signal variation at different points of the system. Suitable attenuation pads are provided in the
amplifiers to adjust the output signal level between 0 and –30 db in steps of 1 db.

c) A test switch on the modem allows a square wave data pattern to be transmitted continuously
at maximum baud rate to allow receiver levels and bias distortion to be set.

2.8.17 Special requirements of SCADA equipment

1. Tripping of bridging circuit breakers on under voltage at SP.
   
a) Instantaneous type under voltage circuits are provided at the SPs operated off 27500/110 V
potential transformers and designed to trip the bridging circuit breakers if the catenary voltage
drops below a preset limit. The operating range for the circuit is adjustable between 15,000 V and
22,000 V continuously, in steps of 1,000 V.

b) The arrangement shall be such that the bridging circuit breakers can be closed only when the
section on one side of neutral section is dead and the under voltage circuit shall become operative
only after the bridging circuit breaker is closed.

2. Interlock release-request facility for circuit breakers/interruptors control at boundary post.
   
   When a controlled station separates the zones controlled by two adjacent RCCs, control of
breakers/interruptors at this controlled station shall be so arranged that the
breakers/interruptors can be operated from one RCC only when an interlock is released from
the other RCC.

3. Auto reclosing scheme for feeder circuit breakers at TSS.
   
a) In case of tripping of the feeder circuit breaker on fault at TSS, a single-shot auto-reclosing
scheme re-closes that breaker automatically only once, after a pre-set time delay.

b) In the event of any fault on OHE persisting, the feeder circuit breaker trips again and the auto-
reclosing scheme gets automatically “locked-out” to prevent reclosing of the breaker a second
time. The locked out condition is telesignalled to RCC. The operator can release the “locked-out”
condition when a telecommand is initiated through the keyboard console.

4. Automatic localization of OHE faults
The system is designed for automatic localization of faults in OHE, segregation of faulty sub-sector/broken sub-sector and restoration of 25 kV power to healthy sections of OHE, through a suitable software package incorporated in the SCADA system. The fault localization process shall be initiated by the operator through the keyboard console. In general, the fault localization process employs the technique of energizing all the sub-sectors/broken sub-sectors that were live prior to the fault one after the other until it identifies the faulty sub-sector/broken sub-sector by the tripping of the feeder circuit breaker.

The system also takes the following into account while localizing the fault automatically:

a) Power block(s) imposed on an interrupter:

Whenever power block is imposed on any interrupter, no further control on that interrupter shall be possible from the master station. For the purpose of fault localization, such interruptors shall be assumed as “open”.

b) Discontinuity caused in any sub-sector due to imposition of power block on an elementary section of that sub-sector.

The software adopted for the fault localization and isolation process is designed to take into account the inputs entered by the operator, and to ensure that no interrupter that was open prior to the occurrence of fault is closed during the fault localization process, and to segregate the fault by opening minimum number of interruptors.

2.8.18 Communication medium

For transmission of signals from the Master station to RTUs; the underground telecommunication trunk cables provided by the Railways are generally used. Three pairs of conductors i.e. one pair for transmission, one pair for reception and the third pair as spare, are used. Star quads of the cable circuits are used for this purpose. The salient features of these conductors which are paper insulated are as under:

i) Diameter of copper conductor 0.9 mm

ii) Loop resistance at 20°C 55.2 ohm/km

iii) Mutual capacitance of the pairs of paper insulated VF quads 0.041 microfarad/km

iv) Characteristic impedance at 800 Hz when loaded 1120 ohm

v) Loading of intervals of 1.33 km 33 milli Henry
vi) Attenuation at 800 Hz when loaded 0.25 dB/km

On these lines isolating transformers are installed at every 10 to 20 km to limit the induced voltages. They have a dielectric strength of 2000 V ac (rms) for one minute. At the point of tapping the underground trunk cable isolating transformers with impedance ratio 1120/1120 ohms are provided. Voice frequency repeaters with a gain of 20 dB incorporating equalizers to compensate for line distortion up to 0.02 dB/kHz/km are provided at every 40 to 50 km to boost the signal level. Cross talk attenuation of repeated section between any two VF pairs at 800 Hz will not be less than 65 dB at far end and 61 dB at near end. SCADA equipment incorporates amplifiers with 30 dB gain to cater for signal variations at different points in the system.

On same sections the communication between Master station is provided by dedicated Microwave channel at carrier frequency of 18 GHz.

Optical fiber cable is also being introduced for communication in some electrified sections, with suitable interface between the optical fiber cable and the MS and RTUs. The particulars of optical fiber cable and optical line terminating unit are as under:

The cable consists of six/eight mono mode fibers as per CCII recommendations No.G652. The optimized wave length band is 1300 nano meters. The nominal mode-field diameter is 9 to 10 micrometer with a cladding diameter of 125 microns. The cut-off wave length is 1120 to 1280 nanometers. The attenuation is less than 0.5 dB/km at 1300 nanometer band and the splicing loss is 0.15 dB/joint. The optical line terminating equipment consists of electrical and optical interfaces. The electrical interface has a line impedance of 75 ohms unbalanced or 120 ohms balanced with a line bit rate of 2048 KB/s. The optical interface has the same line bit rate and uses LED for transmission and SIAPD for reception. Intensity modulation is used.

Failure of communication medium

If a particular station does not receive the signal from master station, or information does not reach the master station a break in the transmission or reception pair is indicated. Sometimes if the repeaters are not properly functioning, the RTUs beyond it are disturbed. If the attenuation in transmission pairs increases, RTUs before the repeaters are disturbed. In all such cases failure of communication is indicated and appropriate rectification action on the communication circuit is called for.

2.8.19 Telephone facilities at RCC

On each of the two desks in the Remote Control Centre, a series of push buttons permits selective calling of each of the telephones connected to the circuit concerned. In case one of the operators is absent the control circuits of both can be concentrated at one desk. A loudspeaker is situated near the operator at the control centre permanently. In case any one
of the persons on the TPC circuit wants to contact the operator, he has to simply take off his receiver and announce himself.

The telephone system enables the operators to communicate directly with the stations responsible for ensuring protection of the overhead equipment when current is switched off, with the substations and switching stations, with the locomotive sheds, overhead equipment maintenance depots and with the high tension substations of the Electricity Boards.

Emergency telephone sockets are installed along the tracks at intervals of a kilometer to enable the train staff or the permanent way staff to plug in their telephones to communicate with the operator for switching off power in cases of emergency etc. These are occasionally used by certain stations not otherwise connected to TPC circuit; they are mostly used by overhead equipment maintenance staff and also by train staff in case of derailments or damages. Such calls can only be initiated from the emergency sockets. A bell rings at the control room when the receiver of any telephone plugged into the emergency socket is lifted.

Moreover direct telephone facilities are available for the TPC to communicate with the adjacent traffic controllers and adjoining remote control centers.

The first computer based SCADA system on Indian Railways was commissioned at Secunderabad for Vijayawada-Balharshah section of S.C. Railway. For better appreciation of the SCADA system, Basic Block Diagram of SCADA schematic& details of Telecommand, Telesignal and Measurands are included.
## Details of Telecommands, Telesignal and Mesurands

<table>
<thead>
<tr>
<th>S.No</th>
<th>Details of telecommands</th>
<th>TSS</th>
<th>SP/SSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>132/220 kv C.B.</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>1.1</td>
<td>25 kv C.B.</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>1.2</td>
<td>25 kv Interrupters</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>1.3</td>
<td>Auto reclosure release with lock out indication</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>1.4</td>
<td>Transformer tap changer</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>1.5</td>
<td>Interlock release request at boundary post</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>1.6</td>
<td>To disable the panto flashover relay from circuit</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1.7</td>
<td>Spare</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>1.8</td>
<td><strong>Total Telecommands</strong></td>
<td>24</td>
<td>#8</td>
</tr>
</tbody>
</table>

*These telecommand includes 24 ON and 24 OFF

*As per site conditions and as specified by the purchaser.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Details of telesignals</th>
<th>TSS</th>
<th>SP/SSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>110 V D.C. low / Battery charger fail</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.2</td>
<td>240 V A.C. Fail</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.3</td>
<td>PSU on D.C.</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.4</td>
<td>PSU overloaded</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.5</td>
<td>Catenary indication</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>2.6</td>
<td>Transformer alarm</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>2.7</td>
<td>Transformer fault</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>2.8</td>
<td>Transformer trip circuit 110 V D.C. fail</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>2.9</td>
<td>Transformer alarm circuit 110 V D.C. fail</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>2.10</td>
<td>Feeder CB operated on DPR</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2.11</td>
<td>Feeder CB operated on OCR</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2.12</td>
<td>Feeder CB operated on WPC</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2.13</td>
<td>Feeder CBs operated on Panto Bridging</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2.14</td>
<td>Panto bridging relay bypassed</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2.15</td>
<td>Transformer tap position 1 to 6 position</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>2.16</td>
<td>Auto recloser locked out</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>2.17</td>
<td>Spare</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>2.18</td>
<td><strong>Total telesignals</strong></td>
<td>48</td>
<td><strong>12</strong></td>
</tr>
</tbody>
</table>

**These 48 telesignal shall exclusive of 24 ON status and 24 off status of devices.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Details of Mesurands</th>
<th>TSS</th>
<th>SP/SSP</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>25 KV bus / OHE voltage</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3.2</td>
<td>Feeder Currents</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3.3</td>
<td>Power factor</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>3.4</td>
<td>Spare</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>3.5</td>
<td><strong>Total Mesurands</strong></td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>
BASIC BLOCK DIAGRAM OF SCADA SYSTEM

- 16-port LAN HUB
- LAPTOP
- Server Main
- Printer
- Printer
- Server Standby
- FEP1
- FEP2
- Modem
- RTU
- Modem
- RTU
- Modem
- RTU
- Modem
- RTU
- Workstation-1
- 21" VDU
- Workstation-2
- 21" VDU
- 21" VDU
- 21" VDU
Chapter 9

TECHNICAL SPECIFICATIONS FOR MAJOR EQUIPMENTS

2.9.1 Basic system insulation level

Insulation level of any apparatus is characterized by two test voltages which the apparatus can withstand.

- Crest value of impulse voltage i.e. impulse withstand level.
- One minute power frequency voltage (rms value).

The above withstand voltages characterize the strength of the apparatus with regard to its capability of withstanding the dielectric stresses.

International Electro-technical Commission (IEC) have standardized the insulation levels for various system voltages on the basis of maximum permissible variations under normal working conditions. As system nominal voltages vary considerably throughout the world, to achieve standardization IEC have attached several nominal system voltages for a given system highest voltage. The following values based on European practice are recommended by IEC (Publication No.71)

<table>
<thead>
<tr>
<th>System highest voltage KV</th>
<th>Corresponding system nominal voltages KV</th>
<th>Impulse (1/50 microsecond) withstand-peak value kV</th>
<th>One minute power frequency withstand wet &amp; dry) kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.5</td>
<td>30:33</td>
<td>200</td>
<td>70</td>
</tr>
<tr>
<td>52</td>
<td>45:44</td>
<td>250</td>
<td>95</td>
</tr>
<tr>
<td>72.5</td>
<td>66</td>
<td>325</td>
<td>140</td>
</tr>
<tr>
<td>123</td>
<td>100:110:115</td>
<td>550</td>
<td>230</td>
</tr>
<tr>
<td>145</td>
<td>120:132:138</td>
<td>650</td>
<td>275</td>
</tr>
<tr>
<td>245</td>
<td>220</td>
<td>950</td>
<td>395</td>
</tr>
</tbody>
</table>

At higher system nominal voltages (100 kV and more) reduced withstand voltages both for impulse and power frequency withstand are also furnished (in IEC 71) which are applicable only if the overvoltage protective devices are adequate and sufficiently near to the apparatus and the coefficient of earthing does not exceed 80% i.e. in an effectively earthed system. But in this country, the supply authorities do not favour adoption of reduced insulation for nominal system voltages up to 132 kV.

2.9.2 Insulation coordination
Insulation coordination consists of the steps taken to prevent damage to electrical equipment due to over-voltages and to localize flashovers to points where they will cause least damage. It is accomplished by establishing necessary correlation between the insulation strength of the electrical apparatus and the characteristics of the protective devices against overvoltages. The overvoltages may be of atmospheric origin or generated within the system; the amplitude of the overvoltages can be limited by appropriate protective devices.

The insulation co-ordination involves the design not only of the individual pieces of equipment but of the complete system. The characteristics of the protective devices adopted have to be correlated with the insulation level of the system.

The traction system with a line to earth voltage of 25 kV corresponds to a three phase system with line to line voltage of $25\sqrt{3} = 43.3$ kV. If an insulation level corresponding to the above is adopted to provide the same degree of protection, the traction system will have to be considered equivalent to a three phase system, having a nominal voltage of $25 \times \sqrt{3} = 43.3$ kV say 44 kV and the corresponding system highest voltage will be 10% more i.e. 48.4 kV. This corresponds to the IEC system highest voltage of 52 kV.

Therefore, the corresponding system highest voltage of IEC for nominal voltage of 44 kV is 52 kV with the following insulation levels:

- 250 kV impulse withstand
- 95 kV power frequency withstand

**Suggested insulation co-ordination**

To check whether satisfactory insulation co-ordination has been achieved, it is necessary to compare the voltage/time characteristics of the apparatus and the overvoltages of protective devices. Fig.2.9.1 illustrates typical characteristics with the values tabulated for 132, 110 and 25 kV systems.

**25 kV feeders and the overhead equipment**

An essential requirement in the selection of insulation levels is that the line insulation under adverse conditions arising from atmospheric pollution, fog and rain must withstand all overvoltages, which are produced in the system itself with switching operations. The minimum standard required is such that the line insulation for transmission lines under wet conditions will withstand a power frequency voltage of three or four times the nominal phase to earth operating voltage and this normally ensures that the impulse withstand voltage is about the same as or exceeds the IEC standard insulation level. Where lightning incidence is high or pollution of insulators may take place or reduction of flashovers is more important, higher insulation levels are used.
From the above considerations the following insulation levels are recommended for all the 25 kV feeders and the overhead equipment.

<table>
<thead>
<tr>
<th></th>
<th>Power frequency withstand (wet)</th>
<th>Impulse withstand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95 kV\text{rms}</td>
<td>250 kV p</td>
</tr>
</tbody>
</table>

The solid core insulators used on the OHE comply with these requirements and in fact the specified impulse level is 270 kV and the test values in some cases are more than 300 kV (nearly 340 kV). The higher values to a certain extent can be justified if the adverse effect of pollution is taken into account.

**Insulation level of transformer, switchgear and busbars**

If the system is effectively earthed, the reduced insulation level for highest system voltages (100 kV and more) as specified by I E C can be adopted together with adequate and effective protective devices. It is, however, necessary to determine the co-efficient of earthing of the system at all points and suitable lightning arrestors are to be chosen at different places so that the rated voltage of the lightning arrester is slightly greater than the product of the system highest voltage and the co-efficient of earthing of the lightning arrester location.

In view of the above difficulties in selection of suitable arrestors of different types in case of reduced insulation, the supply authorities are not in favor of adopting reduced insulation for nominal system voltages upto 132 kV (corresponding to system highest voltage of 145 kV). Therefore, the following higher insulation levels are used for switchgear, busbars and transformers.

<table>
<thead>
<tr>
<th>System nominal voltage, kV</th>
<th>25</th>
<th>66</th>
<th>110</th>
<th>132</th>
<th>220</th>
</tr>
</thead>
<tbody>
<tr>
<td>i) System nominal voltage, kV</td>
<td>95</td>
<td>140</td>
<td>230</td>
<td>275</td>
<td>395</td>
</tr>
<tr>
<td>ii) Power frequency withstand (wet), kV</td>
<td>160*</td>
<td>460*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iii) Impulse withstand (wet), kV_p</td>
<td>250</td>
<td>325</td>
<td>550</td>
<td>650</td>
<td>950</td>
</tr>
</tbody>
</table>

* For CB

The flashover voltage of bushings should not be higher than the internal flashover strength of the transformers. Otherwise there would be a danger in the event of surge voltage for a flashover or puncture to occur internally. In order to avoid such an occurrence porcelain bushings for transformers are fitted with arcing horns the lower electrode being mounted on flange tip and the top one on the cap of the bushing. Such arcing gaps also protect the porcelain from being damaged by the arc in the event of a flashover. The rod gaps when provided for porcelain
bushings of equipments at the substation give additional protection. The arcing distance in the rod gaps should be adjusted to avoid their frequent operation with switching surges.

To avoid excessive demands on the station protection level, the line adjacent thereto should be protected and the amplitude of the incoming surges should be kept as low as possible. This can be done by adequately screening the incoming feeders by earth wires or alternately providing suitable spark gaps on the insulators of the incoming feeders.

*Characteristics of protective devices*

One of the problems associated with insulation levels is the characteristic of protective devices. A protective device is characterized by its impulse protection level i.e. the highest voltage (crest value) which appears at its terminals under specified conditions. Insulation withstand levels of apparatus given in IEC recommendations have been determined with a view to obtain correlation with protection level of the overvoltage protective devices which are commercially available.

If the system is effectively earthed, lightning arrestors giving improved protection values can be used, thus resulting in the safe use of lower insulation levels and consequent saving in the cost of apparatus. This applies to system nominal voltages of 132 kV or more but at lower voltages such reduction in insulation is usually not economically justifiable so that only one insulation level is usually adopted for both effectively and non-effectively earthed systems.

One of the major differences in ratings of lightning arrestors and other pieces of equipment arises from the fact that for arrestors the voltage across an individual arrestor is most important as arrestors are connected between phase and earth. This voltage forms the basis of rating rather than phase to phase voltage which is usually used for rating a system and other equipment such as transformers and switch-gear. A large number of standard ratings with small differences have been formulated by the IEC to suit various operating conditions. The rated voltage of diverter is usually taken at about 80% of system highest voltage for effectively earthed systems or the system highest voltage itself for non-effectively earthed system. The ratings and other particulars of lightning arrestors are given below.

<table>
<thead>
<tr>
<th>a) Nominal system voltage (phase to phase)</th>
<th>Nominal system voltage (phase to phase)</th>
<th>52 kV class (25 kV phase to earth)</th>
<th>66 V</th>
<th>110 kV</th>
<th>132 kV</th>
<th>220kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>b) Permissible variation</td>
<td>22.5 to 27.5 kV (Sometimes touching 30 kV)</td>
<td>66+10%-12.5%</td>
<td>110+10%-12.5%</td>
<td>132+10%-12.5%</td>
<td>220+10%-12.5%</td>
<td></td>
</tr>
<tr>
<td>c) Rated frequency</td>
<td>50 Hz</td>
<td>50 Hz</td>
<td>50 Hz</td>
<td>50 Hz</td>
<td>50 Hz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type of lightning arrestor</td>
<td>Non-linear, metal oxide resistor type, without gaps.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---------------------------</td>
<td>-----------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>e)</td>
<td>Line discharge class</td>
<td>3   3   3 3 3 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f)</td>
<td>Continuous operating voltage capability (Phase to earth)</td>
<td>35 kV rms 50 kV rms 80 kV rms 95 kV rms 168 kV rms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g)</td>
<td>Maximum discharge voltage at nominal discharge current</td>
<td>125 kVp 160 kVp 250 kVp 350 kVp 550 kVp</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h)</td>
<td>Nominal Discharge current (8/20 wave)</td>
<td>10 kA 10 kA 10 kA 10 kA 10 kA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>i)</td>
<td>Power frequency voltage withstand for arrester insulator</td>
<td>105 kV rms 117 kV rms 174 kV rms 228 kV rms 380 kV rms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>j)</td>
<td>Pressure relief class</td>
<td>A  A  A  A  A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**INSULATION CO-ORDINATION**
VOLTAGE TIME CHARACTERISTICS OF THE APPARATUS AND OVERVOLTAGE PROTECTION DEVICES

INSULATION CO-ORDINATION

VOLTAGE VALUES FOR DIFFERENT SYSTEMS

<table>
<thead>
<tr>
<th>VALUE</th>
<th>132kV</th>
<th>110kV</th>
<th>25kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>410kV</td>
<td>290kV</td>
<td>145kV</td>
</tr>
<tr>
<td>b</td>
<td>350kV</td>
<td>250kV</td>
<td>125kV</td>
</tr>
<tr>
<td>c</td>
<td>500kV</td>
<td>440kV</td>
<td>163kV</td>
</tr>
<tr>
<td>d</td>
<td>650kV</td>
<td>550kV</td>
<td>250kV</td>
</tr>
<tr>
<td>e</td>
<td>760kV</td>
<td>700kV</td>
<td>260kV</td>
</tr>
</tbody>
</table>

FIG. 29.1
The important features of insulation co-ordination for the different systems are given below:

<table>
<thead>
<tr>
<th>System nominal voltage kV</th>
<th>Voltage of lightning arrestor kVp</th>
<th>Gap spark over (gap distance) kV</th>
<th>Transformer withstand kV</th>
<th>Switchgear withstand kV</th>
<th>Transmission lines or feeder withstand kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>132</td>
<td>250</td>
<td>500 (660 mm)</td>
<td>650</td>
<td>650</td>
<td>&gt; 760</td>
</tr>
<tr>
<td>110</td>
<td>250</td>
<td>440 (585 mm)</td>
<td>550</td>
<td>550</td>
<td>&gt; 700</td>
</tr>
<tr>
<td>25</td>
<td>125</td>
<td>163 (200 mm) or 181 (230 mm)</td>
<td>250</td>
<td>250</td>
<td>&gt; 260</td>
</tr>
</tbody>
</table>

The typical voltage time characteristics of the apparatus and the protective devices are indicated in Fig.2.9.1.

2.9.3 Salient features of traction transformers

1. Traction power supply system:

   The 25 kV single phase 50 Hz power supply for railway traction is obtained from 220/132 kV three phase grid (at times from 110/66 kV networks also) through step down single phase power transformers. The primary winding of the transformer is connected between two phases of the three phase network. To reduce the unbalance on the grid the power is tapped at such points where the system short circuit levels are high and as an additional measure, adjacent substations are fed from different phases to achieve certain degree of balance on the network.

   One terminal of the 25 kV secondary winding of traction transformer is connected to OHE and the other is solidly earthed and connected to the running rails. A neutral section is provided midway between two adjacent substations to separate the different phases. Two transformers are normally installed at each substation, only one being on load at a time, the other being a standby.

2. Nature of traction load and the OHE system

   The traction load rapidly varies from full load to no load. The transformer is subjected to frequent earth faults and short circuits of the order of 200 per month, fault current varying from 40% to 100% of dead short circuit value. With locomotives and EMUs having rectifier and thyristor control systems, the ripple current in the supply is of the order of 25 to 40% with third harmonic.
current ranging from 15 to 32\%, fifth harmonic from 6 to 18\% and 7\textsuperscript{th}, 9\textsuperscript{th} and 11\textsuperscript{th} harmonics of the order of 8\%, 4\% and 5\% respectively. The average power factor of electric locomotive is between 0.7 and 0.8 without compensation. Shunt capacitors are usually installed at traction substations to improve power factor to over 0.9.

The maximum system short circuit levels on 220 kV, 132 kV, 100/110 kV and 66kV bus are 20000 MVA, 10000 MVA, 6000/6000 MVA & 3500 MVA respectively.

3. Rating and other particulars of typical traction transformers

a) MVA at nominal secondary voltage 20 MVA.
b) MVA at rated secondary voltage (27 kV) 21.6 MVA
c) Maximum efficiency at 50\% of full load------
d) 

<table>
<thead>
<tr>
<th>Insulation</th>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Nominal system voltage</td>
<td>220</td>
<td>132</td>
</tr>
<tr>
<td>b) Highest system voltage</td>
<td>245</td>
<td>145</td>
</tr>
<tr>
<td>c) Power frequency withstand one minute kV (rms)</td>
<td>395</td>
<td>275</td>
</tr>
<tr>
<td>d) Impulse withstand (1.2/50 microsecond) kV peak</td>
<td>950</td>
<td>650</td>
</tr>
</tbody>
</table>

e) Percentage impedance voltage at 21.6 MVA base at the principal tap 12 ± 0.5\% 

f) Non-cumulative overload capacity after the transformer has reached steady temperature on continuous operation at full load.

a) 50\% for 15 minutes
b) 100\% for 5 minutes

g) Withstand time without damage with dead short circuit at terminals.

a) On thermal considerations θ 5 seconds.
b) On mechanical considerations to withstand dynamic current θ 0.5 second.

4. Cooling equipment

Transformer is ONAN cooled. The transformer is designed for ON AF rating for use at a future date when it shall be capable of delivering about 40\% more output by provision of forced cooling.

5. Parts, fittings and accessories
The transformer is provided with

i) Conservator tank
ii) Magnetic type oil level gauge
iii) Silica gel breather
iv) Instantaneous pressure relief valve
v) Buchholz relay double float type with two shut off valves; one between the conservator tank and another between the main tank of transformer and Buchholz relay with one set of alarm contacts and one set of trip contacts and a testing petcock brought down for testing at ground level.
vi) Oil temperature indicator
vii) Winding temperature indicator
viii) Sealed, oil filled, draw lead type condenser bushing with bushing type CTs, two on primary and two on secondary.
ix) Simulated hot spot temperature sensor to give a signal in case of hot spot exceeding specified limit of 115°C.
x) Pressure relief device.

6. Type tests
   a) Temperature rise test on lowest tap position (-15%) to check up that the following values are not exceeded over an ambient of 45°C
      - Temperature rise of winding –50°C (by resistance method)
      - Temperature rise of insulating oil -40°C (by thermometer)
      - Winding hot spot temp. –115°C.
   b) Lightning impulse test
   c) Short circuit test
   d) Separate source voltage withstand test

7. Routine tests
   a) Measurement of voltage ratio on all taps
   b) Checking polarity
   c) Measurement of no load losses, load losses and impedance voltage
   d) Measurement of winding resistance and insulation resistance (with 5 kV Megger)
   e) Induced over voltage test
   f) Separate source withstand test

8. Besides the overhead/return circuit which is responsible for the voltage drop in the OHE, there is also the internal voltage drop of the traction transformer leakage reactance. Though it is possible
to design transformers with low reactance or partly compensate for the transformer and line reactance by use of series capacitors, the short circuits especially close to the substation give rise to disturbances on H.V. network besides dangerous electromagnetic effects in the transformers and in the circuit as a whole. Hence relatively high impedances are specified for traction transformers.

2.9.4 Characteristic features of circuit breakers

1. The circuit breakers used are outdoor minimum oil type or SF6 gas type consisting of identical single poles (two for 132 kV) operated through common shaft of the operating mechanism. They are suitable for mounting on steel structures.

2. The circuit breaking chamber is oil filled (or gas filled) with fixed, and moving contacts within an insulated enclosure mounted on a supporting chamber. Carbonized oil in the circuit breaking chamber should not mix and contaminate the oil in the supporting chamber.

3. The supporting frame shall be such that the minimum height of live parts after erection shall not be less than 5m above ground level and bottom most portion of any insulator or bushing shall not be less than 2.5m above ground level. The distance between pole centers is 3m.

4. The main contact tips are made of cupro tungsten alloy. The CB is operated by a motor compressed spring charging mechanism, with a charging time of not more than 20 seconds. A capacitor tripping device (CTD) is provided to safeguard against failure of trip supply. In case of dc supply failure, capacitor automatically trips the breaker.

5. The aim is to effect the interruption of the circuit with consistently low arc energy over the whole range of currents. An arc is drawn and follows a sinuous path due to the oil vapour pressure and flow. The circuit breakers both for 132 and 25 kV are also manufactured using the better arc quenching properties of sulphur hexa fluoride (SF6). Vacuum breakers are also used on 25 kV side.

6. The 25 kV circuit breakers may be called upon the open under short circuit conditions frequently-average being 100 operations per month and in exceptional cases 150 to 200 per month. Magnitude of short circuit currents interrupted ranges from 2 kA to 6 kA. Under certain circumstances when the two transformers at one substation are paralleled the short circuit current interrupted can reach 12 kA. The 25 kV circuit breaker is also called upon to clear wrong phase coupling faults on OHE.

7. Characteristics of breakers

<table>
<thead>
<tr>
<th>Rated system</th>
<th>25 kV</th>
<th>66 kV</th>
<th>110 kV</th>
<th>145 kV</th>
<th>245 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of poles</td>
<td>Single pole</td>
<td>&lt; -------- 2 or 3 as required -------- &gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rated insulation level</td>
<td>95 kV</td>
<td>160 kV</td>
<td>230 kV</td>
<td>275 kV</td>
</tr>
<tr>
<td>---</td>
<td>--------------------------------------------------------------------------------------</td>
<td>-------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td></td>
<td>- Rated 1 minute power frequency withstand, rms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Rated impulse withstand (1.2/50 micro second)</td>
<td>250 kV</td>
<td>350 kV</td>
<td>550 kV</td>
<td>650 kV</td>
</tr>
<tr>
<td>2.</td>
<td>Rated frequency</td>
<td>50 + 3%</td>
<td>50 + 3%</td>
<td>50 + 3%</td>
<td>50 + 3%</td>
</tr>
<tr>
<td>3.</td>
<td>Rated normal current, A</td>
<td>1600</td>
<td>1250</td>
<td>1600</td>
<td>1600</td>
</tr>
<tr>
<td>4.</td>
<td>Rated short circuit breaking current (kA)</td>
<td>20</td>
<td>31.5</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>5.</td>
<td>Rated breaking capacity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- 2 pole MVA</td>
<td>550</td>
<td>2283.75</td>
<td>4920</td>
<td>5800</td>
</tr>
<tr>
<td></td>
<td>- 3 pole MVA</td>
<td>3955.50</td>
<td>8522</td>
<td>10046</td>
<td>16974</td>
</tr>
<tr>
<td>6.</td>
<td>Rated making current, kA peak</td>
<td>50</td>
<td>78.8</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>7.</td>
<td>Rated operating sequence</td>
<td>0 - 0.3 -CO-15 seconds.</td>
<td>&lt; -------- 0-0.3 Sec co-3 min-co ------ &gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Total breaking time, ms</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; -------------- 60ms ----------- &gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Rated short time current</td>
<td>20 kA for 3 Sec.</td>
<td>&lt; ------- -----31.5 kA for 1 Sec.------ &gt;</td>
<td>40 KA for 1 second</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>Corona Extinction voltage</td>
<td>-</td>
<td>53 kV</td>
<td>88 kV</td>
<td>106 kV</td>
</tr>
</tbody>
</table>

8. The recovery voltage is the voltage which appears across the terminals of each pole of the circuit breaker immediately after the breaking of the circuit. This voltage may be considered as composed of two components, one of service frequency recovery voltage (stated as rms value) and one transient component either oscillatory (at single or multi frequency) or non oscillatory (i.e. exponential) depending upon the combined characteristics of the circuit and the circuit breaker. The transient component exists only for a fraction of a cycle of service frequency.

The rate-of-rise recovery voltage (RRRV) is a rate expressed in volts per microsecond, is obtained by dividing the maximum amplitude of the oscillations by the duration of the first half wave.

9. Breaking current
The current broken by a pole of a circuit breaker is the current in that pole at the instant of contact separation. The symmetrical breaking current is the rms. value of the ac component of the current in that pole at the instant of contact separation.

\[ I_{\text{sym}} = \frac{I_{\text{ac}}}{\sqrt{2}} \]

The asymmetrical (total) breaking current is the rms value of the total current comprising the ac and dc components of the current in that pole at the instant of contact operation.

\[ I_{\text{asym}} = \sqrt{(I_{\text{ac}}/\sqrt{2})^2 + (I_{\text{dc}})^2} \]

The breaking capacity is expressed by two values i.e. symmetrical and asymmetrical (total) breaking capacity.

10. A trip free circuit breaker is a circuit breaker, the moving contact of which returns to and remains in the open position when the opening operation is initiated after the initiation of the closing operation, even if the closing command is maintained.

\[ AA' \] = envelope of current-wave

\[ BB' \] = displacement of current-wave zero-line from normal zero-line at any instant.

\[ CC' \] = displacement of current-wave zero-line from normal zero-line at any instant.
DD’ = rms value of symmetrical current of any instant measured from CC’

EE’ = instant of contact separation (actual or assumed).

\( I_{ac} = \) peak value of ac component of current at instant EE’.

\( I_{dc} = \) dc component of current at instant EE’.

\( \frac{I_{dc}}{I_{ac}} \times 100 = \) Percentage dc component of contact—separation.

\( I_{sym} = \) symmetrical breaking-current = \( \frac{I_{ac}}{\sqrt{2}} \)

\( I_{asym} = \) asymmetrical breaking-current = \( \sqrt{(I_{ac} / \sqrt{2})^2 + (I_{dc})^2} \)

2.9.5 Salient features of potential transformers

Voltage or potential transformers are instrument transformers of small output but of high accuracy. They serve to transform the system voltage, to facilitate measurement, into a secondary low voltage which is as near as possible proportional to and in phase with the primary voltage. Various control applications and connections call for single and double or possibly three-pole insulated voltage transformer. In single phase ac traction system only single pole voltage transformers are used.

Single pole insulated voltage transformers have only one end of primary winding insulated to withstand the full test voltage. The test voltages are as under:

<table>
<thead>
<tr>
<th>Rated voltage (kV)</th>
<th>Highest admissible operation voltage operation kV</th>
<th>ac test voltage insulator end winding (kV)</th>
<th>Impulse withstand voltage (kV peak)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>52</td>
<td>95</td>
<td>250</td>
</tr>
<tr>
<td>66</td>
<td>72.5</td>
<td>140</td>
<td>325</td>
</tr>
<tr>
<td>110</td>
<td>123</td>
<td>230</td>
<td>550</td>
</tr>
<tr>
<td>132</td>
<td>145</td>
<td>275</td>
<td>650</td>
</tr>
<tr>
<td>220</td>
<td>245</td>
<td>395</td>
<td>950</td>
</tr>
</tbody>
</table>
The rated burden of PT is the apparent power supplied at rated voltage within the limits of error. Accuracy is indicated by the class figure giving the highest permissible voltage error in percent for a definite voltage and output range. These transformers are designed for a permanent overload of 20% above their rated primary voltage without exceeding the error or heating limits.

The voltage error or ratio error is the deviation in percent of the secondary terminal voltage from its desired value. The voltage error is termed as positive if the actual value of the secondary voltage exceeds the desired value.

The phase angle error is the displacement in phase angle of the secondary terminal voltage against the primary terminal voltage. The reference angles are so assumed that the displacement is zero degrees (not 180 degrees) for zero error in the transformer. The angle error is expressed in minutes and taken to be positive with a leading secondary voltage vector.

With single pole insulated earth voltage transformers one end of primary winding is connected to earth. The casing of the PT is to be earthed by means of earthing screw usually provided for that purpose. PTs use mineral oil as an insulating medium and are completely sealed off from the ambient air.

Fog-type ceramic insulator bushings with several sheds render the surface insensitive to dirt. As an anti-corrosive measure all the outer steel parts are galvanized. The voltage transformers are provided with an adjustable spark gap.

Single-pole insulated PT must always be connected between phase and earth. Only the high voltage side of the transformer primary winding is insulated for the full test voltage. The earth potential side of the winding is merely insulated against the secondary winding.

For this form of stepped insulation the primary winding is built up as a layer winding with intermediate metallic screens and other means of voltage control. The comparatively high partial capacitances of the layer winding in conjunction with the potential-controlling metallic screening ensure good capacitive coupling of layers and an even voltage distribution over the entire primary winding. This prevents excessive stressing on any part of the winding by incoming transients or by switching surges.

For 132 kV the rated primary voltage is $132/\sqrt{3}$ kV and the rated secondary voltage is $110/\sqrt{3}$ volts and the burden is 100 VA. The rated voltage factor is 15 for 30 seconds.

The accuracy is specified as under:

With burden varying between 25% to 100% of rated burden

<table>
<thead>
<tr>
<th>Ratio error</th>
<th>Phase angle error</th>
</tr>
</thead>
</table>
a) Primary voltage varying from +1% to 110% voltage

b) 5% to 90% of rated voltage ± 3% ± 120 minute

The rated secondary voltage of 25 kV PTs is 100 and the rated burden is 30 VA. For protection type the rated secondary voltage is 110 and the rated burden is 100 VA.

Class of insulation is F class i.e. glass fiber bonded with epoxy resin. The resistance of primary winding has been specified as not less than 27000 ohms for line indication type to eliminate the ferro-resonance effect. The accuracy is specified as under

<table>
<thead>
<tr>
<th>Indication type PTs</th>
<th>Voltage error</th>
<th>Phase angle error</th>
</tr>
</thead>
<tbody>
<tr>
<td>With burden varying from 25% and 100% at power factor 0.8 lag and voltage between 5% and 120% of rated voltage</td>
<td>± 6%</td>
<td>± 240 minute</td>
</tr>
</tbody>
</table>

**Protection type PT** conform to accuracy class 3P of IS-3156.

<table>
<thead>
<tr>
<th>Burden varying between 25% and 100% &amp; pf 0.8 lag</th>
<th>Voltage between 80% and 120%</th>
<th>Voltage between 5% and 120%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage error</td>
<td>± 1%</td>
<td>±3%</td>
</tr>
<tr>
<td>Phase angle error</td>
<td>± 40 minute</td>
<td>± 120 minute</td>
</tr>
</tbody>
</table>

**Ferro-resonance in PTs connected to OHE**

The PTs are connected between OHE and earth. The PTs on certain sections where the value of capacitance of OHE to earth, which is a function of earth conductivity and the mutual inductances of OHE which is in turn depends on the length and number of overhead lines in parallel, are subject to a resonance phenomena called ferro-resonance. The frequency of the oscillation is a sub-harmonic frequency at $16\frac{2}{3}$ Hz. It has been found that the rms voltage of the oscillations can reach and rise beyond 25 kV, when the current in the primary winding which is normally about 10 mA can rise to 800 mA. The insulating material gets heated and is destroyed within a very short time of about 10 minutes. When the voltage is re-applied to the OHE, arcing takes place inside the transformer, causing destruction.

To avoid this phenomenon the primary winding resistance is increased, as a high resistance in an oscillating circuit dampens the oscillation due to its consumption of active power.

2.9.6 **Characteristic features of current transformers**
Current transformers supply a measuring current which is as closely as possible in phase with the operating current and proportional to it. They are therefore designed to have an accurate transformation ratio and their output rating is not restricted by consideration of heating effects but by the requirements of measurement accuracy. They must however be able to withstand the short circuit currents, (unavoidable in traction system) without harmful effects on their performance.

Allowances must be made for the differing requirements of instruments, relays and other equipment connected, which have to be met by the transformer as far as output, accuracy and over current characteristics are concerned. For this purpose multi core versions are available where the secondaries are electrically separate from each other and individual core sections do not influence each other magnetically.

The rated primary and secondary currents are specified. The standardized values of secondary current are one ampere and five amperes. The nominal transformation ratio is the ratio of the rated primary current to rated secondary current. Rated burden is the product of rated impedance and the square of rated secondary current at a power factor of 0.8 inductive. Standardized values of burden are 5, 10, 30 and 60 VA. Current transformers are designed to operate continuously at 120% rated current, and should be able to carry a load of 150% of the rated current for 15 minutes.

The ratio error is the percentage deviation of the secondary current from its nominal value as calculated by dividing the rated primary current by the rated transformation ratio. The error is taken as positive if the actual value exceeds the nominal value.

The phase difference is the difference of phase between the primary and the reversed secondary currents i.e. the reference vectors being chosen so that the phase angle is 0 degree (not 180 degree) for a transformer without phase angle error. The angle is given in minutes and taken to be positive when the reversed secondary current leads.

The accuracy is denoted by a class number which indicates the maximum permissible ratio error as a percentage of the rated current. The rated short circuit current is the current of the primary, whose heating effect the CT with secondary short circuited can withstand for one second without suffering damage, instantaneous short circuit current is the maximum amplitude of the first current cycle in kA whose mechanical force a CT with short circuited secondary can withstand without suffering damage. In single turn CT the internal dynamic strength is practically unlimited.

The sealed tank CT uses mineral oil as insulating medium and is completely sealed off from the ambient air. The bushings are provided with adjustable spark gaps.

Each of the transformer cores, which are arranged vertically side by side has its own secondary winding. The primary winding is common to all cores. Cores are built from high permeable sheet
steel laminations to achieve a low magnetizing current and hence a low error margin of the transformer.

For the CTs in traction application the rated secondary burden is 30 VA, class of insulation being A, accuracy class 5P and accuracy limit factor 15. Other details are as under

<table>
<thead>
<tr>
<th>Nominal system voltage</th>
<th>Transformation</th>
<th>Short time current rating (thermal) for one second in kA</th>
<th>Short time current rating dynamic kA</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>200-100/5</td>
<td>31.5</td>
<td>78.75</td>
</tr>
<tr>
<td>132</td>
<td>400-200/5</td>
<td>25.0</td>
<td>62.5</td>
</tr>
<tr>
<td>110</td>
<td>400-200/5</td>
<td>31.5</td>
<td>78.75</td>
</tr>
<tr>
<td>66</td>
<td>800-400/5</td>
<td>31.5</td>
<td>78.75</td>
</tr>
</tbody>
</table>

The CT shall have a single core with wound primary. The primary is split into two sections insulated from each other. Transformation ratio is changed into series or parallel configuration. Facilities for short-circuiting the secondary terminal are provided on the terminal box, whereas the standard system insulation level is provided on the primary. High voltage power frequency withstand test on secondary is specified at 3 kV (rms) for one minute.

2.9.7 Specification for booster transformers

1. Need for booster transformers

Wherever the induced voltages in the neighbouring line side telecommunication circuits due to single-phase a.c. traction cannot be reduced by various available measures to be within the permissible limits, it might be necessary to take measures to suppress the induction at source. It has been the experience that considerable reduction in interference can be obtained by using the booster transformers. These transformers have a ratio of 1:1 with the primary winding connected in series with the contact wire and the secondary in series either with the rails or with an auxiliary return conductor. The disadvantage of the rail connected booster system is that a considerable voltage can exist across the insulated rail joints across which booster transformer secondary windings are connected which is not safe for maintenance staff working on the track. Further the reduction of induced voltages at higher frequencies is less and this method is not entirely satisfactory for the elimination of noise due to harmonics.

2. Booster transformers with return conductors

In the booster system with return conductors the secondary windings are connected in series with the return conductor strung as close to contact wire as permissible. The return conductor in turn
is connected to the rails midway between booster transformers. The return current flows almost entirely in the return conductor and very little current flows in the rails or earth except in the sections where load is being taken. As the return conductor is strung close to the contact wire, the disturbing loop formed by the traction and return currents is therefore of small width.

3. Since the primary winding is connected in series with the OHE, boosters are subjected to frequent and heavy short circuits due to transient faults. This may occur 150 times a month with short circuit current touching 4000 A.

4. Rating and other particulars

The salient particulars of booster transformers of different ratings which are in use are as under:

<table>
<thead>
<tr>
<th></th>
<th>Nominal rating</th>
<th>100 kVA</th>
<th>150 kVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>Nominal rating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>b)</td>
<td>Rated current</td>
<td>300 A</td>
<td>366 A</td>
</tr>
<tr>
<td></td>
<td>and voltage</td>
<td>336 V</td>
<td>409 V</td>
</tr>
<tr>
<td>c)</td>
<td>Overload rating</td>
<td>450 A</td>
<td>550 A</td>
</tr>
<tr>
<td></td>
<td>(15 minute)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>d)</td>
<td>Impedance at full load at 75°C</td>
<td>0.15 Ohm</td>
<td>0.15 Ohm</td>
</tr>
<tr>
<td>e)</td>
<td>Guaranteed maximum load losses</td>
<td></td>
<td>160 W</td>
</tr>
<tr>
<td>f)</td>
<td>Guaranteed maximum load losses</td>
<td></td>
<td>3000 W</td>
</tr>
<tr>
<td>g)</td>
<td>Bushings</td>
<td>I 2 Nos 52 kv class on HV side</td>
<td>I 2 Nos 12 kV class on LV side</td>
</tr>
<tr>
<td>h)</td>
<td>Excitation current</td>
<td>1 A 336 V</td>
<td>1 A 409 V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9 A 785 V</td>
<td>9 A 785 V</td>
</tr>
</tbody>
</table>

The spacing of booster transformers is maintained at 2.66 km and the different types are used only to suit the anticipated load currents on different sections.

5. Design data
The impedance of all aluminium return conductor (19/3.99 mm with copper equivalent of 140 mm) is 0.42 \(\angle73^\circ\) Ohm/km. At the spacing of 2.66 km voltage drop on return conductor with a line current of 300 A is 0.42 x 2.66 x 300 = 336 volts and kVA rating becomes 336 x 300 = 100.8 or 100 kVA.

The temperature rise after full load operation followed by either of the overloads shall not exceed over an ambient of 45\(^\circ\)C.

- for winding 50\(^\circ\)C (by resistance method)
- for oil 45\(^\circ\)C (by thermometer)

6. Excitation current and harmonics

The excitation current at 50 Hz shall not exceed 2\% of load current in the primary winding for all loads upto 700 A. The harmonic content should be as low as possible to reduce inductive interference.

7. Excitation impedance

The exciting impedance at 800 Hz of 100 kVA booster transformer shall not be less than 450 Ohms. For this purpose, a sinusoidal voltage of 40 V 800 Hz super-imposed on a 50 Hz voltage which can be varied from 0 to 785 V should be applied to primary winding of the booster transformer. The exciting impedance of 150 kVA transformer under similar test conditions shall not be less than 1000 Ohm.

8. Winding insulation level

i) Rated voltage between winding and earth 25 7.2
ii) Rated power frequency one minute withstand or separate source withstand voltage, kV rms 95 20
iii) Rated lightning impulse withstand 250 60 (1.2/50 microsecond wave)
iv) Induced over voltage withstand, kV rms 3 3

The corresponding insulation levels of porcelain bushings are as under:

Rated voltage kV (rms) 52 12
One minute power frequency withstand voltage dry 105 35
Impulse withstand and 1.2 x 50 micro second full wave kV (peak)250 75
Total creepage path in air (min), mm 1040 240

The induced over voltage withstand test shall be conducted at 3000 V (rms), duration of test at full test voltage shall be 60 seconds for any test frequency upto and including twice the rated frequency. When the test frequency exceeds twice the rated frequency the duration of the test shall be 120 x rated frequency/test frequency in seconds, but not less than 15 seconds.
2.9.8 Auxiliary transformers

Auxiliary transformers fed from OHE supply, suitable for floor/pole mounting are used for deriving single phase 240V, 50 Hz power at switching stations and at other locations for meeting signalling and other station loads. They are usually rated at 5 kVA, 10 kVA, 25kVA, 50 kVA & 100 kVA. Auxiliary transformers installed at traction substations have higher ratings i.e. 100 kVA. Whereas the primary of the winding is connected to 25 kV and is fully insulated the other terminal of the winding is brought out through a 3.3 kV class bushing and connected to the tank externally through a link. The tank is connected to the earth.

Ratings and other particulars:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>i)</td>
<td>Rated output at all taps</td>
</tr>
<tr>
<td>ii)</td>
<td>Secondary voltage</td>
</tr>
<tr>
<td>iii)</td>
<td>Impedance voltage at rated current at 75°C</td>
</tr>
<tr>
<td>iv)</td>
<td>Taps</td>
</tr>
<tr>
<td>v)</td>
<td>Insulation level</td>
</tr>
<tr>
<td></td>
<td>25 kV end earthing end</td>
</tr>
</tbody>
</table>

a) One minute wet withstand | 80 kV, rms 16 kV, rms |
b) Impulse withstand 1.2/50 wave | 190 kVp 45 kVp |

The primary and secondary windings (which are of copper conductor) are both completely impregnated and cast under vacuum into moulds which process forms the insulation system of uniform glass fibre-epoxy laminate of highest electrical and mechanical quality into which the windings are embedded without any voids. Both primary and secondary windings are cast separately as one rigid tubular coil with no key between their co-axial arrangement which means no creepage path can form under even dusty or corroding ambient conditions. The windings do not absorb moisture and insulation.

Ratings and other particulars:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>i)</td>
<td>Rated output at all taps shall be 5kVA, 10 kVA, 25kVA, 50kVA &amp; 100 kVA.</td>
</tr>
<tr>
<td>v)</td>
<td>Insulation level : existing text may be replaced by following.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>Rated lighting impulse withstand voltage peak</td>
<td>190 kV peak</td>
</tr>
<tr>
<td>b)</td>
<td>Rated short duration power frequency withstand voltage</td>
<td>70kV rms</td>
</tr>
<tr>
<td>c)</td>
<td>Rated induced over voltage</td>
<td>80 kV rms</td>
</tr>
</tbody>
</table>
2.9.9 Salient features of interrupters

Interrupters are non-automatic circuit breakers i.e load switches capable of interrupting full load currents. They are able to close under fault conditions. The interrupting chamber with fixed and moving contacts of cupro-tungsten alloy is an insulating enclosure filled with either insulating oil SF-6 gas or alternately a vacuum chamber. If it is of SF-6 gas, the gas leakage shall not be more than 1% per annum of the initial filling. No condensation of SF-6 gas shall take place on internal insulating surfaces. Inside the interrupting chamber an absorbent absorbs products of decomposition of SF-6 gas and moisture if any. In case of a drop in the pressure of SF-6 gas the temperature compensated pressure switch actuates an audible alarm. If the drop in pressure continues the interrupter gets locked out in its open condition.

Ratings and other particulars:

i) Nominal system voltage 25 kV
ii) Equipment voltage class 52 kV
iii) Insulation level
   a) Power frequency withstand rms 1 minute 95 kV
   b) Impulse withstand (1.2/50 microsecond wave) 250 kV
iv) Current ratings
   a) Rated normal current 800 A
   b) Rated short circuit breaking current (for 3 seconds) 8 kA
   c) Rated short circuit making current 20 kA
v) Rated breaking capacity 220 MVA
   (calculated at a recovery voltage of 27.5 kV)
vi) Rated short time withstand current (for 3 second) 8 kA
vii) Rated operating sequence CO-15 sec-CO
viii) Total breaking time Not more than 80 ms
ix) Special electrical endurance tests
    (at a recovery voltage of not less 27.5 kV)

<table>
<thead>
<tr>
<th>Current</th>
<th>Test sequence</th>
<th>No. of operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>800 A</td>
<td>CO-3 mn</td>
<td>500</td>
</tr>
<tr>
<td>8000 A</td>
<td>C-3 mn</td>
<td>20</td>
</tr>
</tbody>
</table>

2.9.10 Lightning arrestors

1. Function of the lightning arrestor

Stations connected to overhead transmission lines are invariably exposed to over-voltages during thunder storms. The purpose of the lightning arrestor is to discharge these overvoltages to earth.
and thus prevent service interruptors and damage to station equipment. Lightning arrestors, therefore, serve primarily as protection for the equipment.

2. Nature of overvoltages

Overvoltages which appear in the network take the form of traveling waves, which in overhead lines, are propagated with a velocity approaching that of light, i.e. of the order of 300 m per microsecond. At any point along the line the wave will give rise to a voltage which at any given instant is directly proportional to the current corresponding to the charge which is passing the point at that instant. This approximate constant relationship between the voltage and current is termed the surge impedance of the line, and in the case of overhead lines, is of the order of 500 ohms. Should the wave be diverted to earth through a resistance which is considerably smaller than the surge impedance of the line e.g. a lightning arrester, the current through the latter will be almost twice as great as the traveling current in the line.

With the maximum number of thunder storm days per annum at around 85 one may reckon upto 15 or even more strokes per year per 100 km of line.

For a good arrester the spark over voltage at supply frequency should be as high as possible to minimize the risk of discharge due to earth faults and switching surges.

3. Location of lightning arrestors

The surge voltage to which substation equipment may be subjected to depends largely on the impulse levels of the system.

Inductive equipment such as transformers is particularly prone to damage by lightning surges.

The maximum current which an arrester has to discharge at a given position is determined by the impulse spark over level of the line to which it is connected.

 Arrestors for transformers, circuit breakers, etc. at power stations and substations must be installed as near as possible to the equipment which is to be protected (within 50 m). If the arrester is too distant, the terminal voltage of the equipment will become higher than the arrester’s limiting voltage due to wave reflection. Installation of one common arrester for two circuits imposes an undue burden on the arrester when abnormal voltages enter simultaneously from both circuits. Hence it is necessary to provide one arrester for each circuit in order to insure full protection against lightning.

4. Selection of voltage rating
To obtain maximum degree of protection the lightning arrestor should have a voltage rating near to, but not less than, the highest power frequency line to earth voltage which may occur at the particular location. An arrestor rated at a lower voltage should not be applied, should it spark over while subjected to a power frequency voltage higher than its rated voltage it might be damaged within a few cycles by the follow current. The voltage rating of lightning arrestor depends on the insulation level of the system. Necessary insulation co-ordination must be established between the insulation strength of the electrical apparatus and the characteristics of the lightning arrestors.

5. Type of Lightning arrestors

Metal oxide gapless type lightning arrestors are presently used in preference to conventional lightning arrestors with gaps. The metal oxide gapless lightning arrestor, comprises of a number of non-linear resistor blocks housed inside a porcelain housing. Suitable provision is made to arrest the relative movement of blocks inside the housing and it is hermetically sealed to prevent moisture ingress. The arrestor is provided with pressure relief device for relieving internal pressure to prevent explosive shattering of the housing.

2.9.11 Relevant Specifications of various equipments

A list of relevant specifications for various equipments and devices for power supply installations and remote control equipment of 25 kV ac traction and those pertaining to 2 x 25 kV ac traction as issued by the Railways (RDSO) together with approximate BS or other international specifications is placed Annexure 2.9.1.
Annexure 2.9.1

LIST OF SPECIFICATIONS OF MAJOR EQUIPMENTS USED IN TRACTION POWER SUPPLY INSTALLATIONS

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<td></td>
</tr>
<tr>
<td>14.9</td>
<td>25 kV double pole SF-6 gas circuit breakers for 2*25 kV AT feeding system ETI/PSI/131</td>
<td>(8/89), 1, 2 (8/91)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IEC: 56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.10</td>
<td>25 kV double pole outdoor vacuum interruptors for Railway switching stations for 2 * 25 kV AT feeding system ETI/PSI/132</td>
<td>(8/89) &amp; 1.2 (8/91)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IEC.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.11</td>
<td>25 kV double pole isolator for 2*25 kV AT feeding system ETI/PSI/133</td>
<td>(8/89) &amp; 1, 2 (10/91)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IEC.9921 Part 1,2,3 and 4 IEC 129</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.12</td>
<td>25 kV potential transformer for ETI/PSI/134</td>
<td>(8/89)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td>Reference</td>
<td>Standard</td>
</tr>
<tr>
<td>---</td>
<td>-----------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>14.13</td>
<td>AT boost up current ratio type fault locator for OHE for 2*25 kV AT feeding system</td>
<td>ETI/PSI/135 (8/89) &amp; 1(1/90)</td>
<td>IEC.255-3</td>
</tr>
<tr>
<td>14.14</td>
<td>Automatic high speed reclosing relay</td>
<td>ETI/PSI/136 (8/89)</td>
<td>IEC 255-3, IEC 2500</td>
</tr>
<tr>
<td>14.15</td>
<td>Control and relay board for 2*25 kV AT feeding system</td>
<td>ETI/PSI/138 (8/89), 1(10/91)</td>
<td>IS 3231 (Electric Relays), IS 8686 (Static Relays)</td>
</tr>
<tr>
<td>14.16</td>
<td>25kV double pole outdoor SF-6 interruptors for 2*25 kV AT feeding system</td>
<td>ETI/PSI/139 (8/89) &amp; 1,2 (8/91)</td>
<td></td>
</tr>
<tr>
<td>14.17</td>
<td>25 kV current transformer with ratio 100-50/5 for shunt capacitor banks in 2 x 25 kV AT feeding system</td>
<td>ETI/PSI/147 (3/92), 1(9/92)</td>
<td></td>
</tr>
<tr>
<td>14.18</td>
<td>Harmonic analyzer</td>
<td>ETI/PSI/PSS/LAB/146(11/91)</td>
<td></td>
</tr>
<tr>
<td>14.19</td>
<td>Microprocessor (80486) for PSS Lab</td>
<td>PSS/LAB/142(8/90)</td>
<td></td>
</tr>
<tr>
<td>14.20</td>
<td>11 kV CT with ratio 500/5 for 2 x 25 kV AT feeding system</td>
<td>ETI/PSI/145(3/92), 1(9/92)</td>
<td></td>
</tr>
<tr>
<td>14.21</td>
<td>Technical Specification for Automatic Battery Charger for 110 V, 40 Ah, Lead Acid Battery</td>
<td>ETI/PSI/149(1/93)</td>
<td></td>
</tr>
</tbody>
</table>
Appendix 1

CODE OF PRACTICE
FOR EARTHING OF POWER SUPPLY INSTALLATIONS
FOR 25 kV, ac, 50 Hz, SINGLE PHASE TRACTION SYSTEM

(This is a reproduction of RDSO’s Code No.ETI/PSI/120)

1. Scope

1.1 This code of practice caters for general arrangements of system and equipment earthing at 220/25 kV or 132/25 kV or 110/25 kV or 66/25 kV traction substations, 25 kV switching stations, booster transformer stations and auxiliary transformer stations. Low voltage (LT) electrical power distribution system, 25 kV overhead equipment system as well as signal and tele-communication equipment do not come within the purview of this code.

2. Terminology

2.0 The following terms wherever occurring in this code shall, unless excluded or repugnant to the context, have the meaning attributed thereto as follows:-

2.1 Combined Earth Resistance: The resistance of an earth electrode(s) with respect to earth, with the earth electrode(s) connected to the metal work of electrical equipment other than parts which are normally live or carry current and the mast/structures but without connection with the traction rail(s).

2.2 Earth: The conductive mass of the earth, whose electrical potential at any point is conventionally taken as zero.

2.3 Earth electrode: A conductor (mild steel(MS) pipe) or group of conductors in intimate contact with and providing an electrical connection to earth.

2.4 Earthing grid: A system of a number of interconnected, horizontal bare conductors buried in the earth, providing a common ground for electrical devices and metallic structures, usually in one specific location.

2.5 Equipment earthing: Earthing of all metal work of electrical equipment other than parts which are normally live or current carrying. This is done to ensure effective operation of the protective gear in the event of leakage through such metal work, the potential of which with respect to neighbouring objects may attain a value which would cause danger to life or risk of fire.
2.6 Mesh Voltage ($E_{mesh}$): The maximum touch voltage to be found within a mesh of an earthing grid.

2.7 Power supply installation: The electrical equipments and associated structures provided at a Railway Traction Substation or Switching Station, or Booster/Auxiliary transformer Station on the 25 kV overhead equipment.

2.8 System earthing: Earthing done to limit the potential of live conductors with respect to earth to values which the insulation of the system is designed to withstand and thus to ensure the security of the system.

2.9 Step Voltage ($E_{step}$): The potential difference between two points on the earth’s surface separated by distance of one pace, that will be assumed to be one metre in the direction of maximum potential gradient.

2.10 Traction Rail means a non-track circuited rail of a wired track, not required for signaling purposes and which may be earthed. In non-track circuited sections, both the rails of a wired track are traction rails and in single rail track circuited sections, the traction rail is the non-track circuited rail.

2.11 Touch Voltage ($E_{touch}$): The potential difference between a grounded metallic structure and a point on the earth’s surface separated by a distance equal to the normal maximum horizontal reach of a person, approximately one metre.

3. Object of Earthing

The object of an earthing system is to provide as nearly as possible a surface under and around a station which shall be at a uniform potential and as nearly zero or absolute earth potential as possible. The purpose is to ensure that generally all parts of the equipment, other than live parts are at earth potential and that attending personnel are at earth potential at all times. Also by providing such an earth surface of uniform potential under and surrounding the station, there can exist no difference of potential in a short distance big enough to shock or injure an attendant when short circuits or other abnormal occurrences takes place. The primary requirements of a good earthing system are:

a) It should stabilize circuit potentials with respect to ground and limit the overall potential rise.

b) It should protect men and materials from injury or damage due to over voltage.

c) It should provide low impedance path to fault current to ensure prompt and consistent operation of protective devices during ground faults.

d) It should keep the maximum voltage gradient along the surface inside and around the substation within safe limits during earth faults.
4. **Governing Specifications**

Assistance has been taken from the following standards/codes of practices in the preparation of this code of practice:

i) IS:3043, 1987: Code of Practice for Earthing (first revision)

ii) Indian Electricity Rules, 1956 (latest edition)

iii) National Electrical Code, 1985: Bureau of Indian Standards


5. **Earth Resistance**

At each power supply installation, an earthing system as specified in this Code shall be provided. The combined resistance of the earthing system shall be not more than the following values:-

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Name of the station</th>
<th>The limit of combined earth resistance in Ohm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Traction substation</td>
<td>0.5</td>
</tr>
<tr>
<td>2.</td>
<td>Switching station</td>
<td>2.0</td>
</tr>
<tr>
<td>3.</td>
<td>Booster transformer station</td>
<td>10.0</td>
</tr>
<tr>
<td>4.</td>
<td>Auxiliary transformer station</td>
<td>10.0</td>
</tr>
</tbody>
</table>

6. **Earth Electrodes**

6.1 The earth electrode shall normally be of mild steel galvanized perforated pipe of not less than 40 mm nominal bore, of about 4 m length provided with a spike at one end and welded lug suitable for taking directly MS flat of required size at the other end. The pipe shall be embedded as far as possible vertically into the ground, except when hard rock is encountered, where it may be buried inclined to the vertical, the inclination being limited to 30 degree from the vertical. The connection of MS flat to each electrode shall be made through MS links by bolted joints to enable isolation of the electrode for testing purposes. A sketch for typical arrangement of an electrode is shown in Fig.2A.1.1.

6.2 Earth electrodes shall be embedded as far apart as possible from each other. Mutual separation between them shall usually be not less than 6.0 m (which is twice the length of the electrode).

6.3 If the value of earth resistance specified in clause 5 can not be achieved with a reasonable number of electrodes connected in parallel such as in rocky soil or soil of high resistivity, the earth surrounding the electrodes shall be chemically treated. The earth electrode shall be surrounded in an earth-pit by alternate layers of finely divided coke, crushed coal or charcoal and salt at least 150 mm all-round.
Though substantial reduction in earth resistance can be achieved by coke treated electrode, yet as this method results in rapid corrosion not only of electrode but also of steel framework to which it is bonded, coke treatment shall be used only where absolutely necessary and such electrodes shall not be situated within 6.0 m of other metal work.

6.4 In high embankments, it may be difficult to achieve earth resistance specified in clause 5 even after chemical treatment of electrodes. In those locations, use of electrodes longer than 4 m so as to reach the parent soil is recommended.

6.5 As far as possible, earth electrodes for traction sub-stations/switching stations shall be installed within and adjacent to perimeter fence. At large sites, apart from securing a sufficiently low resistance and adequate current carrying capacity a reasonable distribution of electrodes is also necessary.

7. Earthing Arrangement at Traction Substation

7.1 Earthing grid:

7.1.1 An earthing grid is formed by means of bare mild steel rod of appropriate size as indicated in clause 7.1.2 buried at a depth of about 600 mm below the ground level and connected to earth electrodes. The connection between the earth electrode and the grid shall be by means of two separate and distinct connections made with 75 mm x 8 mm MS flat. The connection between the MS flat and the MS rod shall be made by welding, while that between the earth electrode and the MS flats through MS links by bolted joints. The earth electrodes shall be provided at the outer periphery of the grid as shown in Fig.2A.1.2. As far as possible the earthing grid conductors shall not pass through the foundation block of the equipments. All crossings between longitudinal conductors and transverse conductors shall be jointed by welding. The transverse and longitudinal conductors of the earthing grid shall be suitably spaced so as to keep the step and touch potentials within acceptable limits; the overall length of the earthing grid conductors shall not be less than the calculated length (refer Annexure 1).

7.1.2 The size of the earthing grid conductor shall be decided based on the incoming system voltage and fault level (refer Annexure 1). The fault level considered shall take into account the anticipated increase in fault current during the life span of the station. The size shall be as given below:

<table>
<thead>
<tr>
<th>S.No.</th>
<th>System Voltage kV</th>
<th>Fault level MVA</th>
<th>Diameter of the grid conductor (MS rod) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>66</td>
<td>Upto 4000</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Above 4000 upto 5000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Above 5000 upto 6000</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>Upto 6000</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Above 6000 upto 8000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Above 8000 upto 10000</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>132</td>
<td>Upto 7000</td>
<td>32</td>
</tr>
</tbody>
</table>
7.2  Buried rail

7.2.1  A steel rail of section 52 kg/m (the one used for the railway track) and length about 13 m shall be buried near the track at the traction substation at a depth of about one metre to form part of the earthing system. Two separate and distinct connections shall be made by means of 75 mm x 8 mm MS flat between the earthing grid and the buried rail. The buried rail shall also be connected by means of two separate and distinct connections made of 75 mm x 8 mm MS flat to the rail(s) in a single-rail track circuited section and to the neutral point(s) of the impedance bond(s) in a double-rail track circulated section.

7.2.2  In cases where the feeding post is located separately away from the traction substation, the buried rail shall be provided at the feeding post (where one terminal of the secondary winding of the traction power transformer of the substation is grounded).

7.3  System earthing

7.3.1  One terminal of the secondary winding (25 kV winding) of each traction power transformer shall be earthed directly by connecting it to the earthing grid by means of one 75 mm x 8 mm MS flat, and to the buried rail by means of another 75mm x 8 mm MS flat.

7.3.2  One designated terminal of the secondary of each potential, current and auxiliary transformer shall be connected to the earthing grid by means of two separate and distinct earth connections made with 50 mm x 6 mm MS flat.

7.4  Equipment earthing

The metallic frame work of all outdoor equipments such as transformers, circuit breakers, interrupters and isolators, as well as steel structures shall be connected to the earthing grid by means of two separate and distinct connections made with MS flat of size as indicated below; one connection shall be made with the nearest longitudinal conductor, while the other shall be made to the nearest transverse conductor of the grid:

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Equipment</th>
<th>System voltage and fault level conductor</th>
<th>Ground conductor size</th>
</tr>
</thead>
</table>
| 1    | Equipments on the primary side of traction power transformer | 66 kV, upto 3000 MVA  
110 kV, upto 5000 MVA  
132 kV, upto 6000 MVA  
220 kV, upto 10000 MVA | 50 mm x 6 mm |
<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>66 kV, above 3000 upto 6000 MVA</td>
<td>75 mm x 8 mm</td>
<td></td>
</tr>
<tr>
<td>110 kV, above 5000 upto 10000 MVA</td>
<td>75 mm x 8 mm</td>
<td></td>
</tr>
<tr>
<td>132 kV, above 6000 upto 12000 MVA</td>
<td>75 mm x 8 mm</td>
<td></td>
</tr>
<tr>
<td>220 kV, above 10000 upto 20000 MVA</td>
<td>75 mm x 8 mm</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Equipments on the secondary side of traction power transformer</td>
<td>50 mm x 6 mm</td>
</tr>
<tr>
<td>3</td>
<td>Fencing uprights steel structures</td>
<td>50 mm x 6 mm</td>
</tr>
<tr>
<td>4</td>
<td>Doors/fencing panels</td>
<td>6 SWG G.I. Wire</td>
</tr>
</tbody>
</table>

### 7.5 Earthing inside control room

An earthing ring shall be provided inside the control room by means of 50 mm x 6 mm MS flat which shall be run along the wall on teak wood blocks fixed to the wall at a height of about 300 mm from the floor level. The earthing ring shall be connected to the main earthing grid by means of two separate and distinct connections made with 50 mm x 6 mm MS flat. The earthing ring shall also be connected to an independent earth electrode by means of two separate and distinct connections made with 50 mm x 6 mm MS flat. The metallic framework of control and relay panels, LT ac and dc distribution boards, battery chargers, remote control equipment cabinets and such other equipments shall be connected to the earthing ring by means of two separate and distinct connections made with 8 SWG galvanized steel wire. The connections shall be taken along the wall and in recess in the floor. All recesses shall be covered with cement plaster after finishing the work. Connections between the MS flats shall be made by welding.

### 7.6 Earthing of lightning arrester

In addition to the earth electrodes provided for the main earthing grid an independent earth electrode shall be provided for each lightning arrester. This earth electrode shall be connected to the ground terminal of the lightning arrester as well as to the main earthing grid by means of two separate and distinct connections made with 50 mm x 6 mm MS flat for the 25 kV side lightning arrestors, and with 75 mm x 8 mm MS flat for the primary side lightning arrestors. The earth electrode shall be provided as close as possible to the lightning arrester and the connections shall be as short and straight as possible avoiding unnecessary bends. For lightning arrestors provided for the traction power transformers, there shall also be a connection as direct as possible from the ground terminal of the lightning arrester to the frame of the transformer being protected; this connection shall also be made by means of two separate and distinct connections made with 50 mm x 6 mm MS flat for 25 kV side arrestors, and with 75 mm x 8 mm MS flat for primary side lightning arrester.

### 7.7 Earth screen
The area covered by outdoor substation equipments shall be shielded against direct strokes of lightning by an overhead earth screen comprising 19/2.5 mm galvanized steel stranded wire strung across the pinnacles of the metallic structures. The earth screen wires shall be strung at a height as indicated in the approved traction substation layouts (not less than 2.5 m above the live conductors) and shall be solidly connected to the traction substation earthing grid at each termination by means of 50 mm x 6 mm MS flat.

7.8 Earthing of fencing uprights and panels

Each metallic fencing upright shall be connected to the traction substation main earthing grid by means of two separate and distinct connections made with 50 mm x 6 mm MS flat. In addition, all the metallic fencing panels shall be connected to the uprights by means of two separate and distinct connections made with 6 SWG G.I. wire. All the metallic door panels shall also be connected to the supporting uprights by means of two separate and distinct connections made with 6 SWG G.I. wire.

7.9 Earthing at the point of 240 V ac 50 Hz supply for oil filtration plant.

The 240 V ac 50 Hz distribution board for power supply to oil filtration plant shall be connected to the main earthing grid by means of two separate and distinct connections made with 50 mm x 6 mm MS flat.

8. Earthing Arrangement at Switching Station

8.1 A minimum number of three earth electrodes (excluding the one to be provided separately for the remote control cubicle earthing - refer clause 8.4) shall be provided by each switching station, and they shall be interconnected by means of 50 mm x 6 mm MS flat forming a closed loop main earthing ring. This ring shall be connected by two separate and distinct connections made with 50 mm x 6 mm MS flat, to the traction rail in a single-rail track circuited section and to the neutral point of the impedance bond in a double-rail track circuited section of the nearest track, so as to limit the potential gradient developing in the vicinity of the switching station in the event of fault.

8.2 System earthing

One designated terminal of the secondary of each potential, current and auxiliary transformer shall be connected to the main earthing ring by means of two separate and distinct connections made with 50 mm x 6 mm MS flat.

8.3 Equipment earthing

8.3.1 All masts, structures, fencing uprights, and all outdoor equipment pedestals including auxiliary transformer tank shall be connected to the earthing ring by means of two separate and distinct connections made with 50 mm x 6 mm MS flat. All fencing panels shall be connected to the supporting uprights by means of two separate and distinct connections made with 6 SWG G.I. wire. All the metallic door panels shall be connected to the supporting uprights by means of two separate and distinct connections made with 6 SWG G.I. Wire.
8.3.2 The metal casing of potential and current transformers shall be connected to the mast/structures by means of two separate and distinct connections made with 50 mm x 6 mm MS flat.

8.3.3 The ground terminal of lightning arrester shall be connected directly to the earth electrode by means of two separate and distinct connections made with 50 mm x 6 mm MS flat. The earth electrode shall be so placed that the earthing leads from the lightning arrester may be brought to the earth electrode by as short and straight a path as possible.

8.4 Earthing inside remote control cubicle

An earthing ring shall be provided inside the remote control cubicle by means of 50 mm x 6 mm MS flat; the earthing ring shall be run along the wall on teak wood blocks fixed to the wall at a height of 300 mm from the floor level. The earthing ring shall be connected to the main earthing ring as well as to an independent earth electrode by means of two separate and distinct connections made with 50 mm x 6 mm MS flat. The metal casing of LT ac and dc distribution board, battery chargers, terminal board, remote control equipment cabinets and other such equipments shall be connected to the earthing by means of two separate and distinct connections made with 8 SWG G.I. Wire. The connections shall be taken along the wall and in recesses in the floor. All recesses shall be covered with cement plaster after finishing the work. Connections of earth strips to each other shall be made by welding.

9. Earthing of Neutral of Local Power Supply System

At traction substations and switching stations where power supply at 415 V/240 V, ac, 50 Hz, is taken from the local supply authority and having neutral earth at some distant point in the premises of the supply authority, the neutral of such supply shall also be earthed by means of two separate and distinct connections made with 6 SWG G.I. Wire by connecting to an independent earth electrode.

10. Earthing Arrangement at Booster Transformer Station

10.1 The combined earth resistance of a booster transformer station shall be not more than 10 Ohm. Normally one earth electrode shall be sufficient for a booster transformer station. The earth electrode shall be connected to the lower end of each mast of the supporting gantry by means of two separate and distinct connections made with 50 mm x 6 mm MS flat. In addition each mast of the supporting gantry shall be connected by means of a 50 mm x 6 mm MS flat to the nearest traction rail or to the neutral point of the nearest impedance bond in a double rail track circuited section.

10.2 The booster transformer tank shall be connected to the masts of the supporting gantry by means of two separate and distinct connections made with 50 mm x 6 mm MS flat. These connections shall be as short and as straight as possible without unnecessary bends.

11. Earthing Arrangement at Auxiliary Transformer Station
11.1 The combined earth resistance at the auxiliary transformer station shall be not more than 10 Ohm. Normally one earth electrode is sufficient for an auxiliary transformer station. The earth electrode shall be connected to the mast on which the auxiliary transformer is mounted by means of two separate and distinct connections made with 50 mm x 6 mm MS flat. In addition the mast shall be connected to the nearest traction rail or to the neutral point of the nearest impedance bond in a double rail circuited section by means of a 50 mm x 6 mm MS flat.

11.2 The earthing terminal on the transformer tank shall be connected to the mast on which the transformer is mounted by means of two separate and distinct connections made with 50 mm x 6 mm MS flat. One terminal of the secondary winding of the auxiliary transformer shall be connected to the earthing terminal on the transformer tank and as well as to the mast by means of 50 mm x 6 mm MS flat. These connections shall be as short and straight as possible and avoiding unnecessary bends.

12. **Method of Jointing**

All the joints between the MS flats, MS rods or between MS flat and MS rod shall be made by welding only. No soldering shall be permitted. For protection against corrosion, all the welded joints shall be treated with red lead and afterwards thickly coated with bitumen compound.

13. **Painting of MS Flats**

For protection against corrosion, all the exposed surfaces of earthing connections (MS flats) above ground level shall be given all around two coats of painting to colour grass green, shade-218 of IS:5.

14. **Crushed Rock Surface Layer**

At the traction substations and switching stations, a surface layer of crushed rock shall be provided to a thickness of about 100 mm. If considered necessary from the point of view of containing the step and touch voltages within the acceptance limits, higher thicknesses may be provided depending on calculation based on site conditions.

15. **Step and Touch Voltages**

15.1 The formulae for calculating the tolerable touch and step voltages, estimated mesh and step voltages, earth resistance, earth potential rise, size of earthing grid conductor and length of buried grid conductor are given in Annexure I.

15.2 The design for earthing grid shall be done separately for each location depending on the conditions obtaining and those foreseen.

16. **Drawings**
The following drawings (latest versions) issued by RDSO in connection with this code may be used for reference.

i) Typical earthing of traction substation  
   ETI/PSI/224-1

ii) Typical return current connection of buried rail at traction substation  
    ETI/PSI/0212-1

iii) Typical earthing layout of subsectioning and paralleling station  
     ETI/PSI/201-1

iv) Typical earthing layout of sectioning and paralleling station  
    ETI/PSI/202-1

v) Typical earthing layout of booster transformer station  
   ETI/PSI/211-1

vi) Typical arrangement of an earth electrode at a traction substation  
    ETI/PSI/222-1

vii) Typical earthing arrangement for an auxiliary transformer station  
    ETI/PSI/708
Annexure 1

FORMULAE FOR CALCULATION OF EARTHING GRID BASED ON IEEE GUIDE FOR SAFETY IN ac SUBSTATION GROUNDING, No.ANSI/IEEE Std 80-1986

1.0 Tolerable touch and step voltage

1.1 \[ E_{touch} = \frac{0.116 \{1000 + 1.5 C_s (h_s, k) P_s\}}{\sqrt{t_s}} \] V (for 50 kg body)

1.2 \[ E_{touch} = \frac{0.116 \{1000 + 6 C_s (h_s, k) P_s\}}{\sqrt{t_s}} \] V (for 50 kg body)

where,

\[ C_s (h_s, k) = 1 \] for crushed rock having resistivity equal to that of soil. If crushed rock resistivity is higher than that of soil, reference may be made to Fig.2A.1.3 for obtaining the value of \( C_s \).

\( P \) = Resistivity of surface material (crushed rock) in Ohm-m.

\( P_s \) = Resistivity of earth in Ohm-m.

\( k \) = \[ \frac{P - P_s}{P + P_s} \]

\( t_s \) = Duration of shock current in seconds.

\( h_s \) = Thickness of the crushed rock surface layer in m.

2.0 Estimated mesh and step voltage

2.1 \[ E_{mesh} = P \times K_m \times K_i \times \frac{I_G}{L} \] V

2.2 \[ E_{step} = P \times K_s \times K_i \times \frac{I_G}{L} \] V

where,

\( K_i \) = Corrective factor for grid geometry, which accounts for the increase in current density in the grid extremities.

\[ = 0.656 \times 0.172 \times n \]

\( I_G \) = Average current per unit length of buried conductor in A/m.
\[ K_m = \frac{1}{2\pi} \left\{ \ln\left( \frac{D^2}{16hd} + \frac{(D + 2h)^2}{8Dd} - \frac{h}{4d} \right) + \frac{k_{ii}}{k_h} \ln\frac{8}{\pi} \left( \frac{2n - 1}{2n} \right) \right\} \]

\[ K_h = 1 \text{ for grids with earth electrodes along the perimeter, or for grids with earth electrodes in the grid corners, as well as both along the perimeter and throughout the grid area.} \]

\[ = \frac{1}{(2n)^{2/n}} \text{ for grids without earth electrodes or grids with only a few earth electrodes, none located in the corners or on the perimeter.} \]

\[ K_n = \sqrt{1 + h/h_o} \]

\[ K_s = \frac{1}{\pi} \left( \frac{1}{2h} + \frac{1}{D + h} + \frac{1}{D} \left( 1 - 0.5^{n-2} \right) \right) \text{ for values of } h \text{ between 0.25 and 2.5 m.} \]

\[ h_o = 1 \text{ m (reference depth of grid)} \]

\[ D = \text{ Spacing between parallel conductors of grid in m (same spacing in both directions)} \]

\[ n = \sqrt{n_A n_B} \text{ for calculating } E_{\text{mesh}} \]

\[ = n_A \text{ or } n_B, \text{ whichever is greater, for calculating } E_{\text{step}}. \]

\[ n_A = \text{ Number of parallel conductors of grid in transverse direction.} \]

\[ n_B = \text{ Number of parallel conductors of grid in longitudinal direction.} \]

\[ h = \text{ Depth of earthing grid conductors in m.} \]

\[ d = \text{ Diameter of earthing grid conductor in m.} \]

\[ L = \text{ Total length of earthing system conductor.} \]

\[ = \text{ } L_c + L_r \text{ for grids without earth electrodes or with only a few electrodes located within the grid but away from the perimeter.} \]

\[ = \text{ } L_c + 1.15 L_r \text{ for grids with earth electrodes along the perimeter.} \]

\[ L_c = \text{ Total grid conductor length in m.} \]

\[ L_r = \text{ Total earth electrode length in m.} \]

\[ P = \text{ Resistivity of earth in Ohm-m.} \]

\[ I_G = \text{ As defined in para 4.1 below.} \]

Note: The estimated values of mesh and step voltage should be less than the tolerable touch and step voltages respectively.

3.0 **Ground resistance**
3.1 \[ R_g = \frac{P}{4} \sqrt{\frac{\pi}{A_g} + \frac{P}{L}} \]

where,

\( L \) = Total length of buried conductors in m.
\( A_g \) = Area occupied by the earthing grid in m².
\( R_g \) = Station ground resistance in Ohm.
\( P \) = Resistivity of earth in Ohm-m.

4.0 **Ground Potential rise**

4.1 Ground potential rise = \( R_g \times I_g \)

where,

\( R_g \) = Station ground resistance in Ohm.
\( I_g \) = \( C_p \times D_f \times I_g \)
\( C_p \) = Corrective projection factor accounting for the relative increase of fault currents during the station life span; for a zero future system growth \( C_p = 1 \).
\( I_g \) = rms value of symmetrical grid fault in A.
\( D_f \) = Decrement factor for the entire duration of fault (to allow for the effects of asymmetry of the fault current wave).
\quad = 1.0 for fault current duration of 0.5 second or more.

5.0 **Size of earthing grid conductor**

5.1 \( A = \sqrt{t} / 80 \).

where,

\( A \) = Cross-sectional area of earthing grid conductor in mm².
\( I \) = rms value of fault current in A.
\( t \) = Duration of fault current in second (taken as one second).

Note: To allow for the effects of corrosion, the size of the grid conductor selected shall be such that its cross-section area is nearly twice that calculated above.

6.0 **Minimum length of buried grid conductor**
6.1 \[ L > \frac{K_m x K_i x P x l_G \sqrt{t_s}}{116 + 0.174 C_s (h_s, k) P_s} \] for \( E_{mesh} < E_{touch} \)

where,

\( L = \) Minimum length of buried grid conductor including earth electrodes in m.
\( = 0.5 \) second (assumed maximum duration of shock).
\( C_s (h_s, k), K_m, K_i, P, l_G \) and \( P_s \) have been defined earlier.
Annexure 2

SAMPLE CALCULATION FOR THE DESIGN OF EARTHING MAT FOR A 132/25 kV TRACTION SUBSTATION

1.0 Data assumed for calculation

Average earth resistivity of the soil, \( P = 40 \text{ Ohm-m} \)

Fault level at the incoming bus (i.e. 132 kV side) = 5000 MVA

Fault current on primary side, \( = \frac{5000 \times 10^3}{\sqrt{3} \times 132} = 21870 \text{ A} \)

Duration of fault, \( t = 3 \text{ second to determine the size of earthing mat conductor} \)

\( = 0.5 \text{ second for determining the safe step and mesh potential} \)

Resistance of the main earthing mat = 0.5 Ohm maximum

1.1 Size of the earthing mat conductor

\[
A = 12.15 \times 10^{-3} \times I_g \sqrt{t}
\]

\[
= 12.15 \times 10^{-3} \times 21870 \times \sqrt{3} = 460.23 \text{ mm}^2, \text{ say 460 mm}^2.
\]

1.2 Margin to cater for loss due to corrosion and rusting in the size of earthing mat conductor has been considered 100%.

Therefore, size of the earthing mat = 460 \( \times 2 = 920 \text{ mm}^2. \)

Size of the standard round rod near to 920 mm\(^2\) are is 36 mm dia rod (1018 mm\(^2\)). Therefore, 36 mm dia rod is proposed for the earthing mat conductor.

1.3 Approximate length of earthing mat conductor

Assuming \( L = \frac{K_m \times K_i \times P \times I_g \sqrt{t}}{116 + 0.17 P_s} \)

\( P = 40 \text{ Ohm-m} \)
\[ I_g = 21870 \text{ A} \]
\[ t = 0.5 \text{ Sec} \]
\[ P_s = 3000 \text{ Ohm-m} \]

Therefore,
\[
L = \frac{2.23 \times 40 \times 21870 \times \sqrt{0.5}}{116 + 0.17 \times 3000} = 2203 \text{ m, say 2200 m.}
\]

1.4 Tolerable touch potential:

\[
E_{\text{touch}} = (1000 + 1.5C_s(h_s, k)P_s) \times \frac{0.116}{\sqrt{t_s}} \text{ V.}
\]

Assuming,

\[
k = \frac{P - P_s}{P + P_s} = \frac{40 - 3000}{40 + 3000} = -0.9736
\]

\[ h_s = 10 \text{ cm} = 0.1 \text{ m} \]

\[ C_s = 0.59 \text{ (from Fig.2A.1.3)} \]

For the value of \( k = -0.9736 \) and \( h_s = 0.1 \), the value of \( C_s \) from fig.2A.1.3 = 0.55

Therefore \( E_{\text{touch}} = (1000 + 1.5 \times 0.55 \times 3000) \times \frac{0.116}{\sqrt{0.5}} \)

\[ = 575.85 \text{ V} \]

1.4.1 Estimated touch potential

\[
E_{\text{touch}} = \frac{P_xK_m x_k x_I G}{L} \text{ V}
\]

\[ = \frac{40 \times 2.23 \times 21870}{2200} = 886.7 \text{ V} \]

As estimated \( E_{\text{touch}} = 886.7 \text{ V} \) is more than the tolerable \( E_{\text{touch}} = 575.85 \text{ V} \), hence the length of earthing mat conductor is not adequate.

Therefore, the length of earthing mat conductor shall be increased to 3400 m to get.
Estimated $E_{\text{touch}}$ less than tolerable $E_{\text{touch}}$,

\[ E_{\text{touch}} = \frac{40 \times 2.23 \times 21870}{3400} = 573.76 \text{ Volt Say 574 V}. \]

Hence, length of 3400 m of earthing mat conductor is adequate.

1.5 Tolerable step potential,

\[ E_{\text{step}} = \left\{ 1000 + 6 C_s (h_s, k) P_s \right\} \times \frac{0.116}{\sqrt{t_s}} \text{ V}. \]

\[ = (1000 \times 6 \times 0.55 \times 3000) \times \frac{0.116}{\sqrt{0.5}} \]

\[ = (10900) \frac{0.116}{\sqrt{0.5}} = 1788.40 \text{ V} \]

1.5.1 Estimated step potential

\[ E_{\text{step}} = \frac{P x K_s x K_i x I_G}{L} \text{ V}. \]

Assuming,

\[ P = 40 \text{ Ohm-m} \]

\[ K_s = \frac{1}{\pi} \left\{ \frac{1}{2h} + \frac{1}{D + h} + \frac{1}{D} (1 - 0.5)^{n-2} \right\} \]

\[ = \frac{1}{\pi} \left\{ \frac{1}{2 \times 0.5} + \frac{1}{5 + 0.5} + \frac{1}{5} (1 - 0.5)^{345-2} \right\} = 0.376 \]

\[ k_i = 0.656 + 0.172N = 0.656 + 0.172 \times 23 = 4.612 \]

\[ I_G = 21870 \text{ A} \]

\[ L = 3400 \text{ m} \]

Therefore, \[ E_{\text{step}} = \frac{40 \times 0.376 \times 4.612 \times 21870}{3400} = 446.17 \text{ V} \]

Estimated step potential is less than tolerable step potential, hence, design of earthing mat is in order.

1.6 Ground resistance
Assuming, \( R_n = \frac{P}{4} \left( \frac{\pi}{A} + \frac{P}{L} \right) \)

\( P = 40 \text{ Ohm-m} \)
\( A = 105.0 \times 66.0 \text{ m}^2 = 6930.0 \text{ m}^2 \)
\( L = 3400 \text{ m} \)

Therefore, \( R_n = \frac{40}{4} \sqrt{\frac{\pi}{6930.0} + \frac{40}{3400}} \)

\( = \frac{40}{4} \times 0.0213 + \frac{40}{3400} = 0.2247 \text{ Ohm.} \)

1.7 Ground potential rise:

Ground potential rise = \( R_g \times I_G \)

Assuming, \( I_G = C_p \times D_f \times I_g \)
\( = 1.1 \times 1.0 \times 21870 = 24057 \text{ A} \)
\( R_g = 0.2247 \text{ Ohm} \)

Therefore, ground potential rise = \( 0.2247 \times 24057 = 5405.6 \text{ V} \)

1.8 Number of earth electrodes used in the earthing mat:

No. of earth electrodes at the perimeter = \( 23 \times 2 + 14 \times 2 = 74 \text{ Nos.} \)

Extra earth electrodes at the 4 corners of the earthing mat = \( 4 \times 4 = 16 \text{ Nos.} \)

Earth electrodes for Lightning Arrestors = \( 10 \times 2 = 20 \text{ Nos.} \)

Earth electrodes for transformer earthing = \( 2 \times 3 = 6 \text{ Nos.} \)

Control room earthing = 2 Nos.

Total earth electrodes = 102 Nos.

1.9 Total length of earthing mat conductor:

Longitudinal direction \( 105.0 \times 15 = 1575 \text{ m} \)

Transverse direction \( 66.0 \times 23 = 1518 \text{ m} \)
Earthing rod $102.0 \times 3 = 306$ m

Total length $= 3399$ m, say $= 3400$ m
TYPICAL ARRANGEMENT OF AN EARTH ELECTRODE

FIG. 2A.1.1

150 mm LONG
75 mm X 8 mm
M.S. FLAT WELDED

LID FOR EARTH
50 mm THICK
LAYER OF SAND

GROUND LEVEL

AREA TO BE WELL RAMMED

CUTLINE DELTAION IF REQUIRED

EARTHBOX
(RCC)

ALTERNATE EQUAL LAYERS OF SALT, CHARCOL OR COKE

EARTH ELECTRODE

12 mm DIAM HOLES
AT SIMILAR SPACING FOR ENTIRE LENGTH

50 mm THICK LAYER OF SAND

GROUNDLLEVEL

12 mm DIAM HOLES

100 mm X 10 mm
80 mm X 12 mm
205 mm X 8 mm
300 mm X 100 mm
60 mm X 2 mm

DETAILS OF EARTH ELECTRODE

SECTIONAL ELEVATION
EARTH MAT (MS ROD) FIG.2A.1.2

75mmX8mm MS FLATS FROM POWER TRANSFORMER SECONDARY WINDING TERMINAL

BURIED RAIL 75 mmX8 mm M.S.FLATS TO NON TRACKCIRCUITED RAIL NEUTRAL POINT OF IMPEDANCE BOND WELDED AT CROSSING

SPACING AS PER CALCULATION

BURIED GRID CONDUCTOR WITHIN 1.0 MERE OF FENCE
REDUCTION FACTOR $C_s$ AS A FUNCTION OF REFLECTION FACTOR $K$ AND CRUSHED ROCK LAYER THICKNESS $H_s$.  
FIG.2A.1.3