

Manual on Earthing of AC Power Systems



Editors

• Mata Prasad • Dr. J.K. Arora • Dr. H.R. Seedher • V.K. Kanjlia • P.P. Wahi



CENTRAL BOARD OF IRRIGATION & POWER

Malcha Marg, Chanakyapuri, New Delhi 110 021

Manual on

Earthing of AC Power Systems

Publication No. 311

Editors

Mata Prasad
Dr. J.K. Arora
Dr. H.R. Seedher
V.K. Kanjlia
P.P. Wahi

CENTRAL BOARD OF IRRIGATION & POWER

Malcha Marg, Chanakyapuri, New Delhi 110 021

2011

ISBN 81-7336-318-8

“Reproduction of any part of this publication in any form is permissible subject to proper acknowledgement and intimation to the publisher. The publisher / author / editors have taken utmost care to avoid errors in the publication. However, the publisher / author / editors are in no way responsible for the authenticity of data or information given in the book.”

CENTRAL BOARD OF IRRIGATION & POWER

Malcha Marg, Chanakyapuri, New Delhi 110 021, India

Phone : 011 - 2687 5017 / 2687 6567 Fax : 011 - 2611 6347

E-mail : cbip@cbip.org Web : www.cbip.org



A.S. BAKSHI
President, CBIP &
Chairperson, CEA

दूरभाष (का०) Telephone (O) : 011-26102583
टेलिफैक्स Telefax : 011-26109212
ई-मेल E-mail : chair@nic.in
अध्यक्ष तथा पदेन सचिव भारत सरकार
केन्द्रीय विद्युत प्राधिकरण
सेवा भवन, रामकृष्ण पुरम् नई दिल्ली - 110606
CHAIRPERSON & EX-OFFICIO SECRETARY
TO THE GOVERNMENT OF INDIA
CENTRAL ELECTRICITY AUTHORITY
SEWA BHAWAN, R.K. PURAM
NEW DELHI-110606

Foreword

Earthing systems are intended to protect electrical equipment and personnel involved with the equipment from the dangerous over-voltages and leakages. With the power systems becoming more and more complex, the fault levels in the system are going up. This has resulted in focusing greater attention to the design of earthing systems. Added to this, the technology developments over a period of time and better understanding of the various parameters is resulting in revision of earlier considerations and concepts.

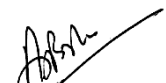


Central Board of Irrigation & Power (CBIP) has been playing a key role to disseminate the latest technological advancement information covering almost all aspects of power sector & renewable sector and it was in 2007, CBIP brought out detailed reference guide on Earthing Systems.

I understand that the manual issued by CBIP is being widely used by power engineers as a reference book in the country & elsewhere.

I am happy to note that this manual is being revised and updated now with the help of Expert Group members from all eminent organizations. This contains the latest technological information on the subject of earthing including earthing of GIS substation which is the upcoming field.

I congratulate CBIP and all experts of the Expert Group for bringing out this manual covering latest state-of-art technology and I am sure that this document will be of great benefit to the engineering fraternity as a reference book.


A.S. Bakshi

Preface



It is pertinent to mention that Earthing plays an important role in proper operation of generation, transmission and distribution systems. The function of earthing in an electric power system is to maintain the potential of current carrying as well as non-current carrying parts of equipment, apparatus and appliances connected to the system, and to ensure safety of equipment and personnel and correct operation of protective devices during earth faults. Earthing also provides safety during lightning strikes on equipments or structures and on occurrence of induced voltage and current on electric equipments of an electric system. Moreover, proper earthing system provides easy and shortest path to the flow of earth fault current without adversely affecting the continuity of service.

The efficacy of an earthing system depends on various factors like resistivity of general mass of earth in and around the area where earth grid is buried and also that of surface layer of soil, duration and magnitude of fault current and grid current, shock duration, the maximum safe current that a human body can tolerate and the permissible values of dangerous voltages that shall arise due to the flow of grid current. Earthing of fence is another issue of importance.

In line with our quality policy, to promote and coordinate professional excellence in water and power sector, CBIP has prepared several Manuals on all important subjects. To disseminate the latest developments among the professionals, CBIP has updated these manuals from time to time. The manual on 'Earthing of AC Power Systems' was firstly published in 2007. To incorporate the latest developments and facilitate the professional engineers associated in the field; this Manual has been updated now. In this edition a chapter on 'Earthing of GIS Substations' has also been added in order to cover the subject relating to this upcoming field

For preparing this manual, CBIP had constituted the Expert Group, comprising of highly experienced engineers from large power utilities, designs organisation, manufacturers etc., who have put in their knowledge and experience in bringing out this updated manual. This group was headed by Shri Mata Prasad, Former Executive Director, NTPC Ltd. and renowned expert in the Power sector who is recipient of many National and International awards.

The Central Board of Irrigation and Power wishes to acknowledge its grateful thanks to all the members of the Expert Group for their valuable contribution. Special thanks are due to Shri Mata Prasad, Chairman of the Expert Group for their active involvement and guidance in giving the final shape of this manual. Special thanks are due to Dr. J.K. Arora & Dr. Hans R. Seedher, Retired Professors Punjab Engineering College, who has put in his best efforts with his rich knowledge and experience in bringing out this updated manual.

We are sure that this manual would serve as a useful guide for the users.



V.K. Kanjlia

Secretary

Central Board of Irrigation & Power

New Delhi
September 2011

EXPERT GROUP ON EARTHING OF AC POWER SYSTEMS

Chairman

Shri Mata Prasad

Power System Consultant

5/100 Vinay Khand

Gomti Nagar, Lucknow – 226010

E-mail: matap6@gmail.com;

Members

Dr. J.K. Arora

Former Professor

P.E.C. Chandigarh

530, Sector 9

Panchkula - 134 113

E-mail : arorajk530@yahoo.com;

arorajk530@rediffmail.com;

Dr. Hans R. Seedher

Former Professor

P.E.C., Chandigarh

H No. 1025

Sector 42B

Chandigarh - 160036

E-mail : hseedher@yahoo.com;

Shri N.N. Misra

Director (Operations)

NTPC Ltd.,

SCOPE Complex, Lodhi Road

New Delhi 110003

E-mail : nnmisra@ntpceoc.co.in

Shri P.J. Thakkar

Director (Technical)

Rural Electrification Corporation

Core - 4, 4th Floor

Scope Complex, Lodi Road

New Delhi - 110 003

E-mail : thakkar_pj@yahoo.co.in

Shri Ravinder

Chief Engineer (SETD)

Central Electricity Authority

Sewa Bhawan, R.K. Puram

New Delhi - 110 066

E-mail: ravinders.only@gmail.com

Shri D.K. Sood

General Manager I/c

Simhadri Super Thermal Power Project,

P.O. NTPC – Simhadri,

Visakhapatnam 531 020 (A.P)

E-mail : dksood@ntpc.co.in;

Shri Atul Shrivastava

General Manager

Khargone Super Thermal Power Project

NTPC Ltd.

61, Maa Ganga Nagar

Sanawad Road, Khargone

Madhya Pradesh – 451 001

E-mail : atulshrivastava58@gmail.com;

Shri J.R. Chaudhary

Chief Engineer (Electrical)

NHPC Ltd.

NHPC Office Complex, Sector 33

Faridabad - 121 003

E-mail : jrchaudhary@nhpc.nic.in

Shri S.K. Ray Mohapatra

Director (Substation)

Central Electricity Authority

SETD Division, II Floor, Sewa Bhavan

R.K. Puram, New Delhi - 110 066

E-mail : skrmohapatra@rediffmail.com

Shri K.K. Sarkar

Chief Design Engineer

Power Grid Corpn. of India Ltd.

“Saudamani” Plot No. 2

Sector-29, Gurgaon - 122 001

E-mail : kksarkar@powergridindia.com;

Shri R.K. Gupta

Dy. Chief Design Engineer
Power Grid Corpn. of India Ltd.
“Saudamani” Plot No. 2
Sector-29, Gurgaon - 122 001
E-mail : rajendra@powergridindia.com

Shri Rajiv Krishnan

Vice President
Substation Automation Systems
(Technology)
ABB Ltd., Plot No. 5&6, Phase II,
Peenya Industrial Area,
Bangalore - 560 058
E-mail : rajiv.krishnan@in.abb.com;

Shri M.M. Babu Narayanan

Former Addl. Director
Central Power Research Institute
Prof. Sri C.V. Raman Road
Sadashiv Nagar PO, PB No. 8066
Bangalore - 560 080
E-mail : babu@powersearch.cpri.res.in

Shri Subodh K. Bhatnagar

Retd. S.E., RRVPNL
B-82, Flat No. 302
Rama Golden Cottage
Raman Marg, Tilak Nagar
Jaipur - 302 004
E-mail : subodhbhatnagar@yahoo.com;

Shri R.P. Nagar

Director
SSS Electricals (India) Pvt. Ltd.
AFCONS Group, Afcons House
16, Shah Industrial Estate
Veera Desai Road, Azad Nagar P.O.
Post Box No. 11978
Andheri (W), Mumbai - 400 053
E-mail : nagar@afconindia.com;

Shri Kalpesh Chauhan

ABB Global Industries and Services
Limited
Corporate R&D, Maneja
Vadodara – 390013
E-mail : kalpesh.chauhan@in.abb.com;

Shri Sanjoy Mukherjee

Senior Deputy Manager
CESC Ltd.
Testing Department
4, Sashi Sekhar Bose Row
Kolkata - 700 025
E-mail : sanjoy.mukherjee@rp-sg.in;

Shri Sonjib Banerjee

Director
SGI Engineers Pvt. Ltd.
252 B, Shanti Bhawan, Shahpurjat
Opp. Panchsheel Commercial Complex
New Delhi - 110049
Email: sonjib@sgihouse.com;

Shri M.P. Kulkarni

Former Managing and Technical Director
Ashida Electronics Pvt. Ltd.
Plot No. A-308, Road No. 21, Wagle
Estate
Thane (W), Maharashtra - 400 604
E-mail : ashida@vsnl.com
bhau_kulkarni@rediffmail.com;

Shri A. Singaiah

Dy. Chief Engineer (Electrical Engineer)
TCE Consulting Engineers Ltd.
Sheriff Centre 73/1 St. Marks Road
Bangalore - 560 001

Shri V.K. Kanjlia

Secretary
Central Board of Irrigation & Power
Malcha Marg, Chanakyapuri
New Delhi - 110 021
E-mail : kanjlia@cbip.org

Shri P.P. Wahi

Director
Central Board of Irrigation & Power
Malcha Marg, Chanakyapuri
New Delhi - 110 021
E-mail : wahi@cbip.org

CONTENTS

Foreword	(iii)
Preface	(v)
Chapter 1: Introduction	1-6
1.1 Introduction	1
1.2 Design & Engineering of Earthing Systems	2
1.3 Field Practices for Execution, Monitoring and Maintenance of Earthing Systems	4
1.4 Field Tests and Measurements	4
Chapter 2: Reference Standards and Definitions	7-12
2.1 Standards and CBIP Publications	7
2.2 CBIP Publications	8
2.3 Definitions	8
Chapter 3: Earthing Design : Parameters, Methodology, Criteria & Corrosion	13-44
3.1 Introduction	13
3.2 Design Parameters	14
3.3 Soil Resistivity	15
3.4 Dangerous Voltages	20
3.5 Earth Resistance of Earth Electrode, EPR and Dangerous Voltages	21
3.6 Safe Limits of Dangerous Voltages	22
3.7 Earth Fault Current and Related Parameters	27
3.8 Size of Earth Conductors	29
3.9 Material of Earth Conductors	33
3.10 Corrosion of Earth Conductors	33
3.11 Specific Considerations	37
3.12 Earthing of Station Fence	38

3.13 Summary	40
Chapter 4: Fault Current Distribution for Design of Earthing Systems	45-58
4.1 Introduction	45
4.2 Current for Design of Earth Conductor	46
4.3 The Maximum Grid Current	47
4.4 Current Division Factors S_f	58
4.5 Computational Methodology	52
4.6 Summary	57
Chapter 5: Design of Earthing System and Limitations of Method	59-74
5.1 Introduction	59
5.2 Simple Electrodes	59
5.3 Design of Earthing System in Uniform Soil	62
5.4 Limitations of Empirical Formulae	70
5.5 Summary	71
Chapter 6: Special Considerations for Earthing Design under Difficult Conditions	75-82
6.1 Introduction	75
6.2 Analytical Approach	76
6.3 Measures Related to Parameters of Earthing System	76
6.4 Other Measures	78
6.5 Extension of Earth Electrode	81
6.6 Summary	82
Chapter 7: Earthing of Electronic Equipment in Power Stations	83-90
7.1 Introduction	83
7.2 Functional Earthing	83
7.3 Noise Coupling Mechanism	84
7.4 Methods of Earthing of Electronic Equipment	58
7.5 Summary	89

Chapter 8: Execution, Field Practices, Monitoring and	
Maintenance of Earthing Systems	91-104
8.1 Execution of Earthing System	91
8.2 Measurements and Field Quality Checks	93
8.3 Field Practices and Techniques for Equipments	95
8.4 Monitoring and Maintenance of Earthing System	100
8.5 Safety Considerations during Excavations	103
8.6 Summary	104
Chapter 9: Measurement of Soil Resistivity and	
Interpretation of Results	105-122
9.1 Introduction	105
9.2 Measurement of Soil Resistivity	105
9.3 Interepratation of Measured Data	108
9.4 Measurements at a Site in Hilly Terrain	115
9.5 Accuracy of Earth Testers	116
9.6 Measurement of Resistivity of Gravel	117
9.7 Summary	119
Chapter 10: Field Measurement of Erected Earthing System	123-140
10.1 Introduction	123
10.2 Basic Techniques and Test Circuits	124
10.3 Test-Current-Reversal Method	129
10.4 Measurement of Earth Resistance	131
10.5 Measurement of Step and Touch Voltages	134
10.6 Miscellaneous Requirements / Considerations	135
10.7 Earthing Audit	138
10.8 Summary	139

Chapter 11: Typical Examples	141-192
11.1 Calculation of Earth Fault Current and Grid Current	141
11.2 Design of Grid Earth Electrode for a Station	148
11.3 Analysis of Grid Using Earthing Analysis Software	162
11.4 Single Layer Versus Two-Layer Soil	169
11.5 Earth Grid in High Resistivity Soil	171
11.6 Fence Earthing	179
11.7 Example - Interpretation of Soil Resistivity Measurements and Choice of Soil Model & its Impact on Design	187
11.8 Summary	191
Chapter 12: Earthing of GIS Substations	193-200
12.1 Introduction	193
12.2 Standard and CBIP Publications	194
12.4 Earthing Requirements of GIS	194
12.6 Implementation	198
12.7 Summary	199
Appendix A : Earth Electrode for Generating Stations	201
Appendix B : Preparation of Data for Program ‘gridi’ for Computation of Grid Current and Operation of Program	203
Appendix C : Preparation of Data for Program ‘SOIL_MODEL’ for Computation of Soil Model and Operation of Program	209
Appendix D : on CD	
(i) README for gridi	
(ii) Grid_Current software folder for determining grid current	
(iii) Read_Me_Soil_model for soil model	
(iv) Soil_model software folder for determining soil model	

CHAPTER -1

Introduction

Synopsis : This Chapter lists the objectives of various chapters of the manual.

1.1 INTRODUCTION

Earthing system is a vital part of all electric systems. A well designed earthing system is necessary to ensure safety of equipment and personnel, and correct operation of protective devices during (i) earth faults in electric systems, (ii) lightning strikes on equipment / structures, and (iii) occurrence of induced voltages and currents on equipments, conductors, cables, structures etc. of an electric system.

Basic objectives of earthing systems design are generally the same for all electric systems. The methodology for design, engineering, installation, testing, commissioning and maintenance of earthing systems varies with requirements of individual electric systems depending on their design parameters, layout, construction, operation, etc. Therefore, it is not possible to prepare a valuable document covering comprehensively all matters concerning earthing systems for all types of electric systems.

High Voltage Alternating Current (HVAC) Stations are major electric installations of the organizations/ enterprises responsible for generation, transmission and distribution systems of electricity in India. The existing national documents on earthing systems do not include comprehensive information on earthing system for HVAC stations. Application of the recommendations of standards, codes of practices, and publications of other countries presents numerous problems.

Over the years, the Central Board of Irrigation & Power (CBIP), India, has contributed substantially to the development of techniques, methods and procedures, and assimilation and exchange of information on earthing for various components of electric power systems. With its in-house information about existing status of technology and needs of Indian industry, the CBIP constituted a committee to prepare the document 'Manual on Earthing of AC Power Systems'.

This document on Earthing of AC Power Systems has been prepared with contributions by representatives of organizations and individuals who have been actively associated with various matters concerning earthing systems of electric power stations in India and also have information about international practices. As such this document covers techniques, methods, procedures, practices etc. that are generally and commonly followed by the Indian industry with regards to earthing systems for AC power systems, the document does not cover matters that require special techniques and analysis.

Various standards and CBIP documents referred in the preparation of this document and terminology/definitions related to the earthing are given in Chapter 2 of the document.

Based on a review of general requirements and practices, this document contains information about the following matters concerning earthing systems of AC electric systems in general and HVAC outdoor type stations in particular:

- Design and Engineering

- Erection, Monitoring and Maintenance
- Field Tests and Measurements
- Typical Examples of Calculations

1.2 DESIGN & ENGINEERING OF EARTHING SYSTEMS

The earthing system of a typical HVAC Station comprises an interconnected network of (a) horizontally buried grid of bare conductors (b) vertical earth electrodes and (c) earthing conductors or earth leads connecting equipment enclosures, metallic structures, cable armour etc. with horizontal grid conductors and / or vertical earth electrodes.

The design and engineering of a typical earthing system for HVAC Station includes the basic activities listed in subsections below.

1.2.1 Design Data / Parameters & Criterion

The design of earthing system of an HVAC Station is often customized. Even though the operating voltage of a station may be the same as that of another, but the magnitude of some or all of the vital inputs namely, (i) resistivity of the soil at the substation site, (ii) the maximum earth fault current, (iii) the maximum grid current, (iv) the geometry and size of the area covered by the station, and (v) fault clearing time for conductor size and for shock duration differ from station to station. The importance of the various inputs in earthing design, and commonly obtained values of these parameters in practice, and information about the following matters concerning design of earthing systems are brought out in Chapter 3-Earthing Design: Parameters, Methodology, Criteria and Corrosion:

- Descriptions of touch and step voltages and methodology for determination of their maximum permissible values used in design of earthing systems for safety of personnel.
- Selection of material and determination of size of horizontal grid conductors, earth leads and vertical earth electrodes etc.
- Special considerations regarding dangerous touch, step and transferred voltages, location of station fence etc.

1.2.2 Magnitude and Distribution of Earth Fault Current

The determination of the maximum earth fault current for calculation of (a) size of earth conductors and (b) dangerous step and touch potentials and total EPR is first major step for the design of earthing system. Recommendations for calculation of magnitude and distribution of fault current are given in detail under Chapter 4. This document includes a computer program for determination of magnitude and distribution of earth fault current and thereby the grid current as per recommended procedure. Instructions for use of the program are included in Appendix B.

1.2.3 Main Design Calculations

The layout of horizontal grid earth conductors should be determined, by design calculations, to keep the touch and the step voltages within permissible limits. These voltages occur because of the flow of current between grid conductors/earth electrodes and surrounding soil. Basic considerations, and empirical mathematical expressions used to prepare a layout of horizontal grid conductors to

keep the actual touch and the step potentials within permissible limits are given under Chapter 5. Suggestion for optimizing the layout are also given.

The second important phase of design calculations of an earthing system is determination of (i) earth resistance of the earth electrode, and (ii) the maximum magnitude of transferred potential or total earth potential rise (EPR). EPR is dependent on total earth resistance of earthing system and magnitude of the maximum grid current. Formulae for calculation of earth resistance of simple earth electrodes as well as grid earth electrode are also given in Chapter 5.

1.2.4 Control of EPR

In case of a grid earth electrode, the earth resistance is mainly dependant on size of grid earth electrode and soil resistivity. These two parameters of an earthing system are not easy to alter. Also, the maximum grid current is dependent on earth resistance of grid electrode and the earth fault current, which are also more or less fixed. Thus it is not easy to alter EPR, to any large extent, once the size of earth grid and its location are decided. However, the possible measures that may be adopted for controlling the step and touch voltages and EPR are described in Chapter 6.

1.2.5 Vertical Rod / Pipe / Plate Electrodes

Vertical earth electrodes are directly connected to (a) neutral earthing terminal of power generators and transformers, (b) lightning current discharge terminals of lightning arresters, CVTs etc. and (c) down conductors of lightning prevention systems as described under Chapter 8. A common earthing system is formed for HVAC station by interconnecting these and other vertical earth electrodes (if provided for fulfillment of design requirements) with main grid conductors.

1.2.6 Limitations

Design of earthing system for HVAC stations involves complex calculations. The recommended procedure of manual (hand) calculations can be used only when the soil is uniform. Limitations of the formulae even for this case are brought out in Chapter 5. For optimizing the design, the spacing of conductors of grid earth electrode has to be non-uniform. The empirical formulae cannot be used to determine touch and step potentials over selected area of the station to optimize spacing between grid conductors or for design of earthing systems for stations where electrical resistivity of soil is subject to variation with depth and is to be represented by a two-layer soil resistivity model described under Chapter 9. Design of earthing systems for such cases requires the use of special computer programs.

1.2.7 Earthing System for Electronic Equipment / System

Specific recommendations and requirements of designers and manufactures of electric / electronic equipment and systems on matters concerning safety through earthing system for their equipment/ systems should be separately considered and implemented as a part of design, engineering, construction and installation of earthing system for HVAC station due to technical and other considerations given under Chapter 7.

1.2.8 Typical Examples

Examples that illustrate the methods of calculating parameters of design of an earth electrode presented in Chapters 4 and 5 are included in Chapter 11. Analyses of typical examples with software, exhibiting several features of earthing design, are also included in Chapter 11.

1.3 FIELD PRACTICES FOR EXECUTION, MONITORING AND MAINTENANCE OF EARTHING SYSTEMS

1.3.1 Field Practices for Installation and Construction of Earthing Systems

Proper installation and construction of earthing systems in accordance with design drawings and recommended procedure is an essential pre-requisite for safe and reliable performance of an earthing system. Its importance is due to the following considerations:

- All elements of earthing are buried under the ground and remain passive during normal operating conditions of electric system. At all times, grid conductors and vertical earth electrodes are subject to corrosion in soil and earth lead conductors are subject to atmospheric corrosion.
- It is not possible to assess the physical condition and deterioration of underground grid conductors and other electrodes after their installation
- Identification of damaged / deteriorated underground grid conductors by routine system monitoring and their repair / replacement by routine maintenance are problematic under normal operating conditions of electric system

1.3.2 Field Practices for Monitoring and Maintenance of Earthing Systems

Monitoring and maintenance of earthing systems is required to ensure that conditions of all grid conductors, vertical earth electrodes and earth leads remain close to what they were at the time of their installation and commissioning.

The earthing system monitoring activities should include (i) inspection during constructional activities to prevent damage to various elements of earthing system, (ii) periodic inspection of status of earth lead connections, and deterioration of grid conductors due to corrosion at critical underground locations, (iii) periodic measurements to determine performance of various components of the earth electrodes and circuit continuity etc.

The maintenance activities should include necessary actions as required to maintain the system based on results of periodic inspection and measurements.

1.3.3 General field practices / guidelines for execution, monitoring and maintenance of earthing systems are given in Chapter 8 with the understanding that a comprehensive program for the erection, monitoring and maintenance will be made by the concerned authority with reference to conditions and requirements of earthing system.

1.4 FIELD TESTS AND MEASUREMENTS

1.4.1 Electrical Resistivity of Soil

The electrical resistivity of soil of the area covered by the earthing system is an important parameter for determination of size and layout of grid conductors. Performance of HVAC station earthing systems during flow of earth currents between local and remote stations depends mainly on resistivity of natural soil up to large depths. Therefore a survey is carried out to determine electrical resistivity of natural soil up to large depths in all areas to be covered by the earthing system.

Measurement of soil resistivity is almost the first task for the design of earth electrode for a station once the site of the station has been selected. It is so because time at which soil resistivity may

be measured should be well chosen. Equipment and procedures for the measurement of electrical resistivity of soil and methodology for the analysis of measured data to determine soil resistivity model (homogenous or two-layer) that is used for earthing system design calculations, are covered under Chapter 9.

1.4.2 Earthing System Performance Tests and Measurements

The performance of earthing system can be determined and assessed by (i) the resistance that earthing system offers to flow of current and (ii) the touch and step potentials that are created during the flow of current between earthing system and soil. Equipment and procedures for the measurement of these parameters and methodology for the analysis of measured data are covered under Chapter 10. Determination of real performance of earthing systems by field tests and measurement is problematic and therefore installation and construction of earthing systems in accordance with design calculations and recommended practices is normally recommended as a criterion for the acceptance of earthing systems. Notwithstanding this recommendation / practice, field tests and measurements should be carried out to obtain as much data as possible about actual performance of earthing system and its components.

1.4.3 Earthing of GIS Substations

A chapter on Earthing of GIS was not included in the first print of this publication brought out in October 2007. The fact is that requirements of the earth electrode for GIS are given by the manufacturer of the equipments. The electrode design should meet these requirements. Some features which distinguish earth electrode design for a GIS from that of a substation with conventional outdoor air insulated equipment (AIS) are:

- The area of GIS station is much less than that of AIS.
- GIS equipment uses earthed metal screens/enclosures around individual phase conductors. Current is continuously induced in these and a residual ac current is likely to flow continuously via the earthing system. This may cause additional corrosion of earth conductors.
- Switching transients can occur while current is interrupted in a circuit breaker. These transients can include components at very high frequencies. The impedance presented to high frequency currents is different from that to 50 Hz currents. Quite often it may require closely spaced earth conductors in immediate vicinity of flow of such currents, specific screen terminating arrangements, and routing of control wiring to minimize inductive interference. High frequencies should be confined to the inside of screened enclosures.
- It is also important to ensure that earthing design does not permit circulating currents, which would cause interference, to flow.

Various aspects of GIS earthing are brought out in Chapter 12.

CHAPTER - 2

Reference Standards and Definitions

Synopsis : During the preparation of this document reference has been made to several standards and publications. These standards are listed below so that they can be referred to for information on various aspects of earthing covered in this document.

2.1 STANDARDS AND CBIP PUBLICATIONS

2.1.1 Standards

The following standards and technical reports provide information related to the topics covered in this publication.

- Indian Standard IS: 3043 - 1987, Code of Practice for Earthing (First Revision).
- Indian Electricity Rules 1956 (as amended from time to time).
- ANSI/IEEE Standard 80-2000, IEEE Guide for Safety in AC Substation Grounding, IEEE, New York, 2000.
- IEEE Std. 81.2-1991, IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems.
- IEEE Std. 81-1983, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System.
- IEEE Std. 665-1995, IEEE Guide for Generating Station Grounding.
- IEEE Std. 1050-2004, IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations, IEEE, New York, 2005.
- IEEE Std. 1100-2005, IEEE Recommended Practice for Powering and Grounding Electronic Equipment, IEEE, New York, 2006.
- IEEE Std. 142-1991, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems, IEEE, New York.
- BS 7354:1990, Code of Practice for Design of High-voltage Open-terminal Stations, Section 7- Earthing, British Standards Institution, London, 1990.
- BS 7430:1991 Code of Practice for Earthing, British Standards Institution, London, 1991.
- Technical Specification 41-24, Guidelines for the Design, Installation, Testing and Maintenance of Main Earthing Systems in Substations, Engineering & Safety Division, The Electricity Association, London, 1992.
- International Standard IEC 61936-1, Power Installations Exceeding 1 kV ac, International Technical Commission, Geneva, Switzerland, 2002.
- International Standard IEC 61479-1, Effect of Current on Human Beings and Livestock, International Technical Commission, Geneva, Switzerland.

2.2 CBIP PUBLICATIONS

- Review No. 1, Review on Corrosion in Earthing Equipment, New Delhi, 1973.
- Technical Report No. 5, Steel Grounding Systems where Grounding Grid is not Needed, 1976.
- Technical Report No. 43, Interconnection of Grounding Mats of Different Materials, New Delhi, 1985.
- Technical Report No. 49, Earthing System Parameters for EHV and UHV Substations, 1985.
- Technical Report No. 78, Evaluation of Concrete Encased Earthing Electrodes and Use of Structural Steel for Earthing, August 1991.
- Manual on Substation Earthing System, January 1992.
- Proceedings of National Seminar on Design of Earthing Systems, 18-19 December 2003, CBIP, New Delhi.

2.3 DEFINITIONS

Definitions of terms that are used very often in relation to the subject of this publication are given below :

(i) *Earth*

A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth or to some conducting body of relatively large extent that serves in place of the earth.

Quite often the word “earth” refers to the common point in a circuit from which voltages are measured. In U.S. context an “earth” is referred to as “**Ground**”.

(ii) *Earth (local)*

It is the part of earth, which is in local contact with an earth electrode and the electric potential of which is not necessarily equal to zero.

(iii) *Reference earth*

It is part of the earth considered as conductive, the electric potential of which is conventionally taken as zero, being outside the zone of influence of the relevant earthing arrangement.

(iv) *System earthing*

Intentional earthing of neutral conductor for controlling circuit voltage to earth and detection of unwanted connection between live conductors and earth.

The objective of system earthing is primarily to preserve security of the electric system by ensuring that the potential on each conductor is restricted to such a value as is consistent with the insulation applied. Also, it should ensure efficient and fast operation of protective gear in the case of earth faults.

(v) *Safety/equipment earthing*

Earthing that eliminates hazards to equipment and personnel due to failure of system insulation.

The basic objectives of equipment earthing are:

- (a) To ensure freedom from dangerous electric shock voltage exposure to persons in the area,
 - (b) To provide current carrying capability, both in magnitude and duration, adequate to accept the earth fault current permitted by the over-current protective system without creating a fire or explosive hazard to building or contents,
 - (c) To contribute to better performance of the electrical system.
- (vi) **Functional earthing**
- It is related to earthing of electronic equipment. It minimizes interference from unwanted electrical signals (Electromagnetic Interference or EMI) and prevents accumulation of static charge on the equipment.
- (vii) **Earth electrode**
- A conductor or interconnected conductors imbedded in the earth and used for collecting earth current from or dissipating earth current into the earth. An electrode is simple if it is a vertical pipe or rod, or a horizontal strip or round conductor or a plate.
- (viii) **Earth conductor**
- The bare metallic conductors of which an earth electrode is comprised are earth conductors.
- (ix) **Earth rod or vertical rod electrode**
- An earth electrode consisting of a metal rod or pipe driven into earth.
- (x) **Composite electrode**
- When an earth electrode is formed from interconnected simple electrodes, it is a composite electrode.
- (xi) **Grid earth electrode/Grid**
- It is a system of interconnected, bare, horizontal conductors together with or without vertical bare conductors buried in the earth, providing a common earth for electrical devices or metallic structures, usually in one specific location. A grid is a composite electrode.
- (xii) **Earth mat**
- A solid metallic plate or a system of closely spaced bare conductors that are connected to and often placed in shallow depths above a grid earth electrode or elsewhere at the earth's surface, in order to obtain an extra protective measure minimizing the danger of the exposure to high step or touch voltages in a critical operating area or places that are frequently used by people. Earthed metal gratings placed on or above the soil surface, or wire mesh placed directly under the surface material, are common formats of an earth mat.
- (xiii) **Counterpoise earth mat**
- An earth mat fabricated from bare conductors of small diameter arranged in closely spaced meshes installed on earth's surface and below surface material to equalize the gradient field near the surface and thus reducing the touch voltage.
- (xiv) **Structural earth electrode**
- The metal part, which is in conductive contact with the earth or with water pipes directly or via concrete, whose original purpose is not earthing, but which fulfills all requirements of an earth electrode without impairment of the original purpose.

(xv) Earthing conductor

It is the conductor which provides a conductive path, or part of a conductive path, between a given point in a system or in an installation or in equipment and an earth electrode.

(xvi) Earthing system

It is the complete interconnected assembly of earthing conductors, earth electrodes and devices necessary to earth equipment or a system in a specific area.

(xvii) Earth impedance

It is the impedance at a given frequency between a specified point on earthing system or in equipment and reference earth. The resistive part of impedance is earth resistance.

(xviii) Soil resistivity

It is electrical resistivity of a typical sample of soil. Its units are ohm-m (Ω -m).

(xxix) Uniform soil model

Homogeneous soil condition in which the apparent measured soil resistivity exhibits moderate variation.

(xx) Earth fault

It is a fault resulting from a live conductor being connected to earth or from the insulation resistance between live conductor and earthed conductor becoming less than a specified value.

(xxi) Earth fault current

It is the current that flows from the main circuit to earth or earthed parts at the earth fault location. On single earth faults, this is,

- in systems with isolated neutral, the capacitive earth fault current;
- in systems with high resistance earthing, the earth fault current;
- in systems with solid or low impedance neutral earthing, three times the zero sequence component of the line to earth short-circuit current.

(xxii) Zero sequence current

In three-phase four-wire system, it is representative of the component of current that flows in neutral return wire. It is calculated as $\frac{1}{3} (I_a + I_b + I_c)$

(xxiii) Earth/grid current

A current flowing into or out of the earth or its equivalent serving as an earth.

(xxiv) Symmetrical grid current

It is that portion of the symmetrical earth fault current that flows between the earth electrode and the surrounding earth.

(xxv) dc offset

It is the difference between the symmetrical current wave and the actual current wave during a power system transient condition. The actual fault current can be represented mathematically as sum of a symmetrical alternating component and a unidirectional component, which decreases at a predetermined rate.

(xxvi) Decrement factor

It is a factor that is used in conjunction with Symmetrical earth fault current to determine the rms equivalent of the asymmetrical current wave for a given fault duration. It accounts for the effect of initial dc offset and its attenuation during the fault.

(xxvii) Maximum grid current

It is a design value of the maximum grid current.

(xxviii) Subtransient reactance

It is the reactance of a generator at the initiation of a fault. This reactance is used in calculation of initial symmetrical fault current. The current continuously decreases, but it is assumed to be steady at this value as a first step, lasting approximately 0.05 s after a suddenly applied fault.

(xxix) Earth electrode/Grid potential rise (EPR)

It is the maximum voltage that the earth electrode, at a station, may attain relative to a distant earthing point assumed to be at the potential of remote earth or reference earth.

(xxx) Earth surface potential

It is voltage between a point on earth surface and reference earth.

(xxxi) Dangerous voltages

The potential difference that can be experienced by a human being during an earth fault in certain basic situations. For detailed definitions, may refer to Chapter 3.

(xxxii) Step voltage (E_s)

It is the difference in potential between two points on earth surface that are 1 m apart. This voltage will be experienced by a person because length of stride is considered 1 m. Its maximum value usually occurs outside and at a corner of earth grid.

(xxxiii) Touch voltage (E_t)

It is the potential difference between an accessible earthed conductive part and the earth surface potential at the point where a person is standing while his hands are in contact with an earthed part. Voltage of earthed conductive part is assumed to be equal to EPR; therefore, it equals the potential difference between the EPR and potential at a point on the earth surface.

(xxiv) Mesh voltage (E_m)

It is the maximum touch voltage to be found within a mesh of earth grid.

(xxxv) Transferred voltage (E_{trans})

It is the touch voltage where a voltage is transferred into or out of a substation. This situation occurs when a person standing within the station area touches a conductor earthed at a remote point or a person standing at a remote point touches a conductor connected to the station-earth electrode. Its maximum value is equal to EPR.

CHAPTER -3

Earthing Design: Parameters, Methodology, Criteria and Corrosion

***Synopsis** Design of earthing system for an AC substation or generating station has to fulfill the safety requirements during earth fault conditions in the electric system. This involves (i) determination of the maximum permissible magnitude of dangerous voltages to which personnel may be exposed during earth fault conditions and (ii) selection of material, size, type, layout, depth etc. of earth conductors to keep the dangerous voltages within the maximum permissible limits without adversely affecting safety of equipment and their performance. Proper understanding of parameters of design and design methodology is essential for safe and economic design of earthing systems. It includes an understanding of the criteria for determination of the parameters such as the maximum permissible body current, resistance of human body and feet, and duration of shock current, which affect the maximum permissible dangerous voltages. Proper appreciation of the parameters such as electrical resistivity of soil, magnitude and duration of earth fault current etc. and other considerations that affect material, size, type, layout, depth etc. of earth conductors to keep the dangerous voltages within the maximum permissible limits is also necessary.*

3.1 INTRODUCTION

3.1.1 General

AC Power Stations are centers of large and concentrated power exchange and places of major operational and control activities involving a large number of equipment and devices interconnected by a complex network of underground and aboveground cables and overhead bare conductors and bus bars. An earth fault anywhere in the electric power system results in the flow of very high magnitude currents between the earthing system of power station and earth in and around the station area. The earthing system of AC Power Stations also shares the responsibility of discharging lightning current to earth. The flow of power frequency earth fault currents and lightning current through station's earthing system may create dangerous voltage exposures to personnel and directly / indirectly affect the safety of and proper functioning of associated equipment / devices unless station earthing system is properly planned, designed, installed and maintained. Based on extensive research work and experience, guidelines and criteria for design of AC Power Station Earthing System have been well-established and are extensively used all over the world with some minor variations here and there.

3.1.2 Objectives of an Earthing System

Objectives for the design of an earthing system are:

- (i) To ensure freedom from dangerous electric shock voltage exposure to persons in the area,
- (ii) To provide current carrying capability, both in magnitude, and duration, adequate to accept the earth fault current permitted by the over-current protective system without creating a fire or explosive hazard to building or contents, and

- (iii) To contribute to superior performance of the electrical system.

The layout of equipment / structures and the above objectives make it imperative to provide the earthing system for AC Power Stations in the form of a grid earth electrode consisting of linear earth conductors and rod / pipe / plate electrodes buried close to earth surface and interconnected with each other.

The earthing system for AC Power Stations also includes earth electrodes that are provided and connected to station's earthing system in accordance with specified requirements of (i) system (neutral) earthing system and (ii) electronic equipment earthing system.

3.1.3 The design of earthing system for AC Power Stations requires systematic analysis of various factors and application of proper methodology and criteria for determining -

- (i) Design parameters,
- (ii) Usage of design parameters for deciding
 - Type of earth conductors and their material and size,
 - Maximum permissible dangerous (touch and step) potential differences for human beings in the station area,
 - Layout of horizontal grid conductors to keep touch and step potentials within permissible limits,
- (iii) Locations of rod / pipe / plate electrodes for control of potential differences and fulfillment of statutory and other requirements, and
- (iv) Earth electrodes for system (neutral) and electronic equipment earthing.

3.2 DESIGN PARAMETERS

When an earth fault occurs in an electric power system, current flows between earth electrodes and the surrounding earth. Closed loops are formed between earth electrodes with the earth forming part of the loops. Thus, the current discharged from an earth electrode is collected at other earth electrodes. Because the conductivity of material of earth electrode is very large compared to that of soil, the electrode can be regarded a perfect conductor and thus equipotential. The flow of fault current through earth creates potentials distribution $V(x, y, z)$ around an electrode as a function of x , y , and z coordinates; it raises the potential (V_G) of earth electrode with respect to zero potential of remote earth. Earth resistance of an electrode (R_G) is the resistance offered to the flow of current between the earth electrode and the remote earth. It is known that earth resistance of an earth electrode is a function of

- (i) Resistivity of soil in which the electrode is buried,
- (ii) Geometric configuration of earth grid electrode defined by shape, size, dimensions and layout of earth conductors and their depth of burial, and
- (iii) Pattern of current dissipation in earth around the electrode.

The voltage differences, to which equipment and personnel may be exposed during the flow of current through earthing system of a station, depend on earth grid potential rise (V_G) and earth surface potentials $V(x, y, 0)$. Earth grid potential rise (V_G) depends on

- (i) Magnitude of current that flows between earth grid electrode and surrounding soil, and
 - (ii) Earth resistance of earth grid electrode.
- Earth surface potentials $V(x,y,0)$ depend on
- (i) Magnitude of current that flows between grid earth electrode and surrounding soil,
 - (ii) Resistivity of soil where the electrode is buried, and
 - (iii) Geometric configuration of grid earth electrode defined by shape, size, dimensions and layout of earth conductors and their depth of burial.
- The design of earthing system requires that
- (i) The maximum permissible values of touch voltage and step voltage be calculated in accordance with experience based and well accepted international practices and
 - (ii) Actual calculated values of touch potential and step potentials to which human beings may be exposed during the flow of current through grid earth electrode should be lower than their respective maximum permissible values.

Whereas factors such as maximum permissible body current and resistance of current flow circuit for touch and step voltage conditions are to be considered as per international practices, the duration of current flow for calculation of maximum permissible touch and step voltage depends on earth fault protection schemes of the station.

Simplified equations for calculation of the maximum values of touch and step voltages for simple grid earth electrodes, and computer software for comprehensive evaluation of performance of grid earth electrodes are available.

Area of cross-section of earth conductors to carry the fault current without deterioration of joints and properties of conductor material depends on

- (i) Magnitude and duration of fault current
- (ii) Physical properties of the material of earth conductors
- (iii) Type of joints, and
- (iv) Considerations for mechanical strength of conductors and their deterioration due to corrosion.

Based on these basic considerations, the main parameters for design calculations of grid earth electrode are :

- Electrical Resistivity of Soil
- Earth Resistance & Potential Rise of Earth Electrode
- Maximum Permissible Dangerous Voltages
- Magnitude and Duration of Earth Fault Current

3.3 SOIL RESISTIVITY

3.3.1 Electrical resistivity of soil is an important parameter that is used for determination of

- Earth resistance (R_G) of earth electrode

- Earth electrode potential rise (V_G)
- Earth surface potentials $V(x,y,0)$

The resistance of earth electrode, earth electrode potential rise, and earth surface potentials that affect magnitude of dangerous voltages, are directly proportional to electrical resistivity of soil. Therefore, it is recommended that electrical resistivity of soil should be properly measured and analyzed to determine soil resistivity model for design of grid earth electrode. Equipment and procedures for measurement of electrical resistivity of soil and methods for determinations of soil resistivity model are given in Chapter 9. Supplementary information /considerations on electrical resistivity for design of earth electrodes are given in this section.

3.3.2 Soil Resistivity and Performance of Earth Electrodes

When conductors of an earth electrode buried in earth discharge current into surrounding soil, the current flows in the soil towards the current collecting electrode. Usually, the current collecting electrode is at a large distance from the electrode, which is discharging the current into the earth. Under these conditions, the current flow in the earth from the conductors of the electrode is assumed to be radial; thus the voltage in the earth and on earth surface changes inversely as the distance from the electrode discharging current. The current collecting electrode being at a large distance from the current discharging electrode, current can flow in the earth up to a large depth from the surface. Therefore, the resistance offered to the flow of the current in the earth is not that of only the soil in the immediate vicinity of the conductors forming the electrode but of the general mass of earth up to a large distance from these conductors. When the electrode discharging current into earth is a grid electrode, the soil resistivity as far away from the grid conductors as the larger dimension of the grid, in each direction, is the most important. For the purpose of establishing an earth electrode, variations in resistivity of earth both in the lateral direction and along the depth below earth surface are to be considered.

3.3.3 Factors Affecting Soil Resistivity

In general, earth consists chiefly of sand or silicon dioxide besides other metallic oxides and calcium carbonate. The surface soil layer consists of clay mixed sand and often mixed with decayed vegetable matter also. When dry, this admixture may not conduct much electricity. In the presence of moisture, ionic conduction takes place according to the types of salts present in the water contained in soil. As a result soil resistivity is dependent on physical and chemical composition of soil, moisture contents and even temperature. Resistivity of soil can vary within extremely wide limits, between $1 \Omega\text{-m}$ and $100,000 \Omega\text{-m}$. It depends on the type and nature of soil. Table 3.1 is indicative of the resistivity of various types of soils and other materials. Black dirt, or soils with high organic content are usually good conductors because they retain higher moisture levels and have a higher electrolyte level, leading to low soil resistivity. Sandy soils, which drain faster, have a much lower moisture content and electrolyte level. Therefore, they have higher resistivity. Solid rock and volcanic ash contain virtually no moisture or electrolytes; these soils have high levels of resistivity, and effective earthing is difficult to achieve. Resistivity of the soil in the area, where the earth electrode is to be installed, must be determined by measurement. Actual soil resistivity model of the site of earth electrode, obtained from soil resistivity measurements, is important to design an effective and economic earth electrode.

Table 3.1: Resistivities of various soils

Sl. No.	Type of soil	Resistivity ($\Omega\text{-m}$)	
		Average	Usual variation
1	Surface soil (loam - clay and sand and decayed organic matter)		5-50
2	Clay (stiff viscous earth chiefly aluminium silicate), black clay	30	8- 100
3	Sand and gravel	100	40 - 300
4	Sand clay and gravel mixture	150	50 - 250
5	Shale (fine grained sedimentary rock of mud and clay), Sandstone wet (sedimentary rock chiefly quartz cemented together), slate, schist		5-500
6	Sandstone dry		1000 - >10000
7	Surface limestone (chiefly calcium carbonate)		100 -10000
8	Deep limestone		5-4000
9	Granite (crystalline rock of quartz, mica etc.)	1000	200-10000
10	Basalt (dark colored fine grained rock)		1000
11	Decomposed gneiss (rock containing minerals and quartz)		50 - 500
12	Gravel	3000	1000 - 10000
13	Primary rock (gneiss, granite)	25000	10000 - 50000
14	Lake water non polluted lakes in hilly terrains		200 and up
15	Tap water		0.01 to 500
16	Sea water		0.02 - 20
17	Concrete, new or buried in earth	100	25 - 500
18	Concrete dry	10000	200 - > 1000000
19	Asphalt wet		10000 6000000

Table 3.1 has been prepared with inputs from various sources including [1,2]

3.3.4 Effect of Moisture, Salts and Temperature

It may be observed that the resistivity of a rock is not unique to it and that there is considerable overlapping of resistivity ranges of several rock types, depending on clay content, water saturation, quality of water, salinity and porosity. Dry soil is generally very poor conductor of electricity. Resistivity is much smaller below subsoil water level than above it. Also, if variation in soil resistivity during a year is considered, soil resistivity below water table is more constant than that above this level. The amount of water held in soil is dependent on weather conditions, time of the year and nature of subsoil. To a certain extent, temperature of the soil has an effect on resistivity, lower temperature causing higher resistivity. When water freezes, resistivity up to frost penetration level changes markedly. Water that has salts dissolved in it reduces the resistivity of soil. If salts have been purposely added to soil, these may be washed out in very wet season and resistivity shall increase after salts have been leached out.

Rudenberg [3] gave graphs showing very large variation of resistivity of a certain soil with respect to moisture content, temperature change, and added salt in percent weight. These are reproduced in Fig. 3.1. Tables 3.2 - 3.4, reproduced from “A Simple Guide to Earth Testing” booklet issued by AVO International Limited, show the effect of variation in resistivity due to (i) change in moisture content, (ii) salt content, and (iii) temperature of particular samples of soil [1].

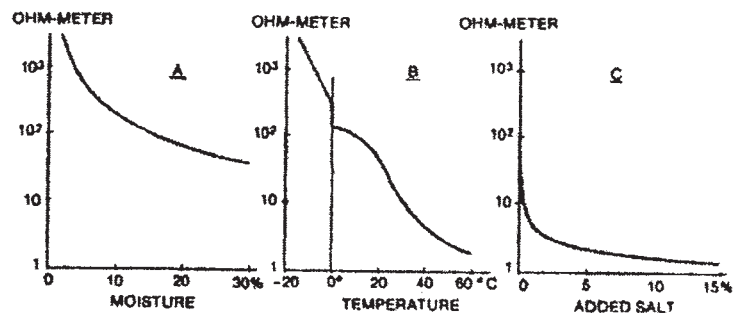


Fig. 3.1 : Effect of moisture, temperature and salt content on resistivity of soil

Table 3.2 : Effect of moisture content on earth resistivity

Sl. No.	Moisture content % by weight	Resistivity (Ω-m)	
		Top soil	Sandy loam
1	0	10000000	10000000
2	2.5	2500	1500
3	5	1650	430
4	10	530	220
5	15	210	130
6	20	120	100
7	30	100	80

Table 3.3 : Effect of salt content on earth resistivity
(For sandy loam - moisture content 15% by weight, temp. 17°C)

Sl.No.	Added salt % by weight of moisture	Resistivity (Ω-m)
1	0	107
2	0.1	18
3	1.0	4.6
4	5	1.9
5	10	1.3
6	20	1

Table 3.4 : Effect of temperature on earth resistivity (For sandy loam - moisture content 15.2%)

Sl. No.	Temperature (°C)	Resistivity ($\Omega\text{-m}$)
1	20	72
2	10	99
3	0 (water)	138
4	0 (ice)	300
5	-5	790
6	-15	3300

3.3.5 Soil Model

Earth resistance of an electrode is directly proportional to the earth resistivity and so is the permissible magnitude of dangerous voltages namely step voltage and mesh voltage. Therefore, determination of soil model is of primary importance. Resistivity of soil in an area may vary with depth as well as in lateral direction. Variation of resistivity with depth is usually more pronounced because of non-uniformity of subsoil strata. Two types of soil model are commonly used, namely (i) the uniform soil model and (ii) the two-layer model. Soil models with more than two layers are possible; however, as the number of layers is increased, analysis of an earth electrode becomes very complex and therefore only homogenous and two-layer soil resistivity models are used for design of earthing systems.

In uniform soil model, the soil is assumed to have uniform resistivity ρ ($\Omega\text{-m}$) to a very large depth below earth surface. Actually the soil is rarely homogeneous in all directions; nevertheless this approximate representation is used when non-uniformity is comparatively small.

A two-layer soil model is shown in Fig. 3.2. It consists of an upper layer of depth h (m) and resistivity ρ_1 ($\Omega\text{-m}$), overlaying a lower layer of infinite depth and resistivity ρ_2 ($\Omega\text{-m}$). Both the layers are of very large extent in the transverse direction. Measurement of soil resistivity and determination of soil model are described in Chapter 9.

When deciding upon the soil model to be adopted, the question that arises is whether to adopt an average of apparent measured resistivity as the uniform soil model or a multilayer model. The following may be considered in this context:

- At many sites there is a definite trend of soil resistivity decreasing with depth either because top soil is such that it cannot absorb and hold moisture and resistivity decreases as water table is reached or the top sandy soil of higher resistivity overlays clayey soil below. At other places soil resistivity increases with depth as top loamy soil covers rocky soil below.

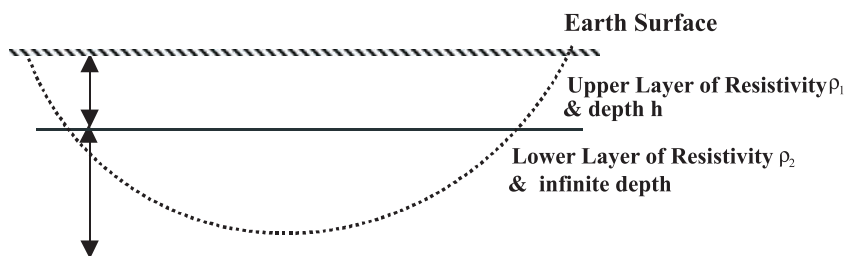


Fig. 3.2 Two -Layer soil model

- (ii) If topsoil resistivity is higher than that of the bottom layer, the current dissipation from all conductors of the earth electrode is more uniform than for uniform soil. The earth resistance is less for the two-layer case than for the uniform soil case (resistivity = ρ_i). The step voltage would be smaller than with uniform soil and touch voltage would be usually smaller than with uniform soil. Vertical rods that penetrate the bottom layer are very profitably used in such a case.
- (iii) If topsoil resistivity is less than that of the bottom layer, the current dissipation from conductors near the periphery of the earth electrode is greater than for uniform soil. The earth resistance is higher for the two-layer case than for the uniform soil case (resistivity = ρ_i). The step voltage would be higher than with uniform soil, and touch voltage would be usually higher than with uniform resistivity soil.
- (iv) At many locations the topsoil is covered with surface materials. If thickness of top layer is much larger than that of surface layer and resistivity of surface layer is significantly higher than that of topsoil, the surface layer is neglected when computing earthing system performance. However, if the resistivity of surface layer is lower than that of topsoil, a two-layer model should be used for calculating earthing system parameters

3.4 DANGEROUS VOLTAGES

Types of dangerous voltages that are considered for design of earthing systems for AC stations are illustrated in Fig. 3.3. These are defined as follows in accordance with IEEE Std 80-2000 and other international practices / recommendations:

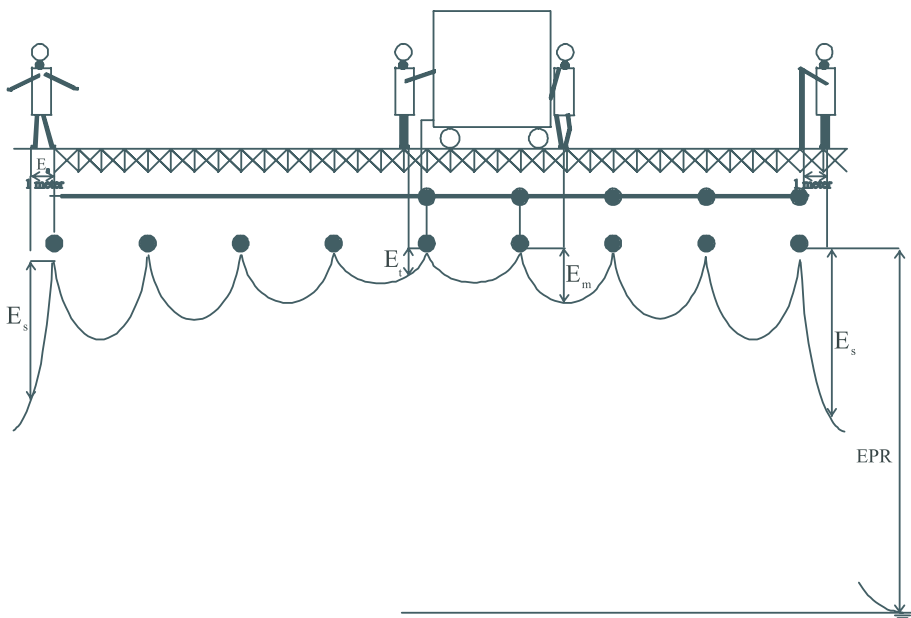


Fig. 3.3 : Basic shock situations

(i) **Earth potential rise (EPR)**

It is the maximum voltage that the earth electrode, at a station, may attain relative to a distant earthing point assumed to be at the potential of remote earth or reference earth.

(ii) **Step voltage (E_s)**

It is the difference in potential between two points on earth surface that are 1 m apart. This voltage will be experienced by a person because length of stride is considered 1 m. Its maximum value usually occurs outside and at a corner of earth grid.

(iii) **Touch voltage (E_t)**

It is the potential difference between an accessible earthed conductive part and the earth surface potential at the point where a person is standing while his hands are in contact with an earthed part. Voltage of earthed conductive part is assumed to be equal to EPR, therefore it equals the potential difference between the EPR and potential at a point on the earth surface.

(iv) **Mesh voltage (E_m)**

It is the maximum touch voltage to be found within a mesh of earth grid.

(v) **Transferred voltage (E_{trd})**

It is the touch voltage where a voltage is transferred into or out of a substation. This situation occurs when a person standing within the station area touches a conductor earthed at a remote point or a person standing at a remote point touches a conductor connected to the station- earth electrode. Its maximum value is equal to EPR.

EPR voltage is transferred out of a substation with an earthed conductor, such as metallic cable sheath, shield wire of aerial transmission line, low voltage neutral wire, pipeline or rail, to areas of low or no potential rise relative to reference earth. It results in a touch voltage between the conductor and the surroundings. This situation also occurs when a conductor earthed at a remote point goes into the area of potential rise.

3.5 EARTH RESISTANCE OF EARTH ELECTRODE, EPR AND DANGEROUS VOLTAGES

Earth resistance of an earth electrode is an important parameter for evaluation of design and performance of earthing systems.

The earth electrode potential rise (EPR) is product of earth resistance of earth electrode and magnitude of current that flows between earth electrode and soil; it is also an important parameter for evaluation of design and performance of earthing systems. In computer software based methods for analyzing performance of earth electrodes, EPR is calculated to determine the dangerous voltages to which personnel may be exposed during flow of current between earth electrode and soil.

An earth electrode / earthing system basically consists of a configuration of interconnected bare metallic conductors. Because the conductivity of material of earth electrode is very large compared to that of surrounding soil, the electrode can be regarded a perfect conductor and thus equipotential. Uniform dissipation of current from surface of an earth electrode is often assumed; however, with the boundary condition that the earth electrode is equipotential, the actual current dissipation per unit

length from the conductors forming the electrode is not uniform throughout. Usually, determination of exact density of dissipation of current to soil is subject to a number of practical limitations. Therefore, accuracy of calculated earth electrode resistance and dangerous potentials depends on method used for their calculations. Computer software have been developed to obtain more comprehensive and accurate results than obtained by simplified empirical equations. Still, determination of exact values of earth electrode resistance and maximum dangerous voltages during an earth fault is not easy and straightforward. Some of the complexity of the task can be observed with reference to methods and equations given in Chapter 4 on determination of fault current distribution, Chapter 5 on design of earthing systems and Chapter 11 on typical examples.

The actual touch and step voltages that may be created in and around the earth electrode during the flow of fault current between earth electrode and soil, and the maximum permissible touch and step voltages are to be determined by design calculations. The earthing system is to be designed, installed and maintained to fulfill the requirement that actual touch and step voltages must be lower than the respective maximum permissible values.

There are no specified limiting values of resistance of earth electrode and its potential rise (EPR). However, as per IEEE Std 80-2000 [4], a good earthing system provides a low resistance to reference / remote earth in order to minimize EPR and thereby to keep dangerous touch and step voltages within the respective maximum permissible limits. The earth resistance may be made as low as possible consistent with local conditions to minimize EPR and dangerous touch and step voltages. Clause 14.1 of IEEE Std-2000 on usual requirements of earth resistance says “A good grounding system provides a low resistance to remote earth in order to minimize the GPR. For most transmission and other large substations, the ground resistance is usually about $1\ \Omega$ or less. In smaller distribution substations, the usually acceptable range is from $1\ \Omega$ to $5\ \Omega$ depending on the local conditions”. In this regard, interpretation of this clause issued by IEEE is reproduced below:

“It is really not essential to determine if the substation is distribution or transmission substation to design ground grid. IEEE Std 80-2000, IEEE Guide for safety in AC substation Grounding is based on the safety criteria of acceptable touch and step potentials. Sub low resistances are not an indication of safe design, nor is a substation with a high resistance necessarily an indication of an unsafe design. The resistivity of the soil, the magnitude of the available fault current and the physical layout of the ground grid itself determines a safe design. The statement referring to the ground resistance being usually about 1 ohm or less for a transmission substation and 1 to 5 ohms for a distribution substation came from experience. It was based on typical resistance values for transmission and distribution substation throughout the United States in the 1950s, mainly determined by the physical size of the substation area. These values of resistance provided an acceptable ground for relay and fuse protection systems. Also, since these resistance values times the available fault current for various voltage levels did not exceed the flashover capabilities of the substation equipment. These values were not set specifically for substation safety, although it is obvious that lower resistance may reduce the Ground Potential Rise (GPR). Before the original IEEE-80, the resistance of the ground grid was the primary concern of the design engineer. Again, that was to assure the system was effectively grounded.”

3.6 SAFE LIMITS OF DANGEROUS VOLTAGES

3.6.1 One of the important aspects of the design of earthing systems is the determination of safe limits of dangerous touch and step voltages in accordance with IEEE Std 80-2000 and other

international practices / recommendations, the safe limits of touch and step voltages are functions of the following parameters:

- Magnitude of permissible body current (I_B)
- Duration of shock current (t_s)
- Resistance of current flow path through human body consisting of body resistance (R_B) and resistance of feet (R_{foot})

3.6.2 Considerations / Equations for Determination of the Maximum Permissible Touch and Step Voltages

(a) *Magnitude of body current I_B*

When a person bridges points at different voltages with his/her hand and feet or with the feet a current can flow through the body of the person. The aim of a safe design is that the magnitude of current through human body shall be less than that which causes ventricular fibrillation for the specified duration of its flow. In case of ventricular fibrillation heart muscle fibers forming walls of heart chambers are twitched in an uncoordinated manner and blood circulation cannot be properly maintained. Its effects can only be suppressed by application of defibrillating electric shock [4]. Magnitude of the current that flows through the human body is dependent on the resistance of the current path.

The limit of body current I_B has been established statistically. The IEEE recommendation is based on the premise that hazard from short duration shock of 0.03 - 3.0 s depends on energy absorbed by the body. It is assumed that the current I_B in amperes that 99.5% of all persons can withstand without ventricular fibrillation is given by

$$I_B = \frac{k}{\sqrt{t_s}} \quad \dots (3.1)$$

where k , a constant related to the electric shock energy, is statistically ascertained; and t_s is duration of current exposure in seconds. Value of k depends on body weight. For persons of average body weight of 50 kg the value has been assumed to be 116 milliamperes [4]. Since the current I_B is the maximum current tolerated by 99.5% of persons, it also means it is the minimum current that would cause ventricular fibrillation in 0.5% of persons.

(b) *Duration of shock current exposure t_s*

IEEE Std 80-2000 mentions that t_s may be based on clearing time of primary protective devices or that of backup protection. It says further - 'A good case could be made for using primary clearing time because of the low combined probability that relay malfunction will coincide with other adverse factors necessary for an accident and it is more conservative to use back-up relay clearing times because they assure greater safety margin. High ground gradients are usually infrequent and shocks from high ground gradients are even more infrequent.' In case automatic reclosure takes place, sum of two consecutive shock durations may be treated as time of single exposure. In examples given in IEEE Std 80-2000, time of 0.5 s is used for shock duration as well as to determine conductor cross-section.

As per IEC 61936 - 1, normal operating time of protection relays and breakers shall be used for personal safety.

BS 7354-1990[5] specifies that shock duration of 0.2 s may be taken in case of high-speed electronic protection, 0.3 s in case of electromagnetic relays; clearing time is current dependent when overcurrent earth fault protection is used and may be up to 1s.

The duration of shock current exposure t_s for determination of safe body current and touch and step voltages is, thus, subject to variations. However, based on fault clearing time of primary protection and the observations made below, HVAC stations where solid state or digital relays are used, t_s may be adopted as 0.5 seconds; and at stations with electromagnetic relays higher value of 1 s may be adopted. The following observations are relevant in this regard:

- Much higher body current and therefore touch and step potentials can be allowed where fast operating protective devices can be relied upon to limit the duration of fault.
 - The use of fault clearing time of primary protection is based on consideration that probability of simultaneous occurrence of relay malfunction and all adverse factors necessary for an accident is extremely low.
 - The fault clearing time of back up protection system ensures greater safety margin.
 - A person may safely withstand the first shock but may be subject to serious accident if he / she experiences the second shock due to automatic reclosure after an .earth fault. A reasonable allowance for such situations can be made by using the sum of individual shock durations as the time of single exposure.
- (c) *Resistance of current flow path through human body and the maximum permissible touch and step voltages*

The circuit of flow of current through the body, shown in Fig. 3.4, follows from IEEE Std. 80. In case of step voltage, the current flows in from one foot, passes through the body and flows out through the other foot. In case of touch voltage it flows in from the hand, passes through body and flows out from the both feet in parallel.

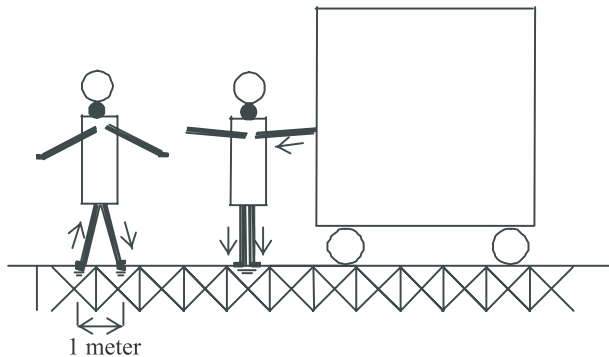


Fig. 3.4 : Path of current flow through body

R_b is resistance of human body. Though there is variation between the hand-to-hand contact and hand-to-feet contact, an average value of 1000 ohm has been adopted for R_b in IEEE Std. 80.

When the resistivity of uniform soil on which a person is standing is ρ_s Ω -m, earth resistance of foot is considered equal to that of a circular disc lying on soil of uniform resistivity. The earth resistance of a disc of radius b m is given by

$$R_{\text{foot}} = \rho_s / (4b) \quad \dots(3.2)$$

The human foot is assumed equivalent to a disc of radius 0.08 m. Thus $R_{\text{foot}} \cong 3\rho_s$

Resistance of the path through the body is the sum of resistance of the body ($R_B=1000 \Omega$.) and resistance of earth between the contact points. The resistance of current path between the two feet in series, for determining permissible step voltage, is given by

$$R_{\text{step}} = (1000 + 6\rho_s) \quad \dots(3.3)$$

Similarly the resistance of current path with two feet in parallel, for determining permissible touch voltage, is given by

$$R_{\text{touch}} = (1000 + 1.5\rho_s) \quad \dots(3.4)$$

The calculated value of step voltage (E_s) and touch voltage (E_t) should be such that the possible body current I is less than the maximum permissible current I_B . The maximum permissible values of step and touch voltages are given, for average body weight of 50 kg, by

$$E_{\text{step}} = (1000 + 6\rho_s) 0.116/\sqrt{t_s} \quad \dots(3.5)$$

$$E_{\text{touch}} = (1000 + 1.5\rho_s) 0.116/\sqrt{t_s} \quad \dots(3.6)$$

A 50 mm to 150 mm thick layer of gravel / crushed rock is usually spread on the ground surface over the earth grid in switchyard area to increase the contact resistance between the soil and feet and thereby the magnitude of maximum permissible touch and step voltages. For such cases, the resistance of a circular disc of radius 0.08 lying on the surface of a two-layer soil is considered as the earth resistance of foot (R_{foot}). By considering that the two layers consist of top layer of gravel, of resistivity $\rho_s \Omega - m$, and thickness h_s meters, and the bottom layer is the same as the natural soil of resistivity $\rho \Omega - m$, the earth resistance of foot (R_{foot}) is computed as

$$R_{\text{foot}} = \rho_s C_s (h_s, K) / 4b \quad \dots(3.7)$$

$$\text{where } K = (\rho - \rho_s) / (\rho + \rho_s) \quad \dots(3.8)$$

C_s , a corrective factor, is used to account for finite thickness of surface layer of gravel. Accordingly, the equations for calculation of maximum permissible E_{touch} and E_{step} for cases where a thin layer of gravel / crushed rock is spread on ground surface over earth grid, are

$$E_{\text{step}} = (1000 + 6\rho_s C_s (h_s, K)) 0.116/\sqrt{t_s} \quad \dots(3.9)$$

$$E_{\text{touch}} = (1000 + 1.5 \rho_s C_s (h_s, K)) 0.116/\sqrt{t_s} \quad \dots(3.10)$$

A realistic formula for C_s , when $0.05 \leq h_s \leq 0.30$ m is given by the expression [6]

$$C_s = 1 - \frac{1.369b}{1.952h_s + 0.608b} \ln(1 - K) \quad \dots(3.11)$$

If $0.001 \leq h_s \leq 0.05$ m, the expression (3.11) is modified as

$$C_s = -10.11233 \left[\frac{1 - (\rho / \rho_s)}{2.0h_s + 0.11233} \right] \quad \dots(3.12)$$

Formulas (3.11) and (3.12) are recommended as these are more accurate than the formula given in IEEE Std. 80-2000 which is

$$C_s = \frac{0.09(1 - \rho / \rho_s)}{2h_s + 0.09} \quad \dots(3.13)$$

A thin layer of gravel /crushed rock, or insulating material such as asphalt on earth surface over the earth grid electrode increases magnitude of the maximum permissible touch and step voltages and thereby reduces the length of earth conductors required to keep dangerous voltages within limits. The gravel /crushed rock layer also restricts, growth of grass /weeds, moisture migration, movement of reptiles and permits the ingress of rainwater into earth. Therefore, gravel / crushed rock layer is always provided unless total electrode potential rise is extremely low. Even in such cases, the gravel /crushed rock is provided around (i) equipment / structures to restrict the movement of reptiles and (ii) oil filled transformers to prevent spread of oil in the event of an accident.

The electrical resistivity of gravel / crushed rock layer is usually assumed as 3000 Ω -m for determination of the maximum permissible touch and step voltages. Considering its effects on safety of human beings, the resistivity of gravel / crushed rock, should be ascertained by measurement of samples of the material and necessary actions should be taken to maintain the high resistance of the gravel / crushed rock layer.

3.6.3 Review of International Practices for Maximum Permissible Touch Potential

In IEC 61936 - 1 [7], typical touch voltage limits are given in the form of curves that are based on the findings given in IEC 60479-1 [8]. These curves are reproduced in Fig. 3.5.

In Fig. 3.5, Z1, Z2 and Z4 are from IEC 60479-1, and the curve Z3 is based on IEEE Std.80-2000 recommendations. The Curve Z3 of Fig. 3.5 represents the equation (3.6), and is given for comparison. Curve Z1 is obtained by assuming body impedance exceeded by 95% of population and a permissible current value that gives probability of ventricular fibrillation much less than 5%. Curve Z2 is similar to Z1 except that assumed body impedance is exceeded by 50 % of population. For curve Z4, bare foot to earth path resistance is assumed 700 Ω . As per IEC 61936 - 1, Z2 presents a low level of risk and should be considered as an acceptable minimum requirement.

Technical specification 41-24 [9] mentions that earth electrode voltage rise may be limited to 430 V rms except in case of high security lines that have fast acting protection, which limits the fault duration to less than 200 ms.

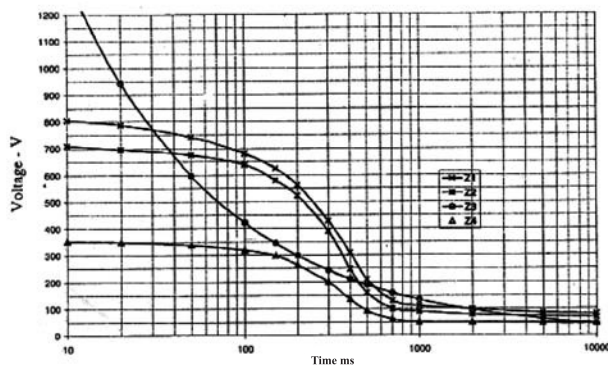


Fig. 3.5 Typical touch voltage limits

3.7 EARTH FAULT CURRENT AND RELATED PARAMETERS

The design of earthing system requires the magnitudes and durations of -

- The maximum current that flows through earthing conductors
- The maximum current (I_G) that flows between earth conductors and soil.

These currents can be obtained from earth fault currents at different buses in the station. Earth fault could be either single line to earth or double line to earth fault. Due to much higher probability of occurrence, generally single line to earth fault is considered. Single line to earth fault currents at different buses might be known from system studies or may be estimated using symmetrical-component method as explained in the following subsection.

3.7.1 Earth Fault Current I_f

For a single line to earth fault, the zero sequence current I_0 is

$$I_0 = E / [(3R_f + R_1 + R_2 + R_0) + j(X_1 + X_2 + X_0)] \quad \dots(3.14)$$

where

E is nominal phase to neutral voltage (V),

R_f is estimated resistances of fault, (Ω); normally assumed zero,

R_1 , R_2 and R_0 are positive, negative and zero sequence Thevenin equivalent system resistances (Ω) computed looking into the system from the point of fault. These are normally negligible in practical systems,

X_1 , X_2 and X_0 are positive, negative and zero sequence Thevenin equivalent system reactances (Ω). These are computed looking into the system from the point of fault.

The current I_f , symmetrical single phase to earth fault current, is

$$I_f = 3 I_0 \quad \dots(3.15)$$

The maximum symmetrical rms value of earth fault current (I_f) and its duration t_f (refer Section 3.8) are used for the determination of the minimum area of cross-section of earth leads and earth conductors of main grid electrode.

3.7.2 Grid Current I_g

Transmission lines carry electric power from one power station to the other. During an earth fault, appropriate phase conductors of transmission lines convey the fault current to the fault point. If the fault occurs at a generating station, part of this current is returned to local generators via the neutral connection. The earth wires / shield wires of transmission lines that shield the phase conductors against direct lightning strokes and are connected to station earthing system, carry a part of the total fault current to the sources of its supply. Thus the grid current is a fraction of the total fault current. The symmetrical grid current, I_g , may be expressed as

$$I_g = S_f I_f \quad \dots(3.16)$$

The factor S_f is termed as fault current division factor. I_f and I_g are magnitude of I_f and I_g respectively.

Because of dc offset, the effective rms value of asymmetrical fault current is denoted by I_f . The maximum value of grid current, I_G , is also determined by taking into account asymmetry of earth fault current due to its dc offset component. It may be increased further to allow for increase of current due to system growth. The total fault current at a station will increase with increase in system capacity. However, when new transmission lines are added, the earth/shield wires of new lines will decrease the grid current. If fault current is determined from System Fault Studies at a future date, typically five years hence, the increase in magnitude of I_G may have been accounted for already. If no projections of system growth are available, current division factor S_f at a substation may be taken as unity even though this may be a pessimistic view [4].

Various considerations regarding the maximum earth fault current I_f and grid current I_G and methodology for computation of I_G are given in Chapter 4. Examples of computation of earth fault currents of a 33 kV generating station and 132 kV substation are given in Chapter 11.

The maximum value of grid current, I_G , is used for the determination of (i) earth electrode potential rise (EPR) and earth surface potentials with respect to remote earth and (ii) magnitudes of touch and step potentials in the station area above the earth grid electrode. The current I_G and duration t_s of shock voltage / current exposure directly affect the length, layout, and depth of earth grid conductors to be provided to keep dangerous voltage within the maximum permissible limits.

3.7.3 Durations t_f and t_s of Current Flow during Fault

The fault duration, t_p for determination of size of earth conductors is higher than fault duration, t_s , for determination of the maximum permissible values of step and touch voltages due to considerations given in this section for the duration t_f and Section 3.6.2(b) for the duration t_s . The practices regarding duration t_f and t_s of earth fault current are dependent on ratings of relays and circuit breaking equipment. There is considerable standardization in the ratings of circuit breakers resulting in recommendations regarding fault duration time t_f and t_s . Normal operating time of protection relays and breakers should be used for personnel safety [7]. Therefore, the shock duration time (t_s) of 0.5 second for stations using digital relays and of 1 second for stations using electromagnetic relays can be used for determination of maximum permissible values of E_{step} and E_{touch} . To calculate the conductor cross-section, the time t_f should be the maximum possible fault clearing time including backup [7]. Therefore, fault duration time (t_f) of 1 second for stations using solid state or digital relays and 3-second for stations using electromagnetic relays may be adopted. A design engineer should choose the appropriate value applicable at the station for which the earth electrode is designed [9].

3.7.4 Specific Considerations

Technical and economic considerations for proper design of earthing systems require that:

- (i) The maximum rms values of current I_f and I_G should be computed accurately taking into account (i) dc offset current which is present during first few cycles after the fault and affects the magnitude of symmetrical rms current (ii) estimated increase in the earth fault current in future,
- (ii) The phase to phase short circuit or three phase short circuit that do not result in flow of fault current through earth should not be considered for the computation of currents I_f and I_G ,
- (iii) Single phase to earth faults which are statistically more frequent than two phase and three phase to earth faults, should be considered for determination of earth fault current,
- (iv) Single phase to earth fault current should be determined at various locations; out of these the one which results in the maximum grid current, should be selected for the design of earthing system. Generally this happens for a fault inside the station,

- (v) The neutral points of electric systems may be considered as solidly earthed for determination of earth fault currents,
- (vi) Standardized short time fault current / MVA ratings of switchgear should not be used for determination of currents I_F and I_G for the design of earthing systems due to experience that design of earthing system based on standardized ratings of equipment for voltage levels at the station is usually unrealistic and uneconomic, and
- (vii) The grid current I_G (actual current flowing between the grid earth electrode and the soil) which depends on transformer connections, neutral connection and a number of other parameters which may differ from station to station, should be determined for the design of station earth grid electrode. Standardization of grid current for stations of various categories is not possible.

3.8 SIZE OF EARTH CONDUCTORS

3.8.1 The main elements of the earthing system of HVAC stations are :

- Horizontally buried bare strip / round conductors
- Vertically buried bare rod / pipe / plate electrodes
- Bare/insulated earth lead conductors between above ground earthing points / terminals equipment /structures and underground buried horizontal conductors / vertical electrodes.

All underground conductors /electrodes are interconnected to form a common earth grid electrode as per requirements of the design of the earthing system.

The capacity of an earthing system to carry and dissipate earth fault current without creating a fire or explosive hazard in the area during its total design /service life depends mainly on material and size of various elements of the earthing system.

Basic considerations for selection of material of earth conductors / electrodes and procedure / guidelines for determination of their size / area of cross-section are given under this section.

3.8.2 Size of Earth Conductors

Various considerations and factors that influence determination of cross-sectional area of earth conductors are as below:

- (i) Technical Report No.5 [10] was prepared for standardizing the size of earth conductor for small substations; however, the expression given in the report can be used for determining area of cross-section of conductors of all types of earthing systems. The equation for determination of area of cross-section is

$$A_c = I \left[\frac{0.00104 \rho \alpha t_f}{\delta s \log \left(\frac{1 + \theta_m \alpha}{1 + \theta_0 \alpha} \right)} \right]^{0.5} \quad \dots(3.17)$$

where,

A_c = Cross-sectional area, mm²

I = Current, Ampere

- ρ = Resistivity of material, micro- Ω m (15 micro- Ω m)
 α = Resistance temperature coefficient of material per $^{\circ}$ C (0.00423/ $^{\circ}$ C)
 t_f = Duration of current flow, seconds
 δ = Density of material, gm/cm 3 (7.86 gm/cm 3)
 s = Specific heat of the material, cal/ gm $^{\circ}$ C (0.114 cal/ gm $^{\circ}$ C)
 θ_m = The maximum permissible temperature deg.C
 θ_0 = Ambient temperature deg.C

The ambient temperature θ_0 and standard values of material constants (ρ, α, δ and s) for the type of material of the conductor are used in (3.17); the values given in parentheses are for mild steel.

The maximum permissible temperature θ_m is dependent on (i) fusing temperature of material (ii) type of conductor-to-conductor joints and (iii) consideration that conductor temperature in flammable areas should not exceed the specified maximum permissible temperature for the area. Considering that (i) basic properties of material will not deteriorate if its temperature is limited to 40 percent of its fusing (melting) temperature and (b) the maximum permissible temperature of conductors with welded joints may be up to the maximum permissible temperature of the material, the temperature, 620 $^{\circ}$ C, is the maximum permissible temperature for steel conductors with welded type conductor-to-conductor joints; the value is 310 $^{\circ}$ C for steel conductors with bolted type conductor-to-conductor joints. These values are considered for determination of area of cross-section of steel conductors in non-inflammable areas. It is understood that the maximum permissible temperature for conductors of other materials are governed by similar considerations. The melting temperature of insulating material with adequate safety margin is considered for determination of the maximum permissible temperature for insulated earth continuity conductors / earth leads. Accordingly, the following simplified equations are used for determination of area of cross-section of earth conductors

$$A_c = 12.15 \times 10^{-3} I \sqrt{t_f} \quad \text{for welded joints} \quad \dots(3.18)$$

$$A_c = 15.7 \times 10^{-3} I \sqrt{t_f} \quad \text{for bolted joints} \quad \dots(3.19)$$

In general, the conductor size can be determined by using the formula [10]

$$A = KI \sqrt{t_f} 10^{-3} \quad \dots(3.20)$$

Values of K for steel, copper and aluminium are given in Table 3.5.

Table 3.5 : Constant K for determination of earth conductor size

Material	K for welded joints	K for bolted joints
Copper	4.7	5.8
Steel	12.15	15.7
Aluminium	8.4	12.0

Duration of current flow (t_f) is discussed in Section 3.7.3.

- (ii) Temperature rise of conductor material of earth electrode is limited by choosing its cross-sectional area in accordance with equations (3.17) to (3.20). Temperature rise at the surface of conductor material is also to be limited to prevent drying up of soil in contact with the conductor. The limit of surface current density is given by [5,9]

$$I_{sd} = 10^{-3} \sqrt{(57.7/\rho t_f)} \text{ A/mm}^2 \quad \dots(3.21)$$

where

ρ is soil resistivity in Ω -m and t_f is duration of current flow in seconds.

In most practical installations of grid earth electrodes, the value of surface current density will be considerably less than the above limiting value due to the vast quantity of electrode conductor used for control of dangerous voltages. Since area of cross-section, determined by equations (3.17) to (3.20), can safely carry the maximum fault current, the length of conductors is normally increased, if required, to fulfill the requirement of (3.21).

- (iii) It is essential that earth conductors should have not only the capacity to carry earth fault current without exceeding the maximum permissible temperature rise but should also be mechanically strong and rugged to maintain their integrity and perform their function under worst case physical conditions to which they may be subjected in actual practices. In most practical installations of grid earth electrodes for HVAC stations, the cross-sections of earth conductors determined as per Section 3.8.2 will fulfill the requirement of mechanical ruggedness and strength.
- (iv) Dimensions of vertical rod / pipe / plate type electrodes and minimum size of earth conductors of various materials for earthing systems of HVAC stations shall be in accordance with specifications / recommendations given in IS 3043 - Code of Practice for Earthing [11] except that -
- Vertical rod / pipe / plate type electrodes of higher size and /or extending up to deeper depth shall be used if required to keep dangerous touch and step voltages, resistance of earth electrode and its potential rise within required limits.
 - When vertical rod / pipe / plate electrode is used as the principal earth electrode, its size shall be increased if required to ensure that current density in A/mm^2 at its surface should not exceed $10^{-3} \sqrt{(57.7/\rho t_f)}$.
 - Horizontally buried bare round /strip type earth conductors and earth leads of higher sizes shall be used if required in accordance with guidelines / methodology given in this section/ document.
- (v) All non-current carrying electrically conductive enclosures, structures etc. which either enclose energized conductors or are adjacent thereto, neutral points of power transformers and generators etc., shield wires of overhead power transmission lines, air termination /down conductors of lightning protective system, etc. are connected to underground buried conductors / electrodes of earthing system. The connection between each above ground earthing point / terminal of each items (to be earthed) and underground earth conductors / electrodes is made by two separate and independent earth leads or earthing conductors [12], each sized to carry full earth fault current and connected to different conductors /electrodes of earth grid electrode in accordance

with accepted practice to ensure the availability of low resistance path for flow of fault current to underground earth conductors / electrodes even under discontinuity of one of the two earth lead conductors. The size of earth lead conductors may be reduced to 60% if there are more than two separate and independent paths for the flow of current between equipment /structure and underground earth grid conductor /earth electrode, The maximum current density in steel earthing conductors should be 80 A/mm² when t_f is 1 s and 45 A/mm² when t_f is 3 s [5].

Although total fault current is divided into two or more paths in underground earth grid electrode, the total maximum earth fault current is considered for determination of area of cross-section of all underground earth conductors by equations (3.17) to (3.20). Lower value of current may be used based on sound technical analysis.

- (vi) The area of cross section of bare steel earth conductors is increased to allow for the loss and deterioration of conductor material due to corrosion in soil in accordance with various considerations given in Section 3.10 and Annexure A.

Based on area of cross-section determined by equations (3.17) to (3.20) and requirements for (i) increase in size of conductor to allow for loss of material due to corrosion, and (ii) mechanical strength of conductor, the final size of steel earth conductor is selected with reference to manufacturer's product sizes of steel strip and round conductors given in Table 3.6 for general reference.

Both mild steel strip conductor and mild steel round conductors are used for fabricating grid earth electrodes. The strip conductor is preferred by some utilities because of ease of welding and mechanical workability. The round conductor is preferred by others because it has the minimum perimeter for a given cross-sectional area. It is said to have better-shape for application in highly corrosive soils and is used where thickness of conductor is to be increased for loss of metal due to corrosion (pitting).

Table 3.6 : Sizes of steel strips / round conductors

Strip	W	25	25	35	35	40	40	40	45	45	50	50	50
W-wide	T	3	6	6	10	6	8	10	6	10	6	8	10
T- Thick	W	65	65	65	75	75	75	75	100		150		
	T	8	10	12	8	10	12	20	10	12	16	12,16,25	
Round, dia mm		8	10	12	16	18	20	22	25	28	32	36	40
Availability depending on size and order quantity													

- (vii) The size of earth conductors and earth lead conductors of different categories of stations may be standardized because of the following reasons:
- The minimum size of conductor is fixed from the viewpoint of ruggedness and mechanical strength.
 - Conductor size is based on the maximum earth fault current (I_f). The maximum earth fault current may occur for an earth fault at the lowest voltage level at the station and it may depend on the size of transformer that may be similar at most stations.
 - Dimensions of vertical rod / pipe / plate type electrodes are generally the same for all stations.

It is understood that sizes of steel conductor, standardized to carry fault current I_f for duration of t_f seconds, will be increased as required by taking into account the requirement of increasing the size of underground Mild Steel conductors to compensate for the loss of metal due to corrosion.

3.9 MATERIAL OF EARTH CONDUCTORS

Copper, Mild Steel (MS) and Aluminium may be used as material of earth conductors.

Area of cross-section of copper conductor required for carrying current I_f for duration of t_f seconds is the lowest of the three, and corrosion of copper conductors is the minimum in almost all types of soil. These considerations and ease of installation of copper conductors of relatively lower weight and area of cross-section, favour the use of copper as the material of earth conductors. Various considerations that do not favour the use of copper as material of earth conductors are discussed under Section 3.10.4.

Area of cross-section of aluminium conductor required for carrying current I_f for duration of t_f seconds is larger than that of copper conductors and is lower than that of MS conductors. The formation of nonconductive oxide film on underground aluminium conductors may not permit proper flow of current between conductor and soil. The galvanic coupling between aluminium conductors and other underground steel structures / pipes may result in corrosion of aluminium conductors. The making of proper aluminium conductor-to-conductor brazed joints and bolted joints between aluminium conductor and steel terminals of equipment is generally problematic. Therefore, use of aluminium as the conductors of earth electrode grids of HVAC stations requires detailed investigations of all attendant circumstances. Based on these consideration, cost, and availability of material, the use of aluminium for earthing systems of HVAC stations in India has not been considered /recommended in this document.

Area of cross-section of MS conductors required for carrying current I_f for duration of t_f seconds is the highest of the three materials. Mild steel is subject to corrosion in all types of soils. Therefore, area of cross-section of MS conductor determined for carrying I_f Amperes for t_f seconds is further increased to allow for the loss of metal due to corrosion. Various considerations, due to which the use of mild steel as the material of earth conductors is recommended, are discussed under Section 3.10.4.

Formation of galvanic corrosion cells between different metals of underground horizontal conductors, and vertical rod / pipe / plate electrodes results in corrosion of relatively less noble of the cell formed between different materials. Therefore material of all underground horizontal conductors, and vertical rod / pipe / plate electrodes should be the same.

3.10 CORROSION OF EARTH CONDUCTORS

3.10.1 Effect and Causes

Loss of material of earth conductor due to corrosion reduces its effective area of cross-section and current carrying capacity. Results of studies of corrosion on short earth electrodes are given in [10,13]. It is known that extent of corrosion depends upon the properties of soil. Generally poor aeration and high values of acidity, electrical conductivity, salt and moisture content are characteristics of corrosive soils.

3.10.2 Mechanism of Corrosion

Corrosion of metals due to presence of electrolyte in soil / water is caused mainly due to operation of corrosion cells. In case of underground earthing systems, the corrosion cell may be formed under the following conditions:

- (i) Variations of metal to soil potentials due to non-homogeneous conditions in soil and on metallic surface, and
- (ii) Electric coupling between dissimilar materials of earth conductors, pipelines, foundations, cable sheaths etc.

Each corrosion cell has an anode and a cathode. The metal to soil potential of anodic area is relatively more electronegative than that of cathodic area. The anodic area is metallically and electrically connected with the cathodic area, and the two are also in contact with each other through electrolyte in soil /water. The corrosion cells are formed only under these conditions and various chemical reaction and activities that take place at anodic and cathodic areas and in soil during the operations of corrosion cells results in

- (i) Corrosion of metal at the anodic area,
- (ii) Flow of current in soil from the anodic area to the cathodic area and the return of current from the cathodic area to the anodic area through external metallic circuit, and
- (iii) Shift of metal to soil processes at anodic and cathodic areas depending on nature of activities and products of reactions that take place at these areas.

In general, corrosion of metal due to operations of corrosion cells is a function of magnitude of corrosion current that depends mainly on,

- (i) Potential difference between anodic and cathodic areas, and
- (ii) Resistance to flow of current through soil and therefore electrical resistivity of soil.

3.10.3 pH Value

pH value of soil is a measure of the acidity or alkalinity of the soil. For neutral soil its value is numerically equal to 7. The value increases with alkalinity and decreases with increasing acidity. Soil pH can be measured with a number of commercially available battery-powered meters. Bare steel is more susceptible to corrosion in acidic rather than neutral or alkaline media i.e., it corrodes more easily in soils of pH value less than 7. For determining corrosion the pH value of soil in immediate vicinity of conductor material is of consequence. Keeping in view effect of pH and other factors (refer Annexure A), the corrosion is mainly related to resistivity of soil as discussed in Section 3.10.6.

3.10.4 Corrosion of Steel and Copper Conductors

Due to its intrinsic properties, copper is subject to very low corrosion in most of aboveground and underground locations of electric power stations and switchyards. In case of galvanic cell between copper and steel, copper acts as cathode and steel acts as anode and corrodes. The use of copper earth conductors may cause [14] -

- (i) Corrosion of underground steel pipelines / conduits, metallic sheaths of cables, structural steel etc. that are normally connected to earthing system, and
- (ii) Corrosion of steel earth electrodes and conductors forming a part of earthing system.

In spite of much higher rate of corrosion than copper, main factors that favour the use of steel as material of earth conductors and earth electrodes are generally as follows:

- (i) Corrosion of other underground steel pipelines / conduits, metallic sheaths of cables, structural steel etc. that are normally connected to earthing system, will not be accelerated due to material (as against copper) of earth conductors,
- (ii) Cost-benefit analysis favours steel even after considering the increased area of cross-section of steel conductors as required to allow for loss of metal due to corrosion under worst conditions during design life of earthing systems.

Underground earth conductors are electrically interconnected to form a common earthing system for all equipment, structures, and installations of electric power stations and switchyards. The formation of galvanic corrosion cell between copper and steel conductors results in rapid corrosion of steel conductors. Therefore, usage of both copper and steel underground earth conductors is not recommended in a common earthing system

3.10.5 Corrosion Prevention Measures

Painting and / or galvanizing of aboveground earth lead conductors is recommended to minimize damage of conductors due to atmospheric corrosion. The painting / galvanizing of underground conductors is not recommended mainly due to following considerations:

- (i) Insulating paint on conductors will prevent the flow of current that is required between underground earth conductors and soil,
- (ii) Possibility of damage of zinc coating of galvanized conductors during transportation, laying and conductor-to-conductor welding,
- (iii) Possibility of rapid consumption of zinc coating of galvanized conductors due to galvanic cell action between zinc coated and bare steel surface of conductors,
- (iv) Paint / galvanizing is not required for earth conductors if their area of cross-section is increased to allow for loss of metal due to corrosion.

3.10.6 Corrosion Allowance for Underground Steel Conductors

- (a) Categorization of soils

Area of cross-section of steel conductors, calculated by equations (3.17) to (3.20), should be increased to allow for loss of metal due to corrosion during the designed life of earthing system. Corrosion of metal, buried underground, depends on various physical and chemical properties of soil that vary from place to place and with time. Electrical resistivity of soil is the best possible measure of (i) physical properties and (ii) moisture, salt and other contents of soil that affect corrosion process. The magnitude of corrosion cell currents also depends on electrical resistivity of soil. Therefore, electrical resistivity of soil generally forms the basis for categorization of corrosiveness of soil as given in Table 3.7 [10,13]. One method of ascertaining corrosiveness of a soil is given in [15]. In this method, relative importance of various factors, which generally affect corrosiveness of soil, is assigned rankings. These are reproduced in Annexure A in tabular form.

Table 3.7 : Soil resistivity and corrosiveness of soil

Sl. No.	Soil resistivity $\Omega\text{-m}$	Class (corrosive) of soil
1	Less than 10	Severely corrosive
2	$> 10 < 25$	Corrosive
3	$> 25 < 50$	Moderately Corrosive
4	$> 50 < 100$	Mildly Corrosive
5	> 100	Very Mildly Corrosive

(b) Corrosion Allowance

Recommendations for increasing area of cross-section of steel conductors to allow for loss of metal are based on data given in Table 3.8. Table 3.8 is based on observations of corrosion of steel at 44 locations for a period of 12 years [10, 16].

Table 3.8 : Corrosion of steel in soil

Sl. No.	Corrosion	Minimum	Maximum	Average
1	Average rate in mg per dm^2 per day (mdd)	0.50	30.0	4.50
2	Max penetration in mils for total exposure period	20	120	61

Recommended corrosion allowance, given in Table 3.9 [10,13,16], is in two forms, namely (i) % loss of steel conductors due to uniform corrosion and (ii) reduction of thickness of steel conductors due to pitting. It is based on corrosion data given in Table 3.8 and the following considerations:

- (i) Average rate (mdd) of corrosion may be considered for determination of % loss of material and depth of pitting (mils) can be considered for determination of reduction of thickness of conductor,
- (ii) Corrosion of metals reduces with time. Therefore, it can be considered that corrosion of steel will be as given in Table 3.8 for first 12 years, 50% of the first 12 years during the next 12 years, and negligible afterwards,
- (iii) The maximum rate of corrosion given in Table 3.8 can be considered for corrosive and severely corrosive soil given in Table 3.7 and the average rate of corrosion may be considered for mildly and moderately corrosive soils,
- (iv) Reduction of thickness of conductor due to the maximum depth of pitting on both sides of the conductor at the same location will result in the maximum loss of metal due to corrosion.

Table 3.9 : Corrosion allowance for steel earth conductors

Sl. No.	Resistivity ($\Omega\text{-m}$)	Class (corrosive) of soil	%	Thickness	
				mil	mm
1	Up to 25	Corrosive & Severely Corrosive	30	180	4.50
2	$>25 < 100$	Mildly & Moderately Corrosive	15	90	2.25
3	> 100	Very Mildly Corrosive	10	30	0.75

Percentage allowance is recommended for short lengths of conductors by considering that resistivity of soil will be uniform around total surface area of conductor and conductor may not be subject to

pitting corrosion under such conditions. Thickness allowance is recommended for grid conductors covering large area comprising soils of varying physical and chemical properties.

3.11 SPECIFIC CONSIDERATIONS

3.11.1 Calculation of Dangerous Touch & Step Voltages

The magnitude of touch and step voltages and earth grid potential rise during earth fault conditions in the electric system depend on number, spacing, length and depth of horizontally buried conductors of earth grid electrode besides electrical resistivity of soil and grid current, I_G , component of earth fault current. Various considerations and methods for determination of the maximum touch and step voltages and earth grid resistance, dependent on these parameters, are given in Chapter 5 for earth grid electrodes comprising uniformly spaced horizontal conductors in homogenous soil. Computer software is required for determination of:

- Touch and step voltages at various locations on ground surface above the earth grid electrode comprising uniformly spaced horizontal conductors in homogenous soil,
- The maximum touch and step voltages and / or touch and step potentials at various locations on ground surface above the earth grid electrode comprising non-uniformly spaced horizontal conductors in homogenous soil. and non-homogenous soil represented by two layer soil resistivity model.

For a given area 'A' m² of grid earth electrode at a site of soil resistivity ρ Ω -m earth resistance $\cong k. \rho / \sqrt{A} \Omega$. Increasing the number of conductors in the grid electrode will reduce the magnitude of k only marginally. On the other hand by increasing the number of parallel conductors of grid earth electrode the step and mesh voltages can be reduced to some extent, but the decrease is not inversely proportional. Reducing the spacing of conductors near the periphery would be more effective.

Determination of touch and step potentials for different spacing of horizontal grid conductors at critical locations is essential for optimization of total length, spacing, depth etc. of horizontally buried conductors of earth grid electrode and also for determination of scheme for earthing of station fence. Therefore application of computer software is essential for safe and economic design of earth grid electrodes of HVAC stations. Examples of design of earth grid electrode by computer software are given in Chapter 11.

3.11.2 Transferred Voltage

The maximum magnitude of transferred voltage is the total voltage rise of earth grid electrode with respect to remote earth during an earth fault at the station. When a person standing within the station area touches a conductor that is earthed at a remote point, the person is exposed to the transfer potential of the earth electrode of the station. Also, when a person standing at a remote point (outside the area of influence of station earth electrode) touches a conductor connected to the station earth electrode, the person is exposed to the transfer potential of station earth electrode. The magnitude of transferred voltage is usually quite high. Therefore, it is essential to take appropriate measures for safety of personnel/equipment in remote areas where total potential rise of station

grid electrode may be transferred by conductors, metallic service lines etc. that are connected to the earth grid electrode of HVAC station. Similarly measures have to be adopted against presence of conductors of communication lines, low voltage supply etc. that may be earthed at some distance from the station. Various considerations and preventive measures with regards to transferred voltage are given in Chapter 5.

3.12 EARTHING OF STATION FENCE

A station perimeter fence or wall is used (i) to mark the boundary of the property/switchyard and (ii) to make it safe from ingress of unauthorized persons from outside. A fence is also used to separate the outdoor switchyard of a substation from the rest of it. The fence is usually accessible to the general public, working personnel and cattle. So far as earthing at a substation is concerned, the decision whether (i) the fence earthing is to be connected to substation earth electrode, or (ii) it may have independent earthing or (iii) it is left unearthed is based on the following considerations and results of design calculations wherever possible.

3.12.1 Completely Unearthed or Partially Earthed Fence

When fence is completely unearthed it is located outside the earth grid area and it is neither connected to the substation earthing system nor is provided with a separate earth conductor. It is assumed insulated from any connection to earth and is somewhat difficult to achieve. In case fence is partially earthed, the metallic fence is connected to the earth through fence post concrete reinforcement. Such an earth connection is only partial and cannot be relied upon as an effective earth. In either case, the grid conductors must end at least 2 m inside the fence.

The danger of a live line falling on a fence is usually of great concern. In such an eventuality, when the fence is unearthed, the fault current dissipates through the earth adjacent to the earth fault. In case of partially earthed fence also, the fault current shall flow through the fault and through the high resistance earth connection. In either case fence shall attain a high voltage under fault condition with respect to the adjacent earth surface. High earth surface voltage gradients shall develop around the fence. The consequent touch voltage and step voltage are likely to be more than their permissible values. Safety is somewhat impractical, unless broken phase conductor not touching the fence can be assured.

3.12.2 Fence Earthing Connected to Substation Earth Electrode

The fence is located within the grid earth electrode or just outside it. An earth conductor may be run below the fence or next to it. The fence voltage will equal EPR in case of an earth fault. Since the area covered by the grid earth electrode is increased as compared to the case when grid earth electrode is terminated well inside the fence line, the station earth resistance is reduced. It also obviates any risk of inadvertent electrical connection between the fence and the grid earth electrode. If the fence is situated at the boundary of the grid earth electrode, a perimeter earth conductor can be run close to the fence and fence is bonded electrically to the grid earth conductors adjacent to it as per design. Bond between the fence and the grid earth electrode should be made at all points where HV overhead conductors cross the fence.

To reduce the touch voltage from outside, a perimeter earth conductor is often buried outside the fence, 1 m away from the fence and at the same depth as the conductors of grid earth electrode.

This conductor is made part of grid earth electrode and is electrically connected to the fence.

Sometimes a second additional perimeter conductor is buried 2 m outside the fence at a depth of 1 m. This conductor further increases effective area of grid earth electrode and is useful for decreasing touch voltage from outside the fence and the step voltage.

In spite of these measures, spreading of gravel/crushed rock up to a distance of 1 m outside the fence may be necessary to make touch voltage from outside safe. In case, it is not possible to provide gravel outside the fence, detailed analysis for the particular case has to be carried out in order to determine suitable location and depth of burial of outer grid conductors so as to ensure that the fence touch potential remains within safe limits.

3.12.3 Independent Fence Earthing

This type of fence earthing is possible only where substation grid earth electrode is terminates at least 2 m inside the perimeter fence such that the fence is isolated from station grid electrode. In this case the fence is earthed by vertical rod electrodes at all corners, at all points where HV overhead conductors cross the fence and with further vertical rod electrodes at about 50 m interval around the periphery. The boundary gatepost should be bonded together with below ground connections to ensure that different potentials do not arise when the two gates are bridged by a person opening the gate.

The fence potential, when an earth fault occurs in the station, shall be equal to the potential of the earth where its earthing conductor is placed. This potential shall be less than the potential of the earthing system of the substation, i.e., Earth Potential Rise (EPR). A fence can be isolated from the station grid electrode only if the distance of fence is more than 2 m from the peripheral earthing conductor of station grid electrode or anything connected to it. Isolating the fence from the main earthing system and using a separate earthing conductor for the fence at a suitable depth shall ensure adequate safety so long as no inadvertent metallic connection is established between the fence and the earthing system. However, once the fence gets connected to the main earth grid it may seriously jeopardize the safety of the personnel outside the fence. The risk factor will increase with the increase in the separation between the fence and the main grid. Complete metallic isolation of the fence from the main earthing system may not be possible as there is always a chance of inadvertent electrical connection between the earth grid and the fence through metallic conduits, water pipes, cable sheaths etc. and the main grid potential may get transferred to the fence leading to dangerous touch potential and potential gradients near the fence during fault conditions.

3.12.4 Protection against Touch Voltage from Outside

It is known that in a grid with nearly rectangular, equispaced meshes, touch voltage would be the maximum at the corner meshes of the grid earth electrode. If a corner mesh inside perimeter fence is considered when fence is earthed to the station earthing system, it is quite likely that there is no equipment with earthed metallic body or earthed structure other than the fence itself. As a result, the touch voltage is likely to occur between the fence and a point on earth surface 1 m away from the fence either inside the fence or outside the fence. The switchyard surface inside the fence can be covered with gravel. Even if gravel is used to cover the earth outside the fence initially, it is very difficult to maintain it. Thus the actual permissible touch voltage outside the fence may be much less

than the value if earth was covered with gravel. At some stations, it may be difficult or uneconomical to make the touch voltage outside the fence less than the permissible value. As a safety measure, the chain link fence could be fabricated from plastic covered material, but due to weathering and wear etc. bare metal would be exposed in course of time and the hazard would remain.

3.12.5 Other Measures

Amongst other measures that could be taken, one is to provide a ditch one meter wide and one meter deep outside the periphery fence to make touching of fence from outside very difficult. This requires ownership of land outside the boundary fence.

A second measure that can be adopted is to construct a 2 m high wall, at the perimeter boundary of the property instead of a chain link fence. For safety against incursion, a 1m high metallic fence can be erected on top of the wall. This fence would be earthed in the same manner as the fence erected at ground level. In this manner touch situation from outside as well as inside can be avoided. In this case it would not be necessary to make the mesh voltage in the corner mesh less than the permissible. It would be the mesh voltage where a metallic earthed body/structure actually exists on ground.

Taking various factors into consideration, fence bonded to the station earth, is the most common, though isolated fence with independent earthing may be employed sometimes.

3.13 SUMMARY

In this chapter the parameters on which design of an earthing system depends are defined. The factors, which affect earth resistance, and dangerous voltages, are given. Several steps of the design methodology are described. These are summarized below:

- (i) Soil resistivity is the main parameter, dependent on physical and chemical composition of soil, its moisture content, presence of salts in it, and its temperature.
- (ii) The soil resistivity should be determined by measurements at the site and the homogenous or two-layer model of soil resistivity, determined by analysis of measured values of soil resistivity, should be used for determination of performance of earth grid electrode.
- (iii) The permissible values of dangerous voltages dependent on maximum permissible body current, resistance of human body and feet should be determined by using well accepted practices and expressions / graphs for computing them.
- (iv) The effect of surface layer of gravel or asphalt should be taken into consideration in expressions for determination of maximum permissible dangerous voltages.
- (v) The earth fault current should be determined for computing the area of cross section of earth conductors and earth electrode.
- (vi) The magnitude of grid current that flows between earth electrodes and soil should be determined and used for calculating the EPR and dangerous voltages.
- (vii) The shock duration for determination of maximum permissible dangerous voltages and fault duration for determination of area of cross section of earth conductors should be ascertained based on clearing time required by primary and backup protection systems and switchgear of the station.

- (viii) Area of cross section of underground steel earth conductors, determined to carry earth fault current, should be increased to account for loss of metal due to corrosion during designed life of earthing system.
- (ix) Factors that affect safety due to (a) touch and step potentials near the fence and (b) transfer potentials at remote locations should be properly analyzed and considered.

REFERENCES

- [I] *A Simple Guide to Earth Testing*, Published by AVO International Limited, Dover, Kent CT17 9EN, 1986.
- [2] *Workshop on Earthing Practices*, 13-18 March, 1978, Punjab Engineering College, Chandigarh.
- [3] Reinhold Rudenberg, "Grounding Principles and Practices-Part 1, Fundamental Considerations on Grounding Currents," *Electrical Engineering*, Vol. 64, No.1, pp. 1-13, Jan. 1945.
- [4] *ANSI/IEEE Standard 80-2000, IEEE Guide for Safety in AC Substation Grounding*, IEEE, NEW York, 2000.
- [5] *BS 7354:1990, Code of Practice for Design of High-voltage Open-terminal Stations*, British Standards Institution, London, 1990
- [6] Hans R. Seedher and Arora, J.K. "A Comparative Study of Expressions for Reduction Factor for Ground Resistance of Foot," *IEEE Trans. On Power Delivery*, Vol. 18, pp. 849 - 851, July 2003.
- [7] *International Standard IEC 61936-1, Power Installations exceeding 1 kV a.c.* International Technical Commission, Geneva, Switzerland, 2002.
- [8] *International Standard IEC 61479-1, Effect of Current on Human Beings and Livestock*, International Technical Commission, Geneva, Switzerland.
- [9] *Technical Specification 41-24, Guidelines for the Design, Installation, Testing and Maintenance of Main Earthing Systems in Substations*, Engineering & Safety Division, The Electricity Association, London, 1992.
- [10] *Technical Report No. 5, Steel Grounding Systems where Grounding Mat is not needed*, Central Board of Irrigation and Power, New Delhi, 1976.
- [II] *Indian Standard IS: 3043 - 1987, Code of Practice for Earthing (First Revision)*.
- [12] *Indian Electricity Rules 1956 (as amended up to 25th Nov., 2000)*
- [13] Thapar, B. "Conductor for Grounding High Voltage Stations," *Power Engineer*, Vol. 15, No. 4, 1965.
- [14] *Technical Report No. 43, Interconnection of Grounding mats of Different Materials*, Central Board of Irrigation and Power, New Delhi, 1985.
- [15] *Hand Book of Cathodic Protection*, W Baeckmann and W Schwenck.
- [16] Manohar, V.N. and Nagar, R.P. "Design of Steel Earthing Grids in India," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-98, No. 6, pp. 2126 - 2134, Nov/Dec 1979.

ANNEXURE A

RANK NUMBERS FOR DETERMINATION OF CORROSIVENESS OF SOIL

Corrosiveness of soil depends on a number of factors. In one of the methods [15], a rank number is given for the corrosiveness of each “critical factor” and corrosiveness of soil is evaluated by the sum of all rank numbers as given in the following Table A.1 Information given in this Annexure may be used for general understanding of contributing effects of some factors on corrosiveness of soil.

Table A.1 – Corrosiveness of Soil

SI. No.	Sum of Rank Numbers	Corrosiveness of Soil
1	>0	Practically non-corrosive
2	0 to (–) 4	Weakly corrosive
3	(–) 5 to (–) 10	Corrosive
4	< (–) 10	Strongly corrosive

Rank Numbers for Critical Factors

SI. No.	Factor	Details	Rank Number
1	Type of Soil	Chalk, Chalk Marl, Sand Marl, Sand	(+) 2
		Loam, Loam Marl, Loamy Sand and Clayey Sand	0
		Clay, Clay Marl, Humus	(–) 2
		Peat, Mud, Bog Soil	(–) 4
2	Soil Conditions	Underground water at the level of structure	
		• Not Present	0
		• Present	(–) 1
		• Variable	(–) 1
		Undisturbed soil	0
		Mechanically shifted soil	(–) 2
		Uniform soil around structure	0
		Dissimilar soil around structure	(–) 3
3	Soil Resistivity	> 100 Ohm - M	0
		> 50 <100	(–) 1
		> 23 < 50	(–) 2
		> 10<23	(–) 3
		<10	(–) 4
4	Water Content	<20%	0
		>20%	(–) 1
5	pH	> 6	0
		< 6	(–) 1

6	Total Acidity to pH =7	< 2.5 mval /kg $> 2.5 < 5$ > 5			0 (-) 1 (-) 2
7	Redox Potential at pH = 7 related to rH	mV > 400 $> 200 < 400$ $> 0 < 200$ < 0	rH > 27.8 $> 20.9 < 27.8$ $> 14 < 20.9$ < 14	Aeration Strong Normal Weak No	(+) 2 0 (-) 2 (-) 4
8	Content of Calcium and Magnesium Carbonate	$> 5 \% = 50000$ mg / kg $> 1 < 5 \% = > 10000 < 50000$ mg / kg $< 1\% = 10000$ mg/kg			(+) 2 (+) 1 0
9	Hydrogen Sulphide	Not Present Traces = < 0.5 mg / kg S^2 Present = > 0.5 mg / kg S^2			0 (-) 2 (-) 4
10	Coke or Coal Content	Not Present Present			0 (-) 4
11	Chloride Ion	< 100 mg / kg > 100 mg / kg			0 (-) 1
12	Sulfate Content	< 200 mg / kg $> 200 < 500$ $> 500 < 1000$ > 1000			0 (-) 1 (-) 2 (-) 3

CHAPTER - 4

Fault Current Distribution for Design of Earthing Systems

Synopsis : One of the most important parameters of earthing design of a station is the grid current that flows between an earth electrode and the surrounding earth. It is a fraction of earth fault current. Maximum value of grid current is generally obtained for an earth fault within the station. The factors that affect grid current are presented in this chapter. An algorithm for calculating grid current is described

4.1 INTRODUCTION

4.1.1 Earthing system of a generating station or a substation is designed with the prime objective of providing safety to personnel during an earth fault. The fault current during an earth fault has several alternate paths for returning to the sources which feed the fault. A part of the current flows between the earthing system and the surrounding earth for returning to the sources of origin; the remaining current may return through earth wires or may flow through a metallic path consisting of the conductors of the earthing system and its connection to the neutrals of the sources of supply. The component of fault current that flows between the earthing system and the surrounding earth is called grid current. Only this component of the current is responsible for creating dangerous voltages, within or around the station, to which a person can be accidentally subjected during an earth fault. Evaluation of grid current is thus of paramount importance for the design of an earthing system.

The size of the conductor forming the earthing system, however, depends on the current that can flow in the conductors of the earthing system. Therefore, for evaluating safety of the station and for determining size of the earth conductor, two different values of currents are of interest.

The grid current may vary between a few percent to almost 100% of the earth fault current depending on the location of fault, configuration and parameters of earth wires and phase conductors, and the earth resistance of the station. The location of an earth fault that results in the maximum value of the fault current may not result in the maximum value of the grid current. The fault location that results in the maximum value of grid current is to be identified by considering various possible fault locations and accounting for the current diversion by alternate paths.

4.1.2 The problem of determination of grid current has been dealt by several researchers and a number of analytical methods have been reported [1-5]. In a survey conducted by IEEE [6], it was, however, found that majority of utilities the world over did not appropriately account for current diversion by the alternate paths to determine the maximum grid current. The maximum value of the earth fault current or an arbitrary fraction of it was being used in place of the maximum grid current. This may be because of the requirement of an elaborate set of data about all the transmission lines, earth wires, transformers and generators of the system for application of analytical methods for its determination. Another reason can be unavailability of the earth fault current resulting from changes in electric power system. A number of simplified methods have also been proposed [7-8] for evaluation of grid current.

In the method proposed by Thapar and Madan [7], the current diverted by aerial earth wires has been divided into two components. One of these components is the current diverted from the

station, where fault occurs, through conduction by all earth wires, connected to the earthing system of the station, of all transmission lines which terminate at the station and which contribute to fault current. The second part is the current diverted by the earth wires because of mutual induction between earth wires and phase conductors of the respective transmission lines. The method, however, may give erroneous results for many situations. In case of two circuits which are coupled conductivity and inductively, it is not possible to separately calculate the current in a circuit as two components, those because of conduction and by induction, and then use superposition to obtain the total current as done by Thapar and Madan. Further, in actual implementation of the method in [7], the current diverted by earth wires of lines not contributing to the fault has not been taken into account. It has been shown by Joy, Meliopoulos and Webb [5] that a substantial amount of current may be diverted by earth wires of such lines. Also the computer implementation of this method has not been reported.

Garrett et al. [8] have prepared a number of graphs drawn on logarithmic scale for obtaining ratio of grid current and earth fault current. These graphs, obtained by using a computer program [5] developed at Electric Power Research Institute (EPRI), however, do not fit into all practical situations. Interpolation and approximation have to be used in most cases. Graphs only provide a rough estimate of the grid current.

4.1.3 A simple but accurate method for computation of grid current at a station has been proposed by Seedher, Arora and Soni [9]. The method follows from the work of Thapar and Madan [7], the limitations of which were discussed in the previous section. An alternate approach of solving for current diversion by earth wires in place of splitting it into inductive and conductive components is proposed. Further, unlike the approach in [7], the current diversion by all the earth wires connected to the station earth, including those of the transmission lines which are not carrying any fault current, is computed. As in [7] as well as [8], it is assumed that the earth fault level for different buses within the station is known from the short circuit studies. A computer program with the symbolic name PAG (Practical Approach for computation of Grid current), has been developed and tested [9]. The data requirement of the program is quite simple.

4.2 CURRENT FOR DESIGN OF EARTH CONDUCTOR

4.2.1 Earth conductor, joints and connecting leads of an earthing system are designed both from considerations of current carrying ability and mechanical reliability. From consideration of current carrying ability, the conductor should resist fusing and mechanical deterioration under most adverse combination of fault current magnitude and its duration. Empirical formulae are available in literature [10,11] and in Chapter 3 of this manual for determining the minimum size of the conductors of different materials in terms of fault current magnitude and fault duration.

When an earth fault occurs between live parts and earthed metallic parts or structures in a station, whole of the fault current may flow in part of the earthing system including conductors joining faulty equipment to the earthing system. This current divides into a number of different paths in the earthing system. The design of the earth conductor, however, is based on the total value of the worst-case earth fault current. The worst-case earth fault current can be determined by carrying out fault calculations at different buses of the station or this information may be available from the results of system short circuit studies,

A conservative design of the earth conductor is desirable in view of the fact that it is less costly to include adequate margin in conductor size during the initial design than to reinforce the earthing

system at a later date. As such, value of the current used to determine the conductor size should take into account the possibility of future growth. Duration of the fault current used for determining conductor size, as discussed in Section 3.7, is taken equal to clearing time of the backup protection system.

4.3 THE MAXIMUM GRID CURRENT

4.3.1 Part of the earth fault current that flows between the earthing system of the station and the surrounding earth is called grid current. The rest of the fault current returns to the sources of supply through metallic paths. The current returned through the metallic paths does not create any earth surface potentials and is of no significance so far as station safety is concerned. The grid current on the other hand emanates into or is collected by the earthing system of the station from the surrounding earth. This current creates potentials on the earth surface within and around the station. It also raises potential of the earthing system to a value equal to the product of the magnitude of the grid current and the resistance offered to the flow of grid current (earth resistance). Potential gradients and EPR created by the grid current are responsible for the possible dangerous voltages, viz. step, touch and transferred voltages, to which a person can be subjected during an earth fault. Thus, from the safety consideration the grid current and not the earth fault current is of interest.

Location of the fault that results in the maximum value of earth fault current, may not result in the maximum value of the grid current I_G . The maximum grid current can be expressed as product of four factors[10]

$$I_G = C_p D_f S_f I_f \quad \dots(4.1)$$

where

I_G = Magnitude of the maximum value of grid current

I_f = Magnitude of symmetrical (without taking dc offset into consideration) earth fault current for fault case, within the station area or on a line, resulting in maximum grid current, A

C_p = Corrective projection factor, accounting for future increase in fault current during substation life span

D_f = Decrement factor to take into account dc offset

S_f = Current division factor, fraction of total earth fault current that flows between the earthing system and the surrounding earth.

The maximum value of the grid current I_G is not necessarily obtained for the largest value of any one of the individual factors, but is the maximum when combined product of all the factors is the maximum. The first three factors in (4.1) are briefly discussed in the following subsections. The current division factor, which is the most predominant factor in the determination of the grid current, is discussed in detail in Section 4.4.

4.3.2 Earth Fault Current

Earth fault current for a power station depends on the type of fault and the fault location. The earth fault current in (4.1) should correspond to such fault location and fault type as result in the greatest flow of the current between the earthing system of the station and the surrounding earth.

Many different types of faults may occur. From a parametric study, however, Joy, Meliopoulos and Webb [5] have concluded that:

- (i) For a given fault location, the maximum grid current is generated from single line to earth or double line to earth fault; and
- (ii) For practical power systems, the grid currents for single line to earth fault and double line to earth fault are approximately equal.

Because of much higher probability of occurrence, only a single line to earth fault may be considered for computation of the maximum grid current.

In this work it is assumed that from system short circuit study data, the single line to earth fault currents for faults at different buses in the station are known. Determination of fault location which would result in the maximum grid current requires consideration of current division by alternate paths. It is discussed in detail in Section 4.4.

4.3.3 Decrement Factor D_f

The maximum grid current I_G in (4.1) is the maximum asymmetrical ac current that will flow between the earthing system and the surrounding earth. It includes a dc offset current. The presence of dc offset is taken into account by multiplying the symmetrical grid current by a correction factor called decrement factor D_f . The decrement factor depends on the fault duration and the system X/R ratio at the fault location. The decrement factor can be shown to be given by the following equation [10]:

$$D_f = \sqrt{1 + \frac{T_a}{t_f} (1 - e^{-2t_f/T_a})} \quad \dots(4.2)$$

where

t_f = fault duration in s

T_a = equivalent system sub-transient time constant in s
 $= X'' / (2 \pi f R)$

X'', R = sub-transient reactance and resistance at the fault location

f = system frequency

Equation (4.2) can be used to compute the decrement factor D_f for specific X/R ratios and fault duration. For fault duration of 0.5 s or above, it is generally acceptable to assume D_f equal to unity.

4.3.4 Corrective Projection Factor C_p

The corrective projection factor is to take into account, adequately, future changes in the system. This factor is the most difficult one to determine with any degree of accuracy. It can be estimated from the value of earth fault current for the present and the forecasted conditions.

4.4 CURRENT DIVISION FACTOR S_f

4.4.1 Only a portion of earth fault current flows between the earthing system and the surrounding earth. The current division factor S_f is the ratio of the magnitude of current that flows between the

earthing system and the surrounding earth to the magnitude of total earth fault current. This factor takes into account diversion of earth fault current by alternate paths. A qualitative discussion of the current division factor is given in this section. An algorithm for determination of this factor is developed in the next section.

4.4.2 For the purpose of discussion about current division factor, equation (4.1) may be rewritten as

$$I_G = C_p D_f I_g \quad \dots(4.3)$$

where,

$$\begin{aligned} I_g &= S_f I_f \quad \dots(4.4) \\ &= \text{Magnitude of the grid current without considering the effect of corrective projection factor and decrement factor} \end{aligned}$$

The value of current division factor may vary between zero and unity. It depends mainly on two factors [7-10]:

- (i) Location of fault, which determines remote versus local contribution to the fault current
- (ii) Overhead earth wires connected to the station earth

Division of earth fault current into various paths is explained by considering the case of a generating station with delta-star step up transformer. As explained in Section 4.3.1, only single line to earth fault may be considered. Fault may be located inside the station on either side of the transformer, or it may be located outside the station.

4.4.3 Fault within the Station on HV Side

A generating station supplying power to an interconnected system through delta-star transformer having single line to earth fault on star side is shown schematically in Fig. 4.1. A part of the fault current I_f (Bold letters are used to denote phasors and complex numbers) is supplied by local source and the rest I_r is supplied by the remote sources through transmission line. Currents I_f and I_r are, obviously, three times the zero sequence currents on the two sides of the fault. The component I_f of the fault current supplied by the local source completes its path through grid conductors. So it does not contribute to the current flowing between the earthing system and surrounding earth. Return of the remote component I_r of the fault current to its sources will be through overhead earth wires connected to the earthing system and through the soil. The current returning through the soil to its source is grid current I_g , which is given by

$$I_g = I_r - I_{re} \quad \dots(4.5)$$

where

$$\begin{aligned} I_r &= \text{Contribution to the total fault current by remote sources through transmission line} \\ I_{re} &= \text{Component of current diverted through overhead earth wires} \end{aligned}$$

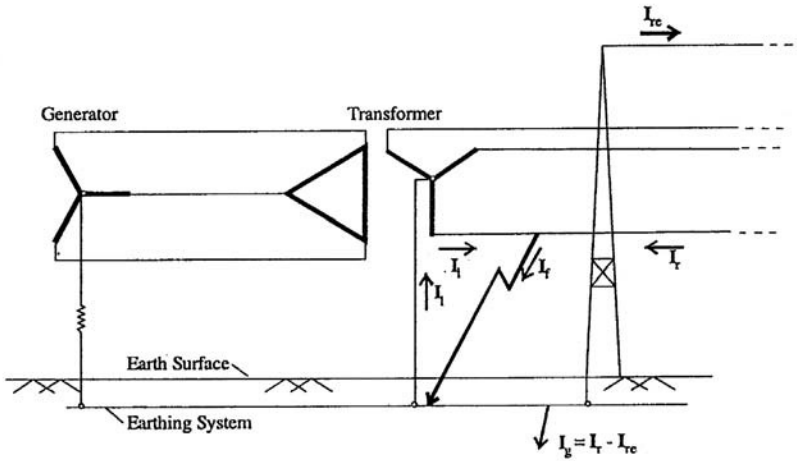


Fig. 4.1 : Division of line to ground fault current for an interconnected generating station with fault within the station on star side of the transformer

4.4.4 Fault within the Station on LV Side

A schematic diagram of the station with single line to earth fault on LV side of the transformer is shown in Fig. 4.2. The generator is connected to remote sources through delta-star transformer and transmission line.

The zero sequence current is restricted to the delta side and fault current flows from the local generator only. There is no contribution to fault current from remote source. The fault current returns to the local source through the conductors of the earthing system of the station and the connection to neutral of the source. Since no part of the fault current flows between the earthing system and the surrounding earth, the grid current I_g for this case is zero.

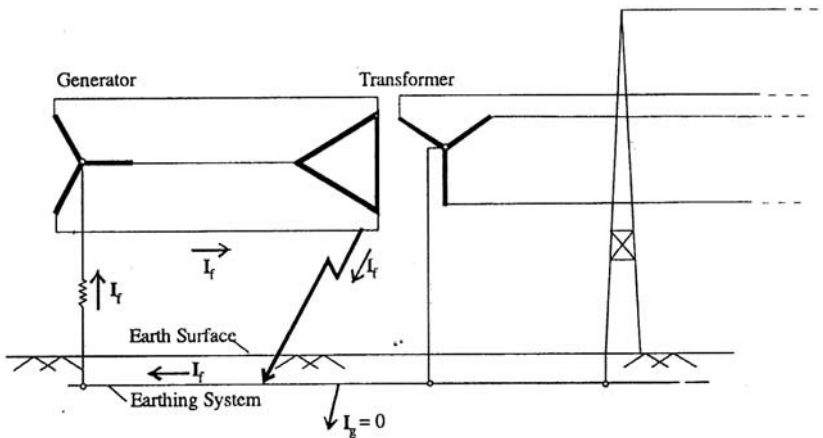


Fig. 4.2 : Division of line to ground fault current for an interconnected generating station with fault within the station on delta side of the transformer

4.4.5 Fault Outside the Station Area

In this case the fault current I_f is sum of the components I_l and I_r supplied by local and remote sources respectively. This is schematically shown in Fig. 4.3. The current contribution I_r of remote sources returns through overhead earth wires and earth. It does not contribute to the grid current of the station. Component of the fault current supplied by the local source completes its path through (i) aerial earth wire, I_{le} and (ii) through surrounding earth to the station earthing system, $(I_l - I_{le})$, from where it returns to the neutral. The component of current $(I_l - I_{le})$, returning through soil to the earthing system of the station is the grid current. Thus

$$I_g = I_l - I_{le} \quad \dots(4.6)$$

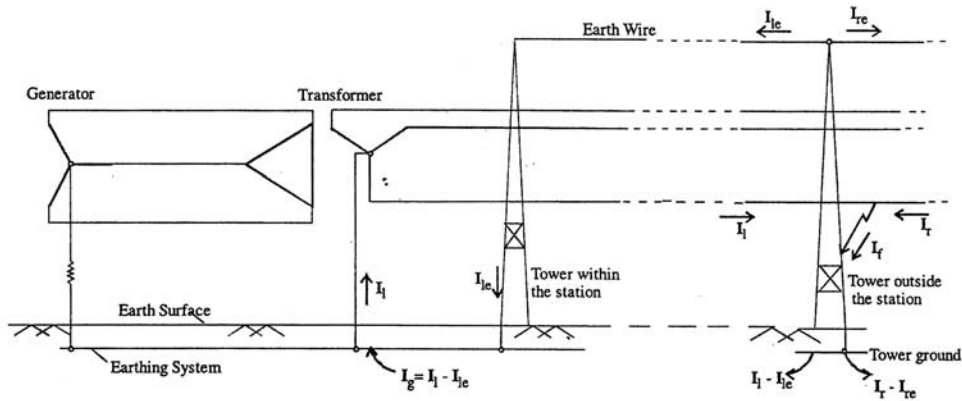


Fig. 4.3 : Division of line to ground fault current for an interconnected generating station with fault within the station on delta side of the transformer.

If the fault is closer to the station, a major part of the fault current supplied by the station will return through earth wire (I_{le}). On the other hand if the fault is far away from the station, the magnitude of the fault current supplied by the station will be lesser because of the line impedance.

4.4.6 Observations

From the discussion of the division into various paths of the single line to earth fault current, presented in Sections 4.4.3 to 4.4.5, following observations are made:

- (i) For a fault inside the station, the component of the fault current supplied by the local source (station transformer or generator) does not contribute to the grid current. Only component of the fault current supplied through transmission line by the remote sources contributes to the grid current. A part of the fault current supplied through transmission lines returns to the remote sources through earth wires. The grid current is equal to the component of the fault current supplied through transmission lines less the part of this component returned via earth wires.
- (ii) For a fault outside the station, only the component of the fault current supplied by the station contributes to the station grid current.
- (iii) The maximum grid current for a station is generally obtained for a fault inside the station. For an outside fault near the station, most of the current supplied to the fault by the station

source returns back via earth wires. A fault at larger distance from the station results in relatively smaller component of the fault current supplied by the station due to larger line impedance.

4.5 COMPUTATIONAL METHODOLOGY

4.5.1 It has been shown in Section 4.4 that the maximum value of grid current for a power station generally occurs for a single line to earth fault within the station. Further only the current fed to the fault through transmission lines contributes to the grid current. The current supplied to the fault by the local sources flows through a metallic path consisting of the conductors of the earthing system and connection to the neutrals of the sources of supply.

The fault current supplied through a transmission line has two paths for returning to the source. A part of it returns to the source through earth wires and neutral conductors and the rest of it flows from earthing system of the station and the source through earth. The grid current is thus equal to the current fed to the fault through transmission lines less the current diverted by earth wires and neutral conductors.

In this section an algorithm for computation of grid current is described [9]. It is assumed that current fed to the fault by different transmission lines connected to the station for single line to earth fault at different buses in the station is known from system short circuit studies. Based on the algorithm a computer program is developed and described.

4.5.2 Model of Earth Wire

An earth wire is connected to the earth at various towers through the tower footing resistance. It can be represented by a ladder network as shown in Fig. 4.4. Each series element of the ladder network has impedance Z_s equal to the self impedance of an average span of earth wire with earth return. Impedance of each shunt branch is equal to the average tower footing resistance R_t .

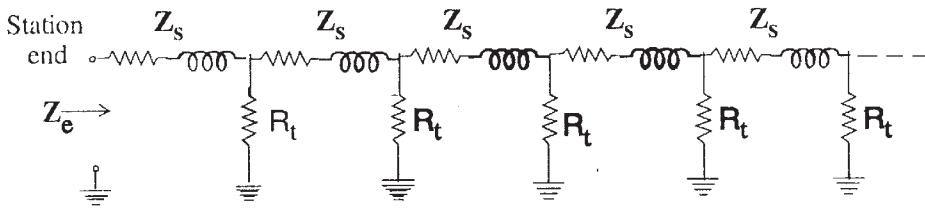


Fig. 4.4 : Ladder network representation of a ground wire

The input impedance Z_e of the earth wire can be determined as input impedance of the ladder network consisting of number of sections equal to number of spans of the line [12]. If the number of spans is 20 or more, the network of Fig. 4.4 can be considered as an infinite ladder network for the purpose of determining its input impedance [7]. Input impedance Z_e of infinite ladder network is [1,7]

$$Z_e = \frac{Z_s}{2} + \sqrt{\frac{Z_s}{3} \times R_t} \quad \dots(4.7)$$

The self impedance per meter length of the earth wire can be obtained by Carson's formula [13, 14] as

$$\mathbf{Z}_g = r_c + 9.87 \times 10^{-7} f + j28.94 \times 10^{-7} f \log_{10} (D_e / \text{GMR}) \quad \dots(4.8)$$

where

$$\begin{aligned} \mathbf{Z}_g &= \text{self impedance of the earth wire in ohm/m} \\ r_c &= \text{resistance of the earth wire in ohm/m} \\ f &= \text{frequency in Hz} \\ D_e &= \text{equivalent depth of earth return in m} = 658.4 \sqrt{\rho/f} \\ \rho &= \text{average resistivity of soil in ohm-m} \\ \text{GMR} &= \text{geometric mean radius of earth wire in m} \end{aligned} \quad \dots(4.9)$$

The impedance of the series arm $\mathbf{Z}_s$ of the ladder network is

$$\mathbf{Z}_s = \mathbf{Z}_g \times l_s \quad \dots(4.10)$$

where

$$l_s = \text{average span length of the line in m}$$

4.5.3 Model of Transmission Line with Earth Wire

A transmission line with one or more earth wires is to be modelled such that diversion of current by earth wires can be computed. To develop such a model a generating station supplying power to an interconnected system through a step up transformer and a single transmission line, shown in Fig. 4.5 is considered. A single line to earth fault on HV side of transformer is considered. The diversion of line to earth fault current for such a system has already been discussed in Section 4.4.1. The current supplied to the fault by the local source does not contribute to the grid current $\mathbf{I}_g$. Only the current $\mathbf{I}_r$ supplied to the fault through transmission line contributes to the grid current. Figure 4.5 is similar to Fig. 4.1 except that the local contribution to the fault current has been omitted, and the component of $\mathbf{I}_r$ that returns to the source through earth wire has been represented by $\mathbf{I}_e$ instead of $\mathbf{I}_{re}$ for simplicity. The grid current is thus obtained as

$$\mathbf{I}_g = \mathbf{I}_r - \mathbf{I}_e \quad \dots(4.11)$$

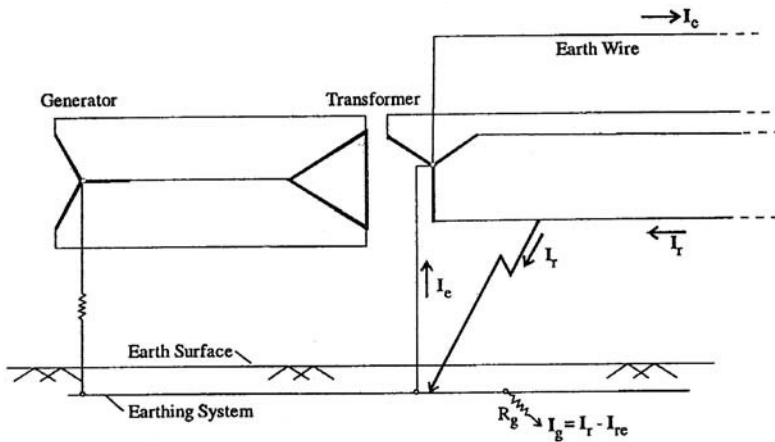


Fig. 4.5 : Path for flow of the current supplied to the fault by remote source through transmission line

The current fed to the fault through the transmission line is assumed to be known. Thus, to compute grid current I_g current I_e diverted by the earth wire is to be determined. The grid current I_g returns to the remote source through soil, and resistance offered to its flow is equal to the station earth resistance R_g .

By application of substitution theorem [15], a known current in a circuit can be replaced by an ideal current source. An equivalent circuit for the system of Fig. 4.5, which is convenient for evaluation of current diverted by the earth wire, is shown in Fig. 4.6. The phase conductors of the transmission line are, by substitution theorem, replaced by an ideal current source of magnitude I_r in series with the self impedance of the line. Since the impedance in series with an ideal current source has no effect on the rest of the network, its value need not be known. The mutual impedance Z_m between the phase conductors and earth wire, however, has to be considered. The self impedance Z_e of the earth wire can be obtained by (4.7) if the number of spans of the line is 20 or more; for a shorter line, it is to be obtained as the input impedance of the ladder network of Fig. 4.4. The mutual impedance per meter, Z_{gm} between the earth wire and the phase conductors is obtained from Carson formula [13,14] as

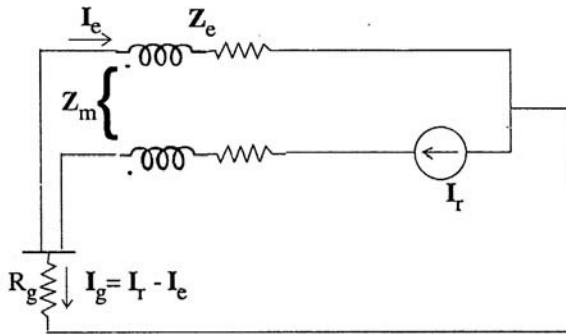


Fig. 4.6 : Equivalent circuit for computation of current diversion by earth wire

$$Z_{gm} = 9.87 \times 10^{-7} f + j28.94 \times 10^{-7} f \log_{10} (D_e / \text{GMD}_{\text{sep}}) \quad \dots(4.13)$$

GMD_{sep} = geometric mean distance between earth wire and phase conductors in m.

The mutual impedance Z_m between phase conductors and earth wire, shown in Fig. 4.6, is assumed to be the same fraction of Z_{gm} as is Z_e of Z_g . It is obtained as

$$Z_m = Z_{gm} \times (Z_e / Z_g) \quad \dots(4.13)$$

Polarity of the emf induced in the earth wire due to mutual coupling with the phase conductors would be as per the dot markings shown in Fig. 4.6.

Writing loop equation for the loop formed by Z_e and R_g in Fig. 4.6.

$$I_e Z_e - I_r Z_m - I_g R_g = 0 \quad \dots(4.14)$$

Substituting expression (11) in (14)

$$I_e Z_e - I_r Z_m - (I_r - I_e) R_g = 0 \quad \dots(4.15)$$

where from current I_e diverted by the earth wire is obtained as

$$I_e = I_r (Z_m + R_g) / (Z_e + R_g) \quad \dots(4.16)$$

The grid current I_g can be computed by (4.11).

4.5.4 Equivalent Circuit for Station with a Number of Lines

The equivalent circuit for a station with a number of transmission lines and feeders, for computing current diversion by earth wires, can be obtained by extension of the equivalent circuit of Fig. 4.6. The equivalent circuit for a station with n lines is shown in Fig. 4.7.

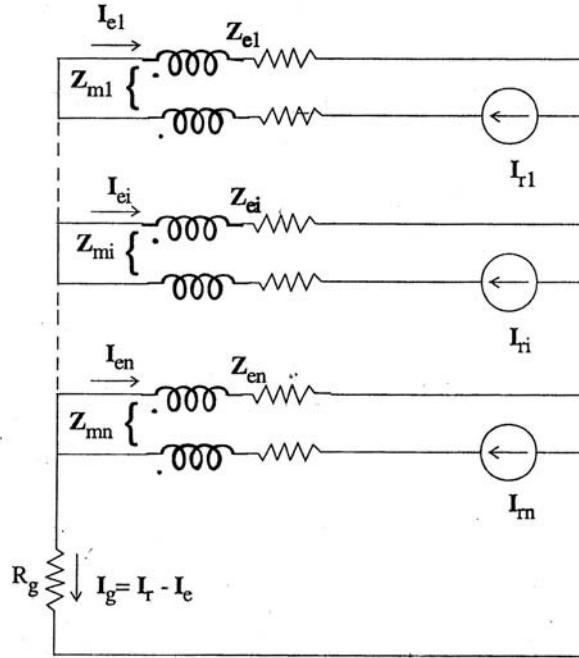


Fig. 4.7 : Equivalent circuit for computation of current diversion by earth wires for a station within lines

In the figure, the following notations are used:

I_{ri} = current fed to the fault by i th transmission line

Z_{ei} = self impedance of earth wire of i th transmission line

Z_{mi} = mutual impedance between i th transmission line and its earth wire

I_{ei} = current diverted by earth wire of i th transmission line

I_r = current fed to the fault by all the transmission lines = $\sum_{i=1}^n I_{ri}$...(4.17)

I_e = current diverted by earth wires of all the transmission lines and feeders

$$= \sum_{i=1}^n I_{ei} \quad \dots(4.18)$$

The equivalent circuit of Fig. 4.7 can also represent a station with a number of lines and feeders. A feeder connected to the station is modelled as a transmission line except that its contribution to the fault current is zero.

4.5.5 Computation of Grid Current

Equations for determining current diverted by earth wires are obtained from equivalent circuit of Fig. 4.7. Loop equation for the loop formed by earth wire of i th line, station earth resistance and the earth can be written as :

$$\mathbf{Z}_{ei} \mathbf{I}_{ei} - \mathbf{Z}_{mi} \mathbf{I}_{ri} - R_g (\mathbf{I}_r - \sum_{k=1}^n \mathbf{I}_{ek}) = 0 \quad \dots(4.19)$$

or

$$R_g \mathbf{I}_{ei} + R_g \mathbf{I}_{e2} + \dots + (R_g + \mathbf{Z}_{ei}) \mathbf{I}_{ei} + \dots + R_g \mathbf{I}_{en} = R_r \mathbf{I}_r + \mathbf{Z}_{mi} \mathbf{I}_{ri} \quad \dots(4.20)$$

In matrix form, these equations can be written as

$$\bar{\mathbf{A}} \bar{\mathbf{I}}_e = \bar{\mathbf{B}} \quad \dots(4.21)$$

where

$\bar{\mathbf{A}}$ is an $n \times n$ square matrix with the elements

$$\begin{aligned} a_{ij} &= R_g & i &\neq j \\ &= R_g + \mathbf{Z}_{ei} & i &= j \end{aligned} \quad \dots(4.22)$$

$\bar{\mathbf{I}}_e$ is a column vector consisting of currents $\mathbf{I}_{e1}, \mathbf{I}_{e2}, \dots, \mathbf{I}_{en}$ and $\bar{\mathbf{B}}$ is a column vector with b_i in the i th row as

$$b_i = R_g \mathbf{I}_r + \mathbf{Z}_{mi} \mathbf{I}_{ri} \quad \dots(4.23)$$

If i th line is a feeder, current $\mathbf{I}_{ri}$ is zero. The solution of (4.21) gives the currents

$\mathbf{I}_{e1}, \mathbf{I}_{e2}, \dots, \mathbf{I}_{en}$, diverted by earth wires. The grid current $\mathbf{I}_g$ is obtained from (4.11).

4.5.6 Computer Program PAG

The equations of the previous section can be easily programmed on computer. A computer program with the symbolic name PAG (Pactical Approach for computation of Grid current) has been developed [9]. With this program grid current at a generating station or a substation can be computed. Besides contributions to earth fault current from different lines, for a line to earth fault at the station, the required data consists of the self impedances of the earth wires and mutual impedances between the phase conductors and the earth wires of the respective lines. In case these impedances are not known, these can be computed in the program by specifying (i) frequency, (ii) average soil resistivity, (iii) resistance per meter length of earth wire, (iv) geometric mean radius of the earth wire, (v) geometric mean distance between the earth wire and phase conductors, (vi) average tower footing resistance, and (vii) the average line span.

The computer program PAG has been tested by using it to determine grid current for a number of test problems [9]. A WINDOWS based version of program PAG, **gridi**, has been written in Visual Basic. A copy of **gridi** along with a README file, which gives instructions for preparation of data file for the program **gridi** and for execution of the program, is given in the attached CD.

4.6 SUMMARY

In this chapter relation between earth fault current and grid current has been discussed. Relation between earth fault current flowing on a transmission line / feeder and the current flowing on earth wire, for faults within a station and those that occur outside it, is explained. A mathematical model relating grid current to components of earth fault current flowing on transmission lines / feeders connected to the station is given. The resulting equations can be used to compute fraction of earth fault current diverted by earth wires and the grid current. A computer program for computing grid current is introduced.

REFERENCES

- [1] Endrenyi, J. "Analysis of Transmission Tower Potentials during Ground Faults", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-86, No. 10, pp. 1274 - 1283, Oct. 1967.
- [2] Sebo, S. "Zero Sequence Current Distribution along Transmission Lines," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-88, No. 6, pp. 910 - 919, June 1969.
- [3] Varma R. and Mukhedkar, D. "Ground Fault Current Distribution in Substation Towers and Ground Wire," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-98, No. 3, pp. 724 - 730, May/June 1979.
- [4] Meliopoulos, A. Webb, R. Joy, E. and Patel, S. "Computation of Maximum Earth Current in Substation Switchyards," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-102, No. 9, pp. 3131-3139, Sept. 1983.
- [5] *Analysis Technique for Power Substation Grounding Systems*, EPRI Final Report EL-2682, Volumes 1 and 2, Electric Power Research Institute, Palo Alto, USA, October 1982.
- [6] Dawalibi, F. Bouchard, M. and Mukhedkar, D. "Survey on Power System Grounding Design Practices," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-99, No. 4, pp. 1396 - 1405, July/August 1980.
- [7] Thapar B. and Madan, S. K. "Current for Design of Grounding Systems," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-103, pp. 2633 - 2637, Sept. 1984.
- [8] Garrett, D.L. IEEE Tutorial Course - Practical Applications of ANSI / IEEE Standard 80 - 1986, *IEEE Guide for Safety*, Chapter 3, pp. 23 - 39, IEEE, New York.
- [9] Seedher, H.R. Arora, J.K. and Soni, S.K. 'A Practical Approach for Computation of Grid Current,' *IEEE Transactions on Power Delivery*, vol. 14, pp. 897-902, July 1999
- [10] ANSI / IEEE Standard 80-1986, *IEEE Guide for Safely in AC Substation Grounding*, IEEE, New York, 1986; ANSI / IEEE Standard 80-2000, *IEEE Guide for Safety in AC Substation Grounding*, IEEE, New York, 2000.
- [11] *Steel Grounding System where Grounding Mat is not Needed*, Technical Report No.5, Central Board of Irrigation & Power, New Delhi, 1976.
- [12] Van Valkenburg, M.E. *Network Analysis* 3rd ed., Prentice Hall of India Pvt. Ltd., New Delhi, 1984.
- [13] Wagner C.F. and Evans, R.D. *Symmetrical Components*, McGraw-Hill Book Company Inc., New York, 1933.
- [14] Glover J.D. and Sarma, M. *Power System Analysis and Design With Personal Computer Applications*, 3rd ed., Thomson Asia, 2003.
- [15] Scott, R.E. *Linear Circuits Part I*, Addison Wesley Publishing Company, Inc., Massachusetts, USA, 1960.

CHAPTER - 5

Design of Earthing System and Limitations of Method

Synopsis : Earth electrodes are designed to provide a reference potential point, and a low impedance path for flow of fault current between earth and the fault point. Flow of current in the earth results in rise of potential of earth electrode and earth surface potentials that are function of earth electrode geometry, soil resistivity in the neighbourhood of earth electrode, pattern of current dissipation from conductors of earth electrode and distance from them. The main design criteria of an earth electrode are safety of equipment/ and personnel, which may be present in and around the earth electrode during the period of earth fault. This can be ensured by making the estimated value of dangerous voltages in and around the earth electrode less than the respective safe limits. Also the conductors of the earth electrode, buried in soil, must last its expected life.

5.1 INTRODUCTION

The two main design goals to be achieved by any substation earthing system under normal as well as fault conditions are [1]:

- (i) To provide means to carry electric currents into the earth without exceeding any operating and equipment limits,
- (ii) To provide a path for flow of current to earth under normal and fault conditions such that continuity of service is not affected, and
- (iii) To ensure that a person in the vicinity of earthed facilities is not exposed to the danger of critical electric shock.

Earth resistance and step and touch voltages are important criteria for designing an earth electrode. For simple earth electrodes viz. vertical rod, horizontal conductor and plate, formulae obtained analytically are used to determine earth resistance. If a combination of a few such electrodes is used, formulae or graphs, if available, may be used to calculate the earth resistance. In such cases, the rise of potential of earth electrode above remote earth should be less than the permissible touch voltage, for the electrode to be safe. For earth electrodes of mid-sized stations, it may be possible to use empirical formulae to determine earth resistance, and step and touch voltage. However, in case of large stations, economical design is possible by using software.

5.2 SIMPLE ELECTRODES

5.2.1 Earth Resistance

The formulae that can be used for determining earth resistance of simple earth electrodes should be used for isolated single electrodes only. A simple electrode may be considered as isolated if distance between two similar electrodes is more than three times the length of the electrode.

5.2.1.1 Vertical Rod or Pipe Earth Electrode

For calculation of earth resistance a vertical rod earth electrode and a vertical pipe earth electrode are equivalent. Earth resistance (Ω) of a vertical rod or pipe earth electrode of length L (m), and

outer radius r (m), buried in uniform soil of resistivity ρ (Ω -m) can be obtained from the expression [2]

$$R = \frac{\rho}{2\pi L} \cdot \left(\ln \frac{4L}{r} - 1\right)$$

...(5.1)

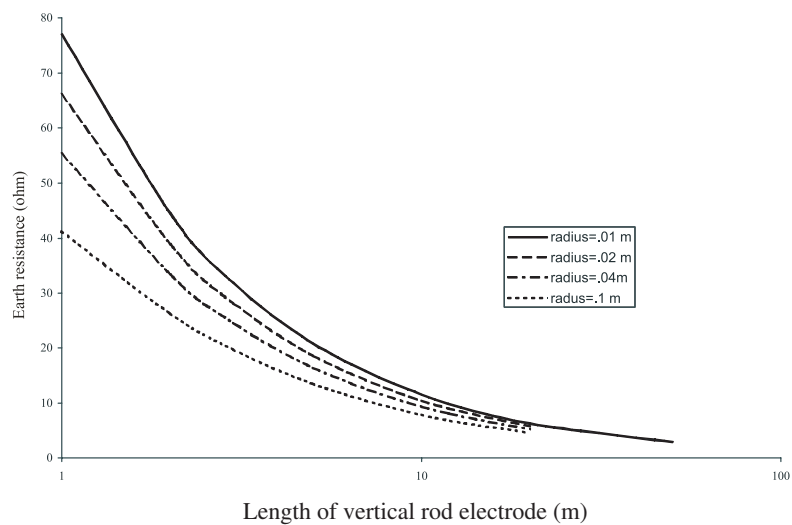


Fig. 5.1 : Earth resistance of vertical ground rod in uniform soil

In case of pipe, r is outer radius. The effect of variation of radius and length of vertical electrode on its earth resistance is shown in Fig. 5.1. Figure 5.2 shows the effect of variation of separation distance between adjacent rods on earth resistance of composite earth electrode when 2, 3, or 4 rods are used; the rods are assumed joined together above earth surface. For both figures soil resistivity is 100 Ω -m and burial depth is 0.05 m. Radius of rods in Fig. 5.2 is 0.01 m.

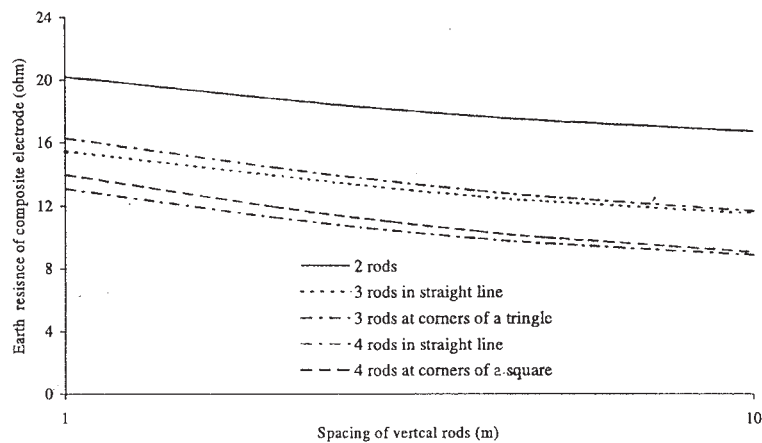


Fig. 5.2 : Earth resistance of multiple, 3-m long, vertical rod electrodes in uniform soil

5.2.1.2 Horizontal Earth Electrode

The earth resistance of a horizontal round conductor of length L (m), radius r (m), buried at depth h (m) below earth surface in uniform soil of resistivity ρ (Ω -m) can be calculated by using expression (5.2)

$$R = \frac{\rho}{\pi L} \left(\ln \frac{2L}{\sqrt{2rh}} - 1 \right) \quad \dots(5.2)$$

If it is a strip conductor of width w (m) and thickness t (m), then equivalent radius is approximated by $r = w/4$ when $t \leq w/4$.

5.2.1.3 Plate Earth Electrode

Approximate value of earth resistance of vertically buried plate earth electrode, having area of one face = A m², can be determined by [2]

$$R = \frac{\rho}{4} \sqrt{\frac{\pi}{2A}} \quad \dots(5.3)$$

Alternatively approximate earth resistance of a plate electrode of equivalent radius r (m) buried with its centre at a depth h (m) from earth surface is [2]

$$\begin{aligned} R &= \frac{\rho}{8r} \left[1 + \left(\frac{4h}{\pi r} \right) \right], \quad h \ll r \\ &= \frac{\rho}{8r} + \frac{\rho}{8\pi h}, \quad h > r \end{aligned} \quad \dots(5.4)$$

5.2.1.4 Composite Earth Electrode

A composite earth electrode will be formed if multiple vertical rod electrodes are joined together with horizontal bare conductors below earth surface. Earth resistance of 2, 3 and 4 vertical rod electrodes, of radius 0.01 m and length 3 m each, buried in straight line at a depth of 0.5 m and joined together with round conductor of radius 0.01m at 0.5 m depth is shown in Fig. 5.3. Soil resistivity is 100 Ω -m.

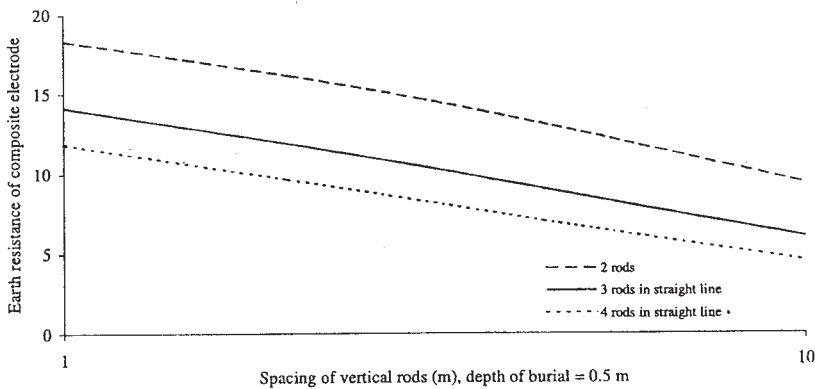


Fig. 5.3 : Earth resistance of composite, vertical, 3-m long, rod electrodes in straight line with horizontal bar electrode between them

5.2.2 Area of Cross-section of Electrode Conductor

As per IS:3043 [3], long-duration loading due to normal unbalance of the system will not cause failure of earth-electrodes provided that the current density at the electrode surface does not exceed 40 A/m^2 . For short duration currents, it is suggested that the maximum current density is given by $I = \sqrt{(57.7/\rho t)} \text{ kA/m}^2$, where t is fault duration in seconds and ρ is soil resistivity in Ωm [4]. For $\rho = 100 \text{ }\Omega\text{m}$ and $t = 3 \text{ s}$, $I = 437 \text{ A/m}^2$. This works out to 82.7 A for a 20 mm diameter and 3 m long vertical rod electrode.

5.3 DESIGN OF EARTHING SYSTEM IN UNIFORM SOIL

5.3.1 Required Data

The data, which ought to be determined before starting the design of earthing system for a high voltage substation, where the soil at the site can be considered to be uniform, are:

- (i) Area covered by the substation
- (ii) Resistivity of the soil at the substation site
- (iii) The maximum earth fault current
- (iv) Fault clearing time for conductor size and for shock duration
- (v) The maximum grid current
- (vi) Resistivity and depth of surface layer

5.3.1.1 Area Covered by the Substation

The area over which the earth electrode is to be placed depends on the substation plan. Layout plan of substation is prepared taking into consideration the number and type of equipments in the station and their layout. The area over which the conductors of earth electrode system are usually buried shall include all the fenced area including switchyard, control room, DG building, fire-fighting building and LT switchyard for supply within the fenced area. The conductors of earth electrode may not be buried under the buildings but only on the periphery of the buildings. Sometimes the conductors of earth electrode system may extend 1 to 2 metres beyond the fenced area.

5.3.1.2 Resistivity of the Soil at the Station

The average resistivity is usually determined by the four-electrode Wenner method. The resistivity value should be preferably obtained by making measurements over a period of at least one year; if time is short, measurements may be made during dry, cold season. The inter-electrode distance, when measurements are made by the Wenner four probe method, should be varied from about 1 m to a large distance along the radials, which are chosen so as to cover the whole of the site as described in Chapter 9. In case of backfill, the soil used as fill should be free of stones and gravel.

5.3.1.3 The Maximum Earth Fault Current

The maximum earth fault current occurs in case of either two-phase to earth or single phase to earth fault. But because of much higher probability of occurrence, the single phase to earth fault current may be used to calculate the maximum earth fault current. Its magnitude should be available from results of System Fault Studies. Its approximate magnitude can also be obtained by estimating

the symmetrical value of earth fault current in case of line to earth fault at the station as given in Section 3.7 and Section 11.1. Magnitude of the maximum grid current is determined by the procedure of Chapter 4.

5.3.1.4 Fault Duration and Shock Duration Time

Importance of fault duration time t_f and shock duration time t_s for high voltage ac substations has been discussed in Chapter 3. Shock duration time is the fault clearing time including that of reclosures, if automatic reclosures are used. The value of 0.5 s, for shock duration time, may be used to determine the permissible values of E_{step} and E_{touch} . However, to calculate the conductor cross-section, the time should be the maximum possible fault clearing time including backup; this can be up to 1 s. In case of small substations, 3-second time has been used. A design engineer should choose the appropriate value applicable at the station for which the earth electrode is designed [5].

5.3.2 Design of Grid Earth Electrode

Design of the grid earth electrode involves the following steps:

- (i) Selection of the material of conductors of earth electrode,
- (ii) Determination of the size of conductors of earth electrode,
- (iii) Preliminary arrangement of the conductors of earth electrode system,
- (iv) Conductor length required for gradient control, and
- (v) Calculation of earth resistance of the earthing system and the grid potential rise.

The last phase of the design consists of

- (i) Checking of earth fault current and grid current,
- (ii) Calculation of step voltage at the periphery of the substation and mesh voltage, and
- (iii) Investigation of transferred potential.

5.3.3 Selection of Material of Conductors of Earth Electrode

The material of earth electrode should have high conductivity and low underground corrosion. Now-a-days mild steel is used in India. Its use avoids galvanic action between earth electrode and other underground utilities, which are mostly of steel. Galvanized steel, if used, retards the rate of corrosion in initial stages; however, if the zinc coating is scratched/eroded at some locations, the rate of corrosion increases. Depending on the corrosivity of soil, zinc coating may be destroyed in two to twenty years. When designing the earth electrode for thirty to fifty years it is preferable to increase the size to make provision for corrosion during its life [6].

5.3.4 Determination of Size of Conductors of Earth Electrode

Proper size of the earth electrode conductor should be such that it has (i) thermal stability to flow of earth fault current, (ii) it lasts for 30 - 50 years without causing break in the earthing circuit due to corrosion, and (iii) it is mechanically strong. Allowance for corrosion, when mild steel conductors are used, is discussed in Chapter 3.

For current of magnitude I kA, conductor size (mm^2), when conductor material is mild steel, is determined by using the formula from Chapter 3 [7]

$$A_c = 12.15I\sqrt{t_f} \quad \dots(5.5)$$

The minimum size of earth electrode conductors in soils where corrosion can be neglected is 100 mm² with the minimum thickness of 3 mm [8]. If soil is corrosive, the minimum thickness shall be 6 mm. Cross-section area in such cases should be 200 mm² whether strip steel or circular steel is used. The minimum size of conductor for connection to equipment above the earth should be 50 mm². All joints should be overlap welded and length of weld should be equal to at least double the width of the strip.

5.3.5 Preliminary Arrangement of the Conductors of Earth Electrode System

The main earthing system is formed of a grid of conductors, mostly perpendicular to each other, buried horizontally, usually at a depth of 0.5 m - 0.6 m below the surface of earth. In the preliminary layout a continuous earthing conductor should be laid along the station perimeter to enclose as much of the station area as possible. At some stations, a continuous conductor at a distance of 1 m or 2 m outside the boundary is part of mandatory specifications. Inside the peripheral conductor, earth conductors should be laid parallel to the rows of equipment or structures. These may be at a reasonably uniform spacing. Cross connections should be provided so as to form meshes; the mesh junctions should be provided at such points where multiple paths are useful such as neutral connection, lightning arrestor connection etc. The minimum spacing of conductors is limited by the distance, at which trenches can be dug. Typical spacing is 3 m - 8 m; however in non-critical areas spacing up to 15 m or even larger can be used.

5.3.5.1 Provision of Vertical Rods

The grid earth electrode may be assumed to consist of only horizontal conductors to start with. Vertical rods may be provided at this stage at stations where resistivity of soil is likely to vary with change of seasons. Driven vertical earth rods of 3 m - 5 m length with their upper ends connected to mesh junctions are suitably provided. A vertical rod is very effective if its length is such that it can penetrate the moist subsoil. Where the top layer of soil is dry and of very high resistivity, enough number of vertical rods may be provided to carry current to the underlying soil without overheating and drying of the soil. Rods on the periphery of grid electrode are more effective than those towards central portion. They should be judiciously distributed over the grid electrode [9].

5.3.6 Permissible Values of Dangerous Voltages

A preliminary layout of conductors of grid electrode is prepared, as described in Sub-section 5.3.5, keeping in view the placement of different equipment and structures in the substation, which need to be earthed. The spacing between conductors of the grid electrode has to be such that the touch voltage is within its safe permissible value. Safe/permissible values of step and touch voltages are obtained from

$$E_{\text{step}} = (1000 + 6C_s\rho_s) \frac{0.116}{\sqrt{t_s}} \quad \dots(5.6)$$

$$E_{\text{touch}} = (1000 + 1.5C_s\rho_s) \frac{0.116}{\sqrt{t_s}} \quad \dots(5.7)$$

C_s is a reduction factor which accounts for the effect of finite depth of surface layer on foot resistance. Its value dependent on h_s , depth of surface layer of crushed rock or stone [1, 10, 11] and the reflection factor K , where

$$K = (\rho - \rho_s) / (\rho + \rho_s) \quad \dots(5.8)$$

ρ_s being resistivity of stone/gravel layer and ρ of the soil. Value of C_s can be determined from the graph of Fig. 5.4. The value of C_s can also be obtained from the relation [1]

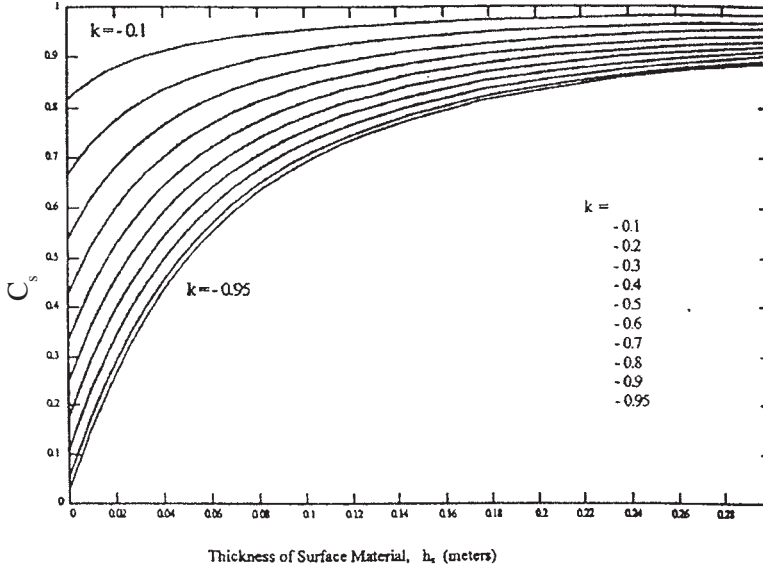


Fig. 5.4 : C_s versus h_s

$$C_s = 1 - \frac{0.09 \left(1 - \frac{\rho}{\rho_s} \right)}{2h_s + 0.09} \quad \dots(5.9)$$

Alternate expressions for C_s [7], which are applicable for a wide range of practical values of ρ/ρ_s are

$$C_s = 1 - 0.11233 \left[\frac{1 - (\rho/\rho_s)}{2.0h_s + 0.11233} \right], \text{ for } 0.001 \leq h_s < 0.05 \text{ m} \quad \dots(5.10)$$

$$C_s = 1 - \frac{1.369b}{1.952h_s + 0.608b} \ln(1 - K), \text{ for } 0.05 \leq h_s \leq 0.30 \text{ m} \quad \dots(5.11)$$

where b = radius of equivalent circular conducting disc representing human foot, m (usually $b = 0.08$ m). Expressions (5.10) and (5.11) are applicable for a larger range of values of h_s than (5.13) and are generally more accurate than (5.9). If no surface material is used, $C_s = 1$.

5.3.6.1 Determination of Magnitude of Dangerous Voltages

Empirical formulae for determining the magnitude of dangerous voltages that will actually occur at the site of grid earth electrode are given below. The mesh voltage and step voltage, which shall occur in the grid earth electrode, can be calculated from the expressions [1,12-14]

$$E_m = \rho k_m k_{im} I_G / L_m \quad \dots(5.12)$$

$$E_s = \rho k_s k_{is} I_G / L_s \quad \dots(5.13)$$

The factors K_m and K_s are given by

$$K_m = \frac{1}{2\pi} \left[\ln \left[\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d} \right] + \frac{K_{ii}}{K_h} \ln \left[\frac{8}{\pi(2n-1)} \right] \right] \quad \dots(5.14)$$

$$K_s = \frac{1}{\pi} \left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D} (1 - 0.5^{n-2}) \right] \quad \dots(5.15)$$

where

D = spacing between parallel conductors, m

h = depth of conductors of earth grid electrode, m

d = diameter of grid conductor (for strip conductor d = width/2), m

L_p = peripheral length of grid, m

L_x = maximum length of grid in x direction, m

L_y = maximum length of grid in y direction, m

D_m = maximum distance between any two points on the grid, m

A = Area of the grid, m²

$K_{is} = 1/(2n)^{(2/n)}$, for grids with no or few vertical earth rods, with none in the corners or on the periphery; = 1 otherwise ... (5.16)

$K_h = (1+h)^{0.5}$... (5.17)

$n = n_a n_b n_c n_d$... (5.18)

$n_a = 2L_c / L_p$... (5.19)

$n_b = [L_p / (4\sqrt{A})]^{0.5}$... (5.20)

$n_c = \left[\frac{L_x L_y}{A} \right]^{0.7A / (L_x L_y)}$, from [5,1] ... (5.21)

$K_{im} = K_{is} = 0.644 + 0.148n$... (5.22)

$n_c = D_m / (L_x^2 + L_y^2)^{0.5}$... (5.23)

Alternate expressions for n_c , separately for mesh and step voltage, and for K_{im} and K_{is} are given in [14] as follows*:

$$n_c = [L_x L_y / A]^{0.92648A / (L_x L_y)}, \text{ for mesh voltage} \quad \dots(5.24)$$

$$n_c = [L_x L_y / A]^{0.29644 / (L_x L_y)}, \text{ for step voltage}$$

$$K_{im} = 0.60803 + 0.14195 n \quad \dots(5.26)$$

$$K_{is} = 0.98953 + 0.14845 n \quad \dots(5.27)$$

In case of grid with only a few vertical earth rods scattered throughout the grid, but none located in the corners or along the periphery, the effective buried conductor length, L_m , is determined from

$$L_m = L_c + L_r \quad \dots(5.28)$$

$$L_c = \text{total length of conductor in the horizontal grid, m.}$$

$$l_r = \text{length of each vertical earth rods, m}$$

$$L_r = \text{total length of vertical earth rods, m} = N_r \cdot l_r$$

$$N_r = \text{Number of vertical rods}$$

For grids with vertical earth rods in the corners, as well as along the perimeter and throughout the grid, the effective buried conductor length L_m is

$$L_m = L_c + \left[1.55 + 1.22 \left(\frac{l_r}{\sqrt{L_x^2 + L_y^2}} \right) \right] L_r \quad \dots(5.29)$$

For determining E_s , for grids with or without vertical earth rods, the effective buried conductor length L_s , is

$$L_s = 0.75 L_c + 0.85 L_r \quad \dots(5.30)$$

For computing the length of conductor in the grid, with equispaced earth conductors, required to keep touch voltage below the permissible value. The total length required to limit the maximum touch voltage within permissible value from (5.7) and (5.12) is

$$L_m > \frac{K_m K_{im} \rho I_G \sqrt{t_s}}{(116 + 0.174 C_s \rho_s)} \quad \dots(5.31)$$

If the length so obtained is less than that obtained from the preliminary layout no change in the layout of conductors is necessary; otherwise closer meshes especially in the areas, which are frequently visited by operating personnel, are to be adopted.

5.3.7 Calculation of Resistance of Grid Earth Electrode and the Maximum Grid Potential

A simple formula, used in [1] is as follows :

$$R_G = \rho \left[\frac{1}{L_t} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h\sqrt{20/A}} \right) \right] \quad \dots(5.32)$$

*For comparison of expressions see Section 5.4

Thaper et al [8] modified the formula (5.32) for calculating the earth resistance of grids of any shapes buried in uniform soil as :

$$R_G = \rho \left[\frac{1}{L_t} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h\sqrt{20/A}} \right) \right] \times 1.52 \left[2 \ln(L_p \sqrt{2/A}) - 1 \right] \left(\frac{\sqrt{A}}{L_p} \right) \quad \dots(5.33)$$

A formula, which has been obtained by Arora et al by optimizing (33), is [10]

$$R_G = \rho \left[\frac{1}{L_t} + \frac{1}{5.01\sqrt{A}} \left(1 + \frac{1}{1 + 27.1(h/\sqrt{A})} \right) \right] \times 1.615 \left[2.136 \ln \left(L_p \frac{1.462}{\sqrt{A}} \right) - 1 \right] \left(\frac{\sqrt{A}}{L_p} \right) \quad \dots(5.34)$$

In (5.32), (5.33) and (5.34) L_t is to the total length of buried conductors i.e. length of horizontal grid conductors and the length of vertical earth rods if any, i.e. $L_t = L_c + L_r$. The maximum rise in potential of the grid above remote earth, $I_g R_G$, needs investigation if a case of transferred potential occurs. If necessary, resistance of the electrode may be decreased by modifying the design by increasing area of the grid; using more conductor length without increasing area is not effective for decreasing R_G to any appreciable extent. Also formulae (5.32), (5.33) and (5.34) have been derived for grids of horizontal conductors. Computer simulation is advisable for accurate determination of R_G , E_s , and E_m .

5.3.8 Sustained Earth Fault Current

Current below the setting of protective relays may flow for extended periods and should be checked so that it does not cause a current greater than the let-go current pass through a person. If the let-go current is assumed 9 mA, the maximum permissible sustained earth fault current can be

$$I_p = \frac{(9 + 0.0135 C_s \rho_s) L_m}{K_m K_{im} \rho} \quad \dots(5.35)$$

If it is not convenient to set the minimum pick up current for earth fault relays corresponding to the value I_p , additional conductor length may be required to be buried.

5.3.9 Step Voltage and Surface Gradients during Earth Fault

The step potential, which can be withstood safely, is given by

$$E_s = (116 + 0.696 C_s \rho_s) / \sqrt{t_s} \quad \dots(5.36)$$

Since the maximum step voltage is likely to occur near and just outside a corner of grid electrode, this expression is applicable if crushed rock or stone extends to outside the grid area. Also, wherever there are pathways near the periphery, they may be laid with 10 cm thick stone slab or have a 10 cm thick layer of bitumen aggregate on top. If stone or gravel layer does not extend outside of the perimeter conductor

$$E_s = (116 + 0.696 \rho) / \sqrt{t_s} \quad \dots(5.37)$$

If the value of E_s comes out to be larger than the permissible value, then the layout may be modified by (i) providing closer meshes and thus decreasing current leakage per metre, (ii) by using vertical earth rods more closely near the periphery thus diverting current to deeper strata

of the earth, (iii) by burying a few conductors outside and parallel to perimeter at greater depth than the grid conductors as distance from the grid increases. Formulae to determine effect of these steps are not available.

Other steps that may be taken to decrease both step and touch voltage and EPR are:

- (i) Diverting a part of the fault current to other parts, by overhead earth / shield wires, which divert current to footing resistance of transmission line towers,
- (ii) Diverting a part of fault current to another earth electrode at a distance from the station, and
- (iii) Limiting earth fault circuit current if possible.

Steps that may be taken to provide safety against unsafe touch voltage are:

- (i) Barring access to limited areas like haying a narrow and deep ditch outside the fence,
- (ii) For limiting the touch voltage inside the grid, the meshes near the comers can be subdivided by additional conductors in between the main conductors or by using unequally spaced conductors. This serves to modify earth surface potential gradients and thus reduces the mesh voltage [15], and
- (iii) Instead of using a chain link fence at the boundary of the property, a 2 m high boundary wall topped by one-meter high chain link fence can be used to mitigate the problem of unsafe touch voltage from outside.

5.3.10 Investigations of Transferred Potential

Transfer of potential between the areas covered by earth grid and outside points, by conductors such as communication signal, and control cables, low voltage neutral wires, water or conduit pipes, rails, metallic fences etc., is possible. Transferred potential should be checked as a serious hazard [1,4,16]. Earth resistance of the earthing system should be kept as low as possible to reduce magnitude of this voltage. However once the area of grid earth electrode and value of soil resistivity are frozen, there is little control over earth resistance of a grid earth electrode

In case of communication circuits protective devices and isolating and neutralizing transformers are used [1]. When such circuits are routed outside the area of grid electrode, an earth conductor should be run along the circuit in the same trench and connected to the metal brackets. Use of fibre optics can eliminate this hazard. Insulation level of control circuit wires should be of proper voltage class. The rails entering a substation can become connected to grid intentionally or otherwise. The hazard due to them can be removed by using several insulating joints at two places such that a metal car or the soil itself cannot short circuit the insulating joints. A simple and practical method to avoid transfer of potential through rails is to remove a section of rails, which is inserted only when needed. If low voltage feeders starting inside the station feed an outside area, the neutral connected to the station grid and possibly earthed at a far point also creates a hazard. In such a case either the neutral should be treated as a phase wire with appropriate level of insulation or preferably no low voltage supply be taken outside the station area. Piping, cable sheaths etc. if any should be tied to the station earthing system at several points in the station area. These can in fact greatly reduce the earth resistance. The distance to and the manner in which voltage is transferred to outside area depend on the propagation constant λ . If voltage of the grid becomes V_G volts the linearized approximate value of voltage gradient along its length is $(V_G/2\lambda)$. If soil resistivity is 100 ohm-m in the area, propagation

constant is approximately half a kilometer. The voltage gradient along the pipe or sheath will be approximately V_G volt/km that is if the pipe is at least 1 km long; and gradient is assumed to be linear [16]. In water supply pipes, insulating pipe sections of concrete or plastic capable of withstanding the potential difference equal to V_G can be inserted in the pipe. If there are buildings at the station site and they are linked to station by LT supply, water pipe, or telephone lines they should be treated as part of the station area. If they are to be kept as separate units, they should be provided with their own earthing and outside LT supply from the local area and adequately protected against potentials transferred from the station. Road side lighting or safety lights outside the station area should also be energized with LT supply from outside.

If there is metallic gate in the boundary wall/fence, it should normally open inside. If however it opens outside, an earth mat should be laid up to its full open position. This mat is to be connected to the earth grid.

5.4 LIMITATIONS OF EMPIRICAL FORMULAE

5.4.1 Empirical Formulae used for Comparison

Empirical formulae for computing earth resistance of a grid earth electrode, mesh voltage inside the grid and step voltage immediately outside the grid available in IEEE Standard 80-1986 [17] have been commonly used by engineers. Revised formulae were proposed by Thapar et al. [12, 13] and Arora et al. [14]. IEEE Standard 80-2000 [1] has been published as a revision of IEEE Standard 80-1986. In IEEE Standard 80-2000 the formulae for mesh and step voltages are the same as were proposed by Thapar et al. [12], and the expression for earth resistance is the same as the one given in IEEE Standard 80-1986 [17].

All these formulae are applicable for grid electrodes buried in uniform soil. The values of earth resistance and mesh and step voltages obtained by these various formulae depend on values of geometrical parameters related to the grid electrode. The formulae give results within specified accuracy provided the geometrical parameters are within certain limits. The conductor spacing must be nearly uniform throughout, shape of grid must be nearly square and the number of parallel conductors must not exceed a specified number. In [18,19], the limits have been determined for the condition that the maximum difference, between the values obtained by using empirical formulae and by using a computer program based on Heppes's algorithm [20], is 20 percent.

5.4.2 Geometrical Parameters and Mode of Comparison

Limits on the following geometrical parameters have been investigated in [18,19];

- (i) Depth of burial of the grid,
- (ii) Diameter of the earth conductor of which the grid is made,
- (iii) Spacing between the parallel conductors of the grid, and
- (iv) Number of parallel conductors.

In the Standard [1], it is recommended that a suitable computer program in place of the expressions of the standard must be used if one or more of the above geometrical parameters lie outside the specified limits. However, the Standard does not mention the order of the error in the values computed by the expressions if the parameters are within the specified limits.

The expression for earth resistance of a grid in [13] has been arrived at for grids buried at a depth of 0.5 m. In [12], limits on geometrical parameters of equations used for calculating mesh and step voltages are recommended, but the order of the error if the limits are violated is not given. No limits on geometrical parameters are mentioned in [14].

The results of investigations have been used to determine the limiting values of geometrical parameters for the formulae for earth resistance, and mesh and step voltages, for the formulae published in IEEE Standard 80 [1, 13] and those proposed by Thapar et al. [12,13] and Arora et al. [14].

5.4.3 Results of Comparison

The results of comparison apply to grid earth electrodes of rectangular and square shape, buried in uniform soil having equal sized meshes. The comparison is summarized in Table 5.1.

Table 5.1 : Limiting values of various parameters for IEEE and modified IEEE expressions

Performance parameter	Limits on values of parameters in various formulae		
	IEEE 2000	Thapar et al.	Arora et al.
Depth of burial, h	$0.2\text{m} \leq h \leq 3.0\text{m}$	$0.2\text{m} \leq h \leq 3.0\text{m}$	$0.4\text{m} \leq h \leq 1.5\text{m}$
Diameter of conductor, d	$d \leq 0.25h$	$d \leq 0.25h$	$d \leq 0.6h$
Distance between parallel conductors, D	$10\text{m} \geq D \geq 3\text{m}$	$10\text{m} > D \geq 3\text{m}$	$D > 4\text{m}$
Number of parallel conductors in one direction, n	$n \leq 15$	$n \leq 20$	$n \leq 25$

5.4.4 Other Limitations

If a graph of earth surface potential across a grid electrode with uniform conductor spacing is drawn, it is seen that mesh voltage magnitude is the largest for the outermost mesh and decreases thereafter. In an optimally spaced grid, the magnitude of mesh voltages should be the same for all meshes. Also, to minimize the length of risers, the grid conductors should be placed near to the equipments and structures. Such a layout will necessarily result in a grid with unequally spaced conductors. The empirical formulae cannot be used to design a grid with such a layout. In short, empirical formulae are applicable only if a grid electrode that is placed in uniform soil, has nearly equispaced conductors and satisfies limitations given in Table 5.1. If all these conditions are not satisfied, use of software based on earthing analysis techniques is necessary for designing the electrode. Examples of grids analyzed with software are given in Chapter 11.

5.5 SUMMARY

The empirical formulae used for design of a grid electrode in uniform soil are described in this Chapter. The topics covered include :

- Formulae for determining earth resistance of simple earth electrodes buried in uniform earth are given.
- Parameters of design of grid earth electrodes are discussed briefly.
- The steps of designing such an electrode buried in uniform soil are given.
- Precautions against transferred potential are discussed briefly.

- (v) Various empirical formulae for carrying out necessary calculations are also given. Limitations on the use of formulae are explained.

REFERENCES

- [1] *ANSI/IEEE Standard 80-2000, IEEE Guide for Safety in AC Substation Grounding*, IEEE, New York 2000
- [2] Sunde, E. D. *Earth Conduction Effects in Transmission Systems*, Dover Publications, New York, 1968.
- [3] IS: 3043 - 1987, *Indian Standard Code of Practice for Earthing* (First Revision).
- [4] BS:7430 - 1991, *Code of Practice for Earthing* (Formerly CP: 1013-1965), British Standards Institution, London, 1992.
- [5] Technical Report No. 49, *Earthing System Parameters for EHV and UHV Substations*, C.B.I.&P., 1985, New Delhi.
- [6] Review No. 1, *Review on Corrosion in Earthing Equipment*, C.B.I.&P., New Delhi, 1973.
- [7] Technical Report No. 5, *Steel Grounding Systems where Grounding Grid is not Needed*, C.B.I.&P. 1976.
- [8] *Siemens Electric Installations Handbook*, Ed. Gunter G. Seip, Haydon & Sons Ltd., London 1979.
- [9] *Proceedings Workshop on Earthing Practices*, March 13 - 18, 1978, Punjab Engineering College, Chandigarh,.
- [10] Thapar, B. Gerez, V. and Kejriwal, K. "Reduction Factor for the Ground resistance of the Foot in Substations Yards", *IEEE Trans, on Power Delivery*, pp. 360 - 368, Jan. 1994.
- [11] Hans R. Seedher, and Arora, J.K. "A Comparative Study of Expressions for Reduction Factor for Ground Resistance of Foot," *IEEE Transactions on Power Delivery*, Vol. 18, No. 3, pp. 849 -851, July 2003.
- [12] Thapar, B. Gerez, V. Balakrishnan A. and Blank, D. A. "Simplified Equations for Mesh and Step Voltages in A C Substations", *IEEE Trans, on Power Delivery*, Vol. 6, No. 2, pp. 601 — 607, 1991.
- [13] Thapar B. et al, "Evaluation of Ground Resistance of Grounding Grid of Any Shape", *ibid.*, pp. 640 - 647.
- [14] Arora, J.K. Seedher H.R. and Kumar, P. "Optimized Expressions for Analysis of Ground Grids", *Proceedings of the Seventh National Power Systems Conference, Calcutta, February 15 -18, 1993*, pp. 360 -364.
- [15] Thapar, B. and Garg, P. P. "Control of Ground Potential Gradients at Modem High Voltage Substations", *Proc. 46th R&D Session of C.B.I.&P., Trivandrum*, Nov. 1977.
- [16] Thapar, B. "Dangerous Potentials due to Total IR of an Earthing Network", *Proc. 47th R&D Session of C.B.I.& P.*, Vol. V, pp. 89 - 94, March 1980.

- [17] ANSI/IEEE Standard 80-1986, *IEEE Guide for Safety in AC Substation Grounding*, IEEE, New York, 1986.
- [18] Seedher, H.R. Arora J.K. and Nijhawan, Parag “Limits on Geometrical Parameters Used in Formulae of IEEE Standard 80 and Variants Thereof”, *Proceedings of Fifth International R & D Conference of C.B.I.&P.*, February 2005, Bangalore
- [19] Nijhawan Parag, ‘Limits on Geometrical Parameters used in Formulae of IEEE Standard 80-1986 and Variants Thereof,’ *M.E. Thesis, Panjab University, Chandigarh, 2001.*
- [20] Heppe, R.J. “Computation of Potential at Surface above an Energized Grid or other Electrode, Allowing for Non-Uniform Current Distribution”, *IEEE Trans. on Power Apparatus and Systems, Vol. PAS-98, No. 6, pp. 1978-1989, Nov/Dec 1979.*

CHAPTER - 6

Special Considerations for Earthing Design under Difficult Conditions

Synopsis : Difficult conditions for the design of an earthing system are any or all of (i) high soil resistivity, (ii) limited area for laying the earth electrode, and (iii) large magnitude of earth current. The earth resistance of a grid electrode is more or less fixed when the soil resistivity and area in which the grid electrode is to be laid are determined. It is possible that the estimated value of earth resistance and the corresponding magnitude of earth electrode potential rise are unacceptably high. The measures that may be adopted under such circumstances are presented in this chapter.

6.1 INTRODUCTION

The earth resistance of a grid earth electrode buried in uniform soil of resistivity ρ Ω -m soil is roughly $\rho/(4r)$, r being equivalent radius of grid earth electrode. Therefore, once the soil resistivity at the site of grid earth electrode has been determined and area of the station is fixed, earth resistance of the electrode can be decreased only to a small extent by increasing the length of buried material or by using earth conductors of larger size. As a result if the soil resistivity is comparatively high and/or space available for the switchyard is limited, the earth resistance may be unacceptably large. Sometimes, it is suggested that if earth conductors are buried in trenches with some low resistivity material like Bentonite clay around them instead of natural soil of high resistivity, it may be possible to reduce earth resistance appreciably. But its effect, in fact, is similar to increasing conductor radius. Using copper conductors instead of mild steel conductors also does not affect earth resistance. Since the earth potential rise (EPR) is product of earth resistance and grid current, if magnitude of earth resistance is comparatively high, the magnitude of EPR may also be unacceptably high.

While preparing specifications of earth electrode of a substation, it is usual to specify that the earth resistance should not exceed 1 ohm. To achieve this value, the equivalent radius of grid earth electrode buried in soils of 100 Ω -m, 200 Ω -m, 500 Ω -m, and 1000 Ω -m has to be approximately, 25 m, 50 m, 125 m and 250 m, respectively. Therefore, in areas where the soil resistivity is rather high or the substation space is limited, it may not be possible to obtain a low enough earth resistance by merely burying a grid earth electrode within the boundary of switch yard area. Also see Section 3.5 in this regard.

At a station located within a city or on industrial premises, or even at a station located on a hill, it may not be possible to spread the grid earth electrode over a large enough area. In such a case not only the earth resistance may be more than the desired value, it may also be difficult to control earth surface voltage gradients. The resulting high EPR can result in problems of transferred potential with respect to communications networks, cables and metallic pipes entering the area of earth electrode. Step voltage even at a distance from the station may be above its permissible value. Thus close attention must be paid to several parameters of earth electrode design.

At many stations an HV system and an LV system coexist in a substation. The LV equipment and the HV equipment are to be earthed to the same earth electrode only if the LV system is totally confined within the area covered by the HV earthing system. If it is found that LV system can

be exposed to excessive voltage stress, steps must be taken to prevent this. These shall include ensuring that LV equipment is not exposed to transferred potential and separating the HV and LV earthing systems.

6.2 ANALYTICAL APPROACH

Shortcomings of empirical formulae of IEEE Std. 80-2000 [1] have been brought out in Chapter 5. Because of limitations of the formulas, it is imperative to use computer programs based on established algorithms when designing earth electrode for a station where the conditions are rather stringent. Earthing design involves four principal tasks. These are:

- (i) Making a soil model that fits well the soil resistivity measurements,
- (ii) Preparation of a practical layout of earth conductors in designated area,
- (iii) Simulation of conductor layout and determination of dangerous voltages with the computer software, and
- (iv) Determination of grid current and finalization of earth electrode design.

Even though a few assumptions are made in the process of computer simulation, computer simulation is useful for analyzing earthing systems under the following requirements:

- (i) Analysis of earth electrodes in two layer or multi-layer soils,
- (ii) Potential distribution on earth surface over whole of the earth electrode and outside it in order to properly analyze the safety requirements,
- (iii) Analysis of grid electrode with unequally spaced conductors,
- (iv) Analysis of grid electrode of any irregular shape,
- (v) Assessing the effect of deep driven rods on earth surface potential distribution,
- (vi) Analysis of performance of grading ring when grading rings are provided at progressively larger depths in peripheral area of earth grid in order to control the step potentials.

The effect of steps outlined in the following sections can be analyzed by digital simulation and analysis of earth electrodes.

6.3 MEASURES RELATED TO PARAMETERS OF EARTHING SYSTEM

6.3.1 Soil Resistivity

Soil resistivity must be measured with a reliable earth tester. In Chapter 3, the factors affecting soil resistivity have been listed. Soil resistivity decreases with percent increase in salt and moisture content of soil. However, it is not possible to increase moisture or salt content of large tracts of land by watering it regularly or by adding chemicals. Adding salts is often opposed from environmental considerations. Also, added salts are leached away by rainwater. Still, if landfill is required for the purpose of levelling the tract of land, it should be done by using rock free loamy soil.

Wherever possible, advantage should be taken of reduction of resistivity at depth due to presence of sub-soil water. If resistivity measurements are made for large enough electrode spacings, it is possible to make a layered model of soil if apparent measured resistivity varies with electrode spacing. In such a case, if the bottom layer is of smaller resistivity, vertical rod electrodes can be installed such that they penetrate the bottom layer.

6.3.1.1 Soil Treatment [1]

Another possibility is to use earth resistivity enhancement material along with vertical rod electrodes. Such materials, which decrease resistivity, are (i) Bentonite clay, (ii) Coke dust, (iii) Conductive cement, and (iv) Salts like sodium carbonate or magnesium sulphate. The materials used should be such that it requires little maintenance and should be environmentally friendly.

The Bentonite clay consists of a hydrous aluminium silicate. It can absorb water up to 5 times its weight and swells up to 13 times. At six times its dry volume, it remains dense and pasty and adheres well to any surface it touches. These two characteristics solve the problem of compaction and rod contact. Resistivity of Bentonite clay at 20°C at water to Bentonite ratio of 4:1 is 8.7 Ω -m. It retains absorbed moisture for a long period. Used with rod electrodes, it increases effective diameter of the electrode.

Another material is the conductive cement; it is premixed with water and also absorbs moisture from the surrounding soil. When vertical electrodes are installed in such materials, earth resistance of the electrode is reduced. However use of such materials will not be feasible for an extended grid earth electrode.

To install an electrode in enhancement material, a hole of about 30 cm diameter is made in the soil. Depth of the hole is 10 - 15 cm shorter than the length of vertical rod/pipe electrode. The rod or pipe is centered in the hole and then driven into earth. The earthing conductor is connected to the electrode. Most of the space around the rod/pipe electrode is filled with the enhancement material with top portion being filled with the soil removed from the hole. This area around the electrode should be watered from time to time.

6.3.2 Maximum Earth Fault Current and Grid Current

The maximum grid current used in design calculations has to be corresponding to the earth fault current obtainable at the station. Lately, there is a practice to specify the fault current value equal to three-phase symmetrical short circuit breaking rating of circuit breakers for the station or an earth fault that gives the maximum fault current. There are several flaws in such specifications. (a) In case of three-phase short circuit no current flows through the earth; so three-phase short circuit current has no relation to earth fault current, (b) The circuit breaker rating may be much more than even the calculated value of three-phase short circuit current depending on the next higher available equipment rating, (c) Some times earth fault current is calculated taking into account some future scenario that will necessitate increase in station area and enhancement of earth electrode, (d) The earth fault current has been worked out for a future scenario, but the number of transmission lines considered for diversion of current by their earth wires is taken as the current number, (e) The earth fault current is calculated at a particular bus, but due to transformer connections, fault at that bus does not result in flow of zero sequence current. This is an anomaly. A system fault study with possible future load growth for a period of about 5 years for the particular installation shall give a realistic value of actual earth fault current; this value should be used for calculation of grid current. If it is difficult to estimate the earth fault current at a future date, it is possible to use grid current equal to 3 times the zero sequence current.

6.3.3 Shock Duration

For earth electrode design for a station that presents difficult condition, actual fault-clearing time may be coordinated with shock duration. At all important stations, modern numerical relays are

used for protection. With modern numerical protection relays, the fault clearing time may be of the order of 0.2 sec. Shock duration has to be based on normal fault clearing time of primary protection system and auto reclosure time. Therefore, a realistic technical assessment of actual fault clearing time of protective devices of HVAC station has to be made if shock duration smaller than 0.5 s is to be used. It is to be ensured that probability of fault remaining on the system for a longer duration together with other parameters causing danger to personnel is negligible.

6.3.4 Materials and Thickness of Surface Layer

The basis for safe design of earthing for a station is that the maximum step and touch voltage in and around the station should be less than the magnitude of the respective permissible value of step and touch voltage. It is also known that the permissible value of step and touch voltage can be increased by using surface layer material of resistivity larger than resistivity of natural soil. Use of such material effectively increases foot resistance. The increase in foot resistance is, to some extent, dependent on the thickness of surface layer. So, by using appropriate thickness of surface material of high resistivity in critical areas, safe design under difficult conditions can be possible. Commonly used high resistivity material is gravel or crushed rock. Bitumen is another material. Inside buildings insulating sheets are used in selected areas. A method of measuring resistivity of gravel or crushed rock is given in Chapter 9.

It is necessary that in the station area, a number of points where critical values of step or touch voltage can occur should be identified and earth surface voltage at such points should be determined. Alternately, graphs of earth surface voltage in areas where such points are located should be obtained to ascertain areas where application of surface material is essential.

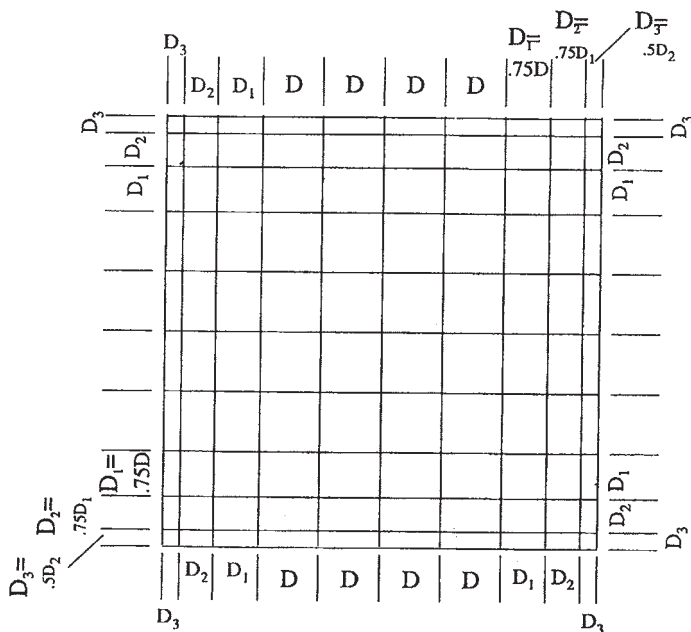
It is important to ensure that the integrity of the surface layer is maintained throughout the life of the substation.

6.4 OTHER MEASURES

6.4.1 Design with Unequal Spacing between Earth Conductors

It has been found that density of current dissipated from a conductor buried in earth is larger near its ends than in the center. In case of a grid earth electrode current dissipation from corners and peripheral conductors is more than from the inner conductors. As a result, equally spaced grid earth electrodes use the earth electrode material inefficiently. It has been found that in a grid electrode with equispaced earth conductors buried in uniform soil, the mesh voltage has the maximum value in corner meshes and the mesh voltage decreases continually towards the interior meshes from the corner mesh. If the earth conductors are unequally spaced with the least spacing at the periphery and spacing increasing progressively towards the interior, more uniform distribution of mesh voltage can be obtained. Thus the material of earth conductors is used more efficiently. It is possible that unequal spacing is used to obtain a safe design that was difficult with equally spaced grid. In a practical grid, unequal spacing has to be used judiciously keeping in view the placement of conductors near equipments to be earthed and for ease of installation.

A grid earth electrode with unequally spaced conductors is illustrated in Fig. 6.1. The distances between conductors shown in figure are as given in [2]. In this presentation first three spacings from edge have been altered as shown and the rest are all equal. The factor by which the spacing is decreased may vary from case to case and the ratio of two consecutive spacings may vary from about 1.2 to 2.0.



6.4.2 Use of Satellite Grid Electrode

The satellite grid may not be located at an impractical distance from the station. If the distance is more than 500 m, the effect of inductive reactance of the conductors, connecting the two grids, on the earth impedance shall have to be considered. During the time an earth fault occurs, the potential rise of satellite grid will be the same as that of the station grid. Appropriate precautions must be taken for safety of persons and animals. If the two grids are connected by bare conductors, additional earth conductors are obtained. However this also requires that the step voltage along the path of these conductors is safe. If this cannot be assured, the connection has to be made by insulated conductors.

6.4.2.1 Use of Remote Grids

If there are several installations or buildings, near each other, each with its own earth electrode, then all earth electrodes can be connected together. If the earth electrodes are at a distance from each other, they may be connected by bare underground conductors, or by insulated underground cable or by

overhead insulated wires. Long connections shall have to be modeled as transmission lines. Earth grid electrodes of nearby stations are also connected to each other by earth /shield wires [3].

6.4.3 Use of Concrete Encased Electrodes [4,5]

Concrete, being hygroscopic, attracts moisture. Resistivity of concrete is a function of its moisture content. When dry, concrete is a very poor conductor with resistivity values ranging from a few kΩ-m to more than 100 kΩ-m. When wet, concrete resistivity value ranges from about 20 ohm-m to approximately 300 ohm-m. Resistivity of 1:1:2 concrete at 30°C and having M% moisture content can be estimated from [4]

$$\rho_{30} = 748 \ln \frac{M}{M - 1.7} - 191 \quad \dots(6.1)$$

This relation is applicable for moisture content between 3% and 6%. Resistivity of 1:2:4 concrete is somewhat lower than that of 1:1:2 concrete for the same moisture content and temperature. Buried in soil, a concrete block behaves as a semiconducting medium with a resistivity of 30 - 90 Ω.-m. This is of particular interest in medium and highly resistive soils because a wire or metallic rod encased in concrete has lower resistance than a similar electrode buried directly in the earth. This encasement reduces the resistivity of the most critical portion of material surrounding the metallic electrode in much the same manner as chemical treatment of soils does. However, this phenomenon may often be both a design advantage and disadvantage. It is impractical to build foundations for structures where the inner steel (reinforcing bars) is not electrically connected to the metal of the structure. Even if extreme care were taken with the anchor bolt placement in order to prevent any direct metal-to-metal contact, the semiconductive nature of concrete would provide an electrical connection.

For determining earth resistance of foundations where there are several columns with small distances between them and length of the horizontal rebars in the spread footings of the columns is of the same order as the spacings between them, the whole system of rebars may be assumed equal to a horizontal plate. The area of the plate is assumed equal to that over which the horizontal rebars are spread. The earth resistance of the plate can be calculated as $(\rho/4r_c)$; ρ is resistivity of surrounding soil and r_c is $\sqrt{(\text{Horizontal area}/\pi)}$.

Passage of alternating current through concrete over an extended period of time does not affect strength of concrete and corrosion of enclosed steel rebar material is not enhanced so long as the current does not exceed the limits given below:

- (i) Low magnitude long duration continuous current from conductor to concrete does not exceed 30 mA per meter length of conductor.
- (ii) High magnitude short duration current to earth when earth conductor is dissipating earth fault current to concrete does not exceed 180 A-sec per meter length of conductor.
- (iii) High magnitude short duration current in the conductor is limited to a value that raises temperature of conductor to 620°C.

When steel in foundations becomes part of the earthing system, the maximum currents that the foundations would carry will not be higher than the values given above.

But passage of a small dc current can cause corrosion of rebar material. Splitting of concrete may occur either due to the above phenomenon because corroded steel occupies approximately 2.2

times its original volume, producing pressures approaching 35 MPa (1 Pa or Pascal is 1 N/m²) or the passage of very high current would vapourize the moisture in the concrete. Experimental evidence shows severe damage to concrete as a result of sustained or short duration alternating currents flowing from concrete encased conductors when above mentioned limits on current are exceeded.

6.4.3.1 The following recommendations should be considered when using concrete encased electrodes:

- (i) Connect anchor bolt and angle stubs to the reinforcing steel for a reliable metal-to-metal contact.
- (ii) Reduce the current duty and dc leakage to allowable levels by making sure that enough primary earth electrodes (earth grid and vertical rods) will conduct most of the fault current.
- (iii) Concrete may be used as earth enhancement material in the areas of a high soil resistivity to reduce the resistance of primary earth electrode.

6.4.4 Counterpoise Earth Electrode [6]

A counterpoise mat is a grid electrode of closely spaced horizontal conductors buried at a shallow depth above the main grid electrode. The main grid is fabricated from conductors of cross-section as determined from the earth fault current. However the counterpoise mat is fabricated from conductors with much smaller cross-section. It is useful in a situation where it is found that spacing between conductors of main grid has to be reduced to a comparatively small value to make it safe against touch voltage even though it is safe against step voltage with a larger conductor spacing. In such a case, counterpoise mat is designed with small spacing. It is fabricated from conductors of 10 - 12 mm diameter. This can result in touch voltage becoming less than the permissible. Typical values are of a main grid with conductor spacing of 10 m buried at 0.6 m depth, and a counter poise mat with conductor spacing of 1m at a depth of 0.1m to 0.2m. Conductor of counterpoise mat carries only a small portion of earth fault current and can be designed from mechanical considerations. The two mats should be electrically connected.

6.5 EXTENSION OF EARTH ELECTRODE

6.5.1 Use of Penstock at a Hydro Station [7,8]

At hydroelectric generating station, generally soil resistivity is very high because of its rocky nature. The area of the station is necessarily small and often the generators, transformers and switchgear are located in underground caverns, or on multiple levels one above the other. If the plant has one or more pressure shafts or penstocks, which are metallic and buried in soil, these can be made parts of the earth electrode. Because of large diameter and long length, these can be very useful for reducing the earth resistance. Besides this, earth conductors can be installed along the lengths of various tunnels and adits. The integrated earth electrode, as a whole, may give an acceptable value of earth resistance.

Even if the penstock is not buried in soil, use can be made of earth below the penstock to lay earth conductors from the powerhouse along the length of penstock.

6.5.2 Earth Conductors away from Station Area

Sometimes at a small hydroelectric generating station, penstock buried in soil or some area of low resistivity to bury a satellite grid may not be available. Even at a substation in hilly terrain,

where area of switchyard is small and no nearby low resistivity area is available for a satellite grid, earth resistance may be unacceptably high. Two possibilities for laying earth conductors may be considered. One is to bury earth conductors by the side of approach road to station up to a certain distance from the station. The advantage of using roadside is that the road having a metallised surface, offers higher permissible values of step voltage than on natural soil. A second possibility is to use right of way of transmission lines / feeders leaving the station to bury earth conductors up to a certain distance from the station.

6.5.3 Extension to Contiguous Areas

In certain plants, the area of switchyard may be small, but large area may be available where sheds or other manufacturing facilities are located. Sometimes there may even be a residential area which is part of the facility. If earth conductors can be laid in and around these extended areas such that the EPR and step and touch voltages can be made safe, then use can be made of earth of these areas to lay the earth electrode.

6.6 SUMMARY

In this Chapter a number of options that are available for planning and design of an earth electrode for a station, where the design parameters are such that the earth resistance or EPR may be unacceptable, are described. By availing these options, it may be possible to obtain a safe design under difficult conditions.

REFERENCES

- [1] ANSI/IEEE Standard 80-2000, IEEE Guide for Safety in AC Substation Grounding, IEEE, New York, 2000.
- [2] Thapar B. and Garg, Prit Paul "Control of Ground Potential Gradients at Modern High Voltage Substations," *Proceedings 46th Research Session of CBIP*, pp. 41 - 45, Vol. VI, November 1977, Trivandrum.
- [3] *BS 7354:1990, Code of Practice for Design of High-voltage Open-terminal Stations*, British Standards Institution, London, 1990
- [4] Evaluation of Concrete Encased Earthing Electrodes and use of Structural Steel for Earthing, *Technical Report No. 78, Central Board of Irrigation and Power*, New Delhi, August 1991.
- [5] Thapar B. and Avinash C. Sharma, "Effect of AC Grounding on Strength of the Concrete Encased Foundations," *Personal communication*.
- [6] Arora J.K. and Seedher, H.R. "A Study on the Role of Counterpoise Mat in Grounding Systems," *Journal of the Institution of Engineers (India), Electrical Engineering Div., Vol. 79, pp. 186-188, February 1999*.
- [7] Arora, J.K. Hans Raj, Thapar, B. Kapoor R.K. and Abrol, N.K. "Use of Penstock as an Earthing System Element in High Resistivity Soils," *Proc. 52nd Annual R&D Session of C.B.I.&P.*, Vol. H, pp. 15 - 18, Feb. 1985.
- [8] Arora J.K. and Seedher, H.R. "Grounding System Design for an Underground Hydroelectric Plant - A Case Study," *Proc. IEEE 10th International Conference on Energy, Computers, Communication and Control Systems*, pp. 467 - 471, New Delhi, August 1991.
- [9] Patel, J.J. Bhale N.V. and Dattatri, V.S. "Grounding Design in a High Resistivity Soil," *Presented at IEEE International Meeting, New Delhi, 1990*.

CHAPTER - 7

Earthing of Electronic Equipment in Power Stations

Synopsis : Proper earthing of electronic equipment is essential for two reasons: (i) to ensure safety of personnel and equipment and, (ii) for proper operation of the equipment. In this chapter, earthing practices for electronic equipment both for safety and functional consideration are described. Suitability of these methods in the power stations environment is discussed.

7.1 INTRODUCTION

7.1.1 Modern power stations use a number of sensitive electronic equipment for instrumentation, control and data processing. These equipment have to work satisfactorily in an environment with abundant sources of electrical noise. Earthing of electronic equipment is necessary for the safety of personnel and equipment (Protective earthing), and for proper functioning of the equipment (Functional Earthing).

Earthing of the metallic cabinets housing electronic equipment, essential for safety of personnel and equipment, is similar to earthing of other accessible metal structures and housings/enclosures in the station. It is called protective, safety or equipment earthing. The usual methods of earthing of the metallic structures and housings of various equipments in the station for safety of personnel are also applicable to earthing of cabinets and housings of the electronic equipment.

Earthing of the electronic equipment for functional reasons is called functional, logic, or circuit/signal reference earthing. It minimizes unwanted electrical signals (Electromagnetic Interference or EMI) that might interfere with the functioning of the equipment and cause component damage. It also prevents accumulation of static charge on the equipment by providing a low impedance leakage path to the earth for the same.

In this chapter essentials of functional earthing of electronic equipment in a power station, and mechanism of noise coupling are given. Suitability of various earthing methods of electronic equipment in power stations, both for protection of personnel and equipment (protective earthing) and for proper functioning of the electronic equipment (functional earthing) are discussed. It is common to use 'Ground' for 'Earth' in the context of electronic circuits.

7.2 FUNCTIONAL EARTHING

7.2.1 On every electronic circuit board, a grid of ground paths is laid for making connections to ground pins of ICs and other circuit elements. This is used as an electrical reference for the electronic circuit and is called 'signal/circuit common' or 'common ground' of the electronic board. All signal voltages of the circuit on the board are measured relative to its common ground. Whereas the protective earth conductors connecting metallic enclosures to earth for safety would carry current only during faults, the conductors of the grid forming common ground on the electronic circuit board form part of the complete circuitry during normal operation. The grid of ground paths on the electronic circuit board provides a low impedance return path for current to the source of supply of the electronic circuit.

The connection of the 'signal/circuit common' of the electronic circuit to the external earth electrode is known as logic, functional, or signal/circuit reference earthing. Apart from stabilizing of the reference potential, the connection of the signal common to the general mass of the earth (through earth electrode) is necessary for suppression of over-voltages due to atmospheric effect, protection of circuit against static charges and reduction of noise (unwanted signals) [1-4].

7.3 NOISE COUPLING MECHANISM

7.3.1 Noise in an electronic circuit is an electrical signal other than the desired signal. Interference is the undesirable effect of noise viz. improper operation of an equipment or component damage. In a power station, there are a vast variety of noise sources. These include lightning, various switching operations, electromechanical equipments, power electronic controlled devices, arcs and discharges, transformer and motor inrush currents, power system faults, electrostatic discharges, hand held transceivers and other RF equipment etc. Noise from the noise sources can be coupled to electronic equipment or signal cables (termed victim circuits or receivers of noise) by four possible means [1,3,5]:

- (a) Conductive coupling (e.g., power leads and common impedance coupling)
- (b) Capacitive coupling (also called electric field coupling)
- (c) Inductive coupling (also called magnetic field coupling)
- (d) Radiation coupling (also called Electromagnetic coupling)

7.3.1.1 Conductively Coupled Noise

Noise is coupled through wires. Noise conducted into the circuit through power leads can be minimized by using separately derived source such as UPS or isolating transformer for feeding power to electronic circuits. Another very prominent conductively coupled noise is the common impedance noise, which is due to sharing of common wire or conductor by two circuits. Figure 7.1 illustrates an example of common impedance noise due to formation of ground loop due to multiple earth connections [1,3]. The figure shows a system earthed at two points with a potential difference V_{noise} between the points. This is generally a very serious noise problem for which there are two possible remedial measures: (i) both circuits can be earthed at one point (single point earthing) making potential difference V_{noise} equal to zero, and (ii) conductive isolation can be created between the two circuits with the help of transformer/common mode choke/optical coupler/fibre optic/wireless signal communication etc. Choice shall depend on frequency of operation, feasibility and economy.

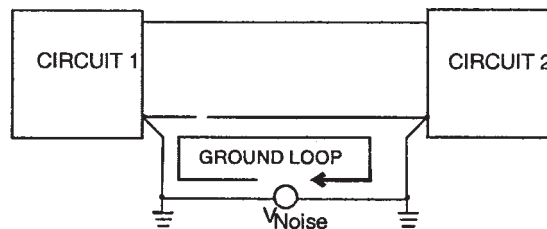


Fig. 7.1 : Example of common impedance coupling (ground loop)

7.3.1.2 Capacitive Coupling

This form of noise coupling is due to the stray capacitance that exists between the noise sources and victim circuits. The coupling can be minimized by increasing distance between noise source and victim circuit and by shielding the victim circuit.

7.3.1.3 Inductive Coupling

Noise can creep into the victim circuit due to its magnetic coupling with the circuit acting as noise source. Reducing area of the coupling loop of the victim circuit can reduce the magnetic coupling. For instance twisted wires instead of straight wires reduce loop area. Shielding the victim circuit can also minimize noise due to magnetic coupling.

7.3.1.4 Electromagnetic Coupling

When the source of interfering electric and magnetic fields is close to the victim equipment (distance less than $1/6$ of the wave length of interfering field), the interfering fields are said to be near fields. For near field situation, electric and magnetic fields can be treated separately, and effect of interfering electric and magnetic fields can be expressed in terms of capacitive and inductive couplings respectively, as has been done in the preceding paragraphs. However, for distances greater than $1/6$ of the wavelength (field is then called far field or radiation field), electric and magnetic couplings cannot be treated separately and the coupling is called electromagnetic coupling. Electric, magnetic and electromagnetic couplings are more serious at higher frequencies. In electromagnetic coupling, noise signal is conveyed to the victim circuit through radiation. Radiated electromagnetic energy (EMR) requires antenna in both the noise source and victim circuits. At higher frequencies lengths of wires joining signal commons to earth electrodes have to be kept electrically short (less than $1/20$ th of wave length) to reduce their impedance and to prevent them from acting as antennas and radiate noise [1, 3]. Shielding of the victim circuit can also reduce electromagnetic coupling.[1,3,4].

7.4 METHODS OF EARTHING OF ELECTRONIC EQUIPMENT

The connection to earth, for safety (protective earthing) and functional considerations (functional earthing) both, is established with the help of an earth electrode. The manner in which the connections are made from the earth electrode to various cabinets, of little significance for protective earthing, is of utmost importance for the functional earthing.

The earthing methods of electronic equipment can be broadly classified into three categories: (i) isolated earthing, (ii) single point earthing, and (iii) multiple-point earthing.

7.4.1 Isolated Earthing System

When a dedicated earth electrode, unconnected to the earthing system of the station, is used for earthing of electronic equipment, it is called isolated earthing system [3-4, 6]. Isolated earthing is neither suitable for safety of personnel and equipment nor for proper functioning of the equipment. It originated with the idea of isolating the earthing system of the sensitive electronic equipment from the noisy power system earthing system. It is true that earthing system of power system is noisy due to abundant presence of various sources of noise. But the problem of earthing electronic equipment to such a system comes not from earthing system of power system being noisy, but from earthing electronic equipment at several different points of the noisy earthing system, resulting in formation of the earth loops. Due to the formation of earth loops, current circulates in the earth circuit of electronic equipment introducing spurious voltages. It is neither possible nor desirable to isolate power system

earthing system from the earthing system of the electronic equipment. Such an isolation can be dangerous for the personnel as well as the equipment. Two of the dangerous situations, which isolated earthing system of electronic equipment can lead to, are described below:

- (a) In case of lightning strike on the building, housing electronic equipment, the potential of the building earth (which would be tied to power system earthing system) is elevated with respect to the isolated earth of electronic equipment. This results in a very high voltage between the two earths. This high voltage, and capacitance between building and electronic equipment combine to impress appreciable voltage on equipment and its components. It may result in a safety hazard and destruction of components of equipment.
- (b) In case of occurrence of an earth fault in the power supply system of the electronic equipment, the high resistance of isolated earth electrode would prevent speedy detection of the fault.

Isolated or dedicated earth electrode for an electronic equipment, thus, is not recommended.

7.4.2 Single Point Earthing System

In single point earthing system, functional earth connection of all the cabinets are connected to the power system earth electrode at one point. The single point earthing is the most frequently used method of earthing electronic equipment in a power station. Single point connection to earth is effective in preventing circulating earth currents which can produce common mode noise. This method of earthing is generally very effective and adequate when dealing with equipment operating at low frequencies, say up to 300 kHz [3,7]. Digital circuits with signal frequency in the mega hertz range should use multi-point earthing, to be discussed in the next subsection.

It is desirable to consult equipment manufacturer for applicability of single point earthing to a specific installation. However, in general it may be stated that while the real microprocessor frequency within equipment could be considered high frequency, the vast majority of instrumentation and control circuits that exist in the cabinets of electronic circuits in a power station are dc or low frequency circuits. Single point earthing is generally adequate in the power stations because of the prevalence of low frequency circuits in instrumentation and control systems.

A schematic arrangement of single point earthing system in a power station, with electronic equipment cabinets in close proximity, is shown in Fig. 7.2 [3,7]. The signal common earth terminals of all electronic equipment are connected by insulated conductor to the common insulated Functional Earthing Bus (FEB). Use of insulated conductor for functional earthing connection helps in safeguarding against any inadvertent connection to earth on its way, and makes it differentiable from the protective earthing conductor. As shown in the figure, FEB is connected to the interconnected power station earthing system with insulated conductor. For protective earthing, all metallic housings/cabinets of the electronic equipment are connected to the Protective Earthing Bus (PEB), which is also connected to the station earthing system. A separate independent protective earth connection for each cabinet increases reliability of the protective earthing system. When the cabinets are in close proximity, adjacent cabinets should additionally be bolted or bonded together with a single strap or cable.

Functional earth connection and protective earth connection in a cabinet are to be kept separate from one another, though the buses (FEB and PEB) from where they originate are connected to the common station earthing system. Sometimes, manufacturers of electronic equipment may tie signal

common of the equipment to the metallic enclosure of the equipment. For adoption of single point earthing system it would be necessary to isolate the signal common of the electronic equipment from the metallic enclosure of the equipment. However, modification of factory connection might violate warranty conditions. For implementation of single point earthing of the equipment, therefore, it is necessary to incorporate this provision in the procurement specifications of the equipment [3,7].

If the equipment cabinets are widely separated in the power station, the implementation of single point earthing system as shown in Fig. 7.2 may not be practical. For such a system the cabinet earth points shall be at relatively different potentials with respect to each other and unwanted currents may flow in the earth connections between the cabinets. Generally, if separation distance between the cabinets is 30 m or more, they may be regarded as widely separated and the single point earthing scheme of Fig. 7.2 may be modified to that of Fig. 7.3 [3]. In the modified version of single point earthing system, shown in Fig. 7.3, a separate single point earthing system has been created for each geographic grouping of electronic equipment. This in effect is multiple single point earthing system. It might be necessary to eliminate all metallic signal paths between widely separated cabinets by the use of alternative communication means such as fiber optic, wireless communication etc.

Further, compatibility requirement of the equipment to such multipoint/single point earthing system should be incorporated in the procurement specifications of the equipment.

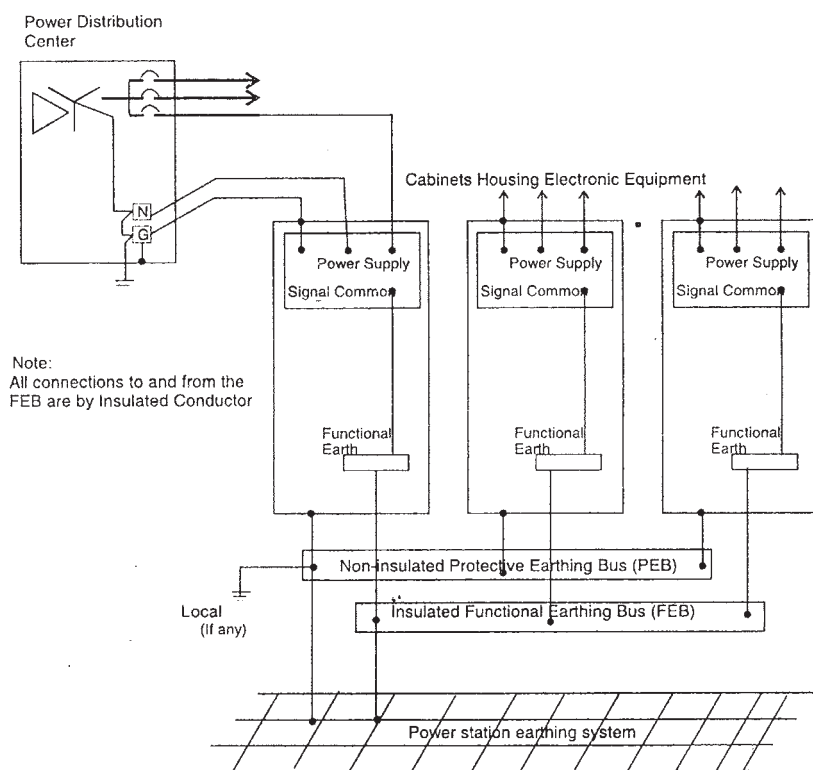


Fig. 7.2 : Single point earthing system with cabinets in close proximity

7.4.3 Multiple-Point Earthing System

Single point earthing system is not suitable at high frequencies as the impedance of conductors used for making connection to earth bus may become excessive due to the increase in their inductive reactance with frequency. The impedance can become too high if the length coincides with odd multiples of quarter wavelength. Such large lengths shall not only result in very large impedances but could act as antennas and radiate noise. The length of these conductors should normally be less than one-twentieth of a wavelength to prevent radiation and to maintain low impedance [1, 3]. At higher operating frequencies (say more than 300 kHz), single point earthing system cannot be implemented without violating this condition. Multiple-point earthing system should be considered for earthing of electronic equipment operating at higher frequencies[3].

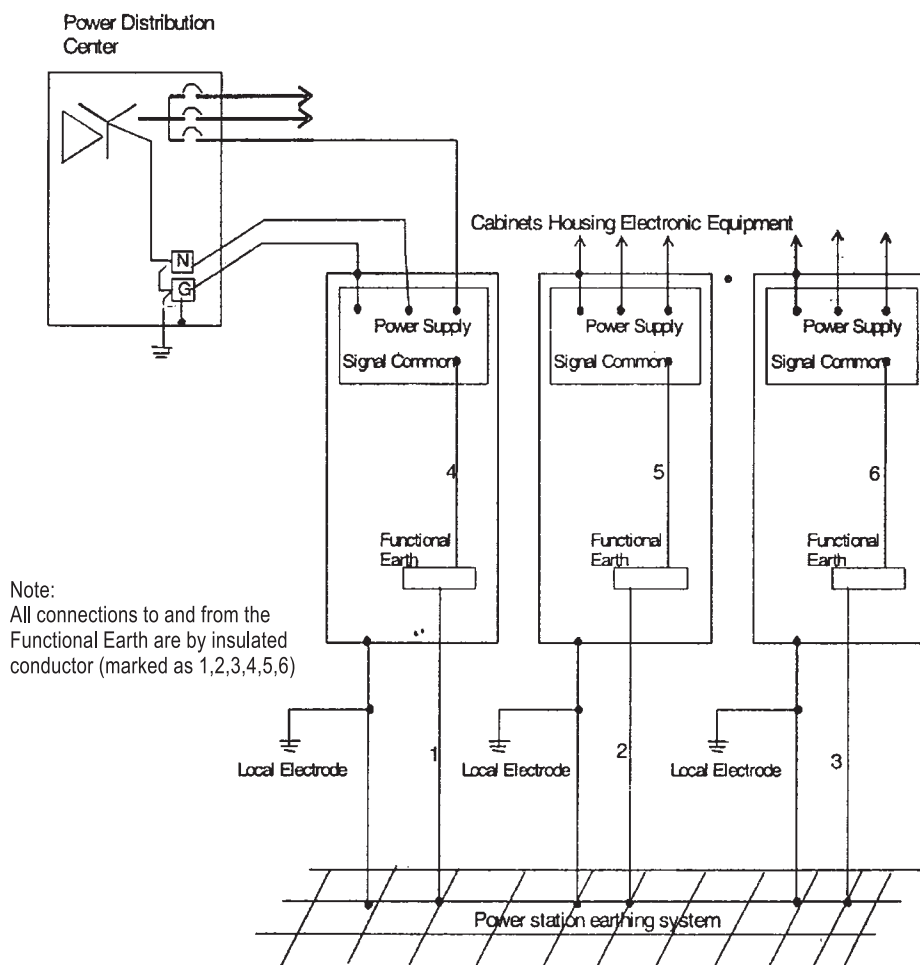


Fig. 7.3 : Single point earthing system with widely separated cabinets housing electronic equipment

A schematic arrangement of multiple-point earthing system for electronic equipment in a power station is shown in Fig. 7.4. The signal common of the electronic equipment is tied to the metallic cabinet of the equipment. Each cabinet is further connected to earth at the nearest point. At times it may be necessary to install a signal reference grid (SRG) beneath the area where cabinets are placed for facilitating implementation of multiple-point earthing system. 'SRG' is a local closely meshed grid tied to station earthing system. Generally, recommended spacing for SRG is $0.6 \text{ m} \times 0.6 \text{ m}$ as it is able to provide good performance up to about 30 MHz, which is sufficient in most practical cases. It may be convenient to install this grid in the cellular raised floor of the room housing equipment cabinets. SRG has to be tied to the station earthing system.

Multiple-point earthing system is advantageous in reducing high frequency noise. A drawback of this system is the formation of low frequency earth loops causing common mode noise. Hybrid forms of earthing where the earthing system acts as a single point earthing system at low frequencies and multiple-point earthing system at high frequencies may alleviate this problem [1, 3].

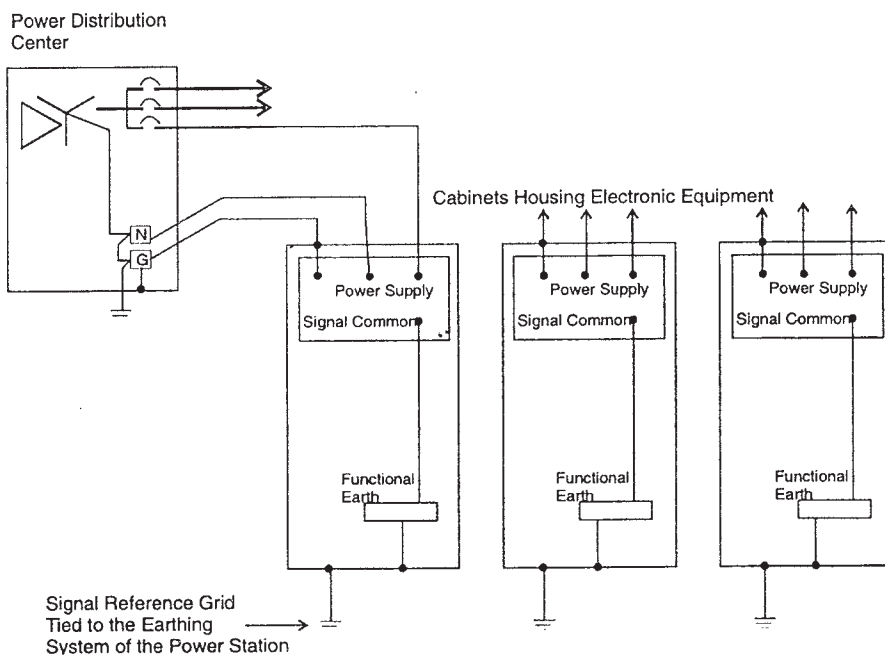


Fig. 7.4 : Multiple-point earthing system

7.5 SUMMARY

Earthing of electronic equipment for safety of personnel and equipment, called protective earthing, is similar to earthing of other metallic housings and structures in the power station. Earthing of signal common of electronic equipment, called functional earthing, is important for proper functioning of the equipment. Proper functional earthing stabilizes circuit reference potential, protects the circuit against static charge and over-voltages, and minimizes interference from unwanted signals (noise).

Various mechanisms of noise coupling between potential noise sources and electronic circuits have been described. Various methods of earthing electronic equipment have been discussed. Isolated earthing system is not suitable for earthing of electronic equipment. In general, single point earthing system is the most suitable method for earthing of electronic equipment in the power station for low operating frequencies (say below 300 kHz or as recommended by the manufacturer). Vast majority of signal communication between equipment in power station is at dc or low frequencies and as such single point earthing system would be suitable. Single point earthing system has been described both when equipment cabinets are in close proximity and when they are widely separated. In the latter case conductive signal communication between circuits is to be avoided. For higher operating frequencies, multiple-point earthing system has been described.

REFERENCES

- [1] Ott, H. W. Noise Reduction Techniques in Electronic Systems, 2nd Ed, John Wiley & Sons, New York, 1989.
- [2] Gumhalter, H. Siemens Power Supply Systems in Communication Engineering, Part 2, Wiley Eastern, New Delhi, 1988.
- [3] IEEE Guide for Instrumentation and Control Equipment Grounding in Generating Stations, IEEE Std. 1050-2004, IEEE, New York, 2005.
- [4] IEEE Recommended Practice for Powering and Grounding Electronic Equipment, IEEE Std. 1100-2005, IEEE, New York, 2006.
- [5] Fowler, K. "Grounding & Shielding, Part 1-Noise," and "Grounding & Shielding, Part 2-Grounding and Return," *IEEE Instrumentation & Measurement Magazine*, vol. 3, issue 2, pp. 41-44 and 45-48, Jun 2000.
- [6] Lee, R. H. "Grounding of Computers and Other Sensitive Equipment," *IEEE Trans, on Industry Applications*, vol. 1A-23, pp. 408-411, May/June 1987.
- [7] Jancauskas, J.R. Grant, L.A.D. and Thaden, M.V. "Use of Single Point Grounding for Instrumentation and Control Systems Installed in Existing Generating Stations," *IEEE Trans. On Energy Conversion*, vol. 4, pp. 402-405, Sept. 1989.

CHAPTER - 8

Execution, Field Practices, Monitoring and Maintenance of Earthing Systems

Synopsis : Earthing system of a station should provide reliable performance during the life of the station. The earth electrode, being underground, can be the case of out of sight out of mind. It is of utmost importance that construction of earth electrode is carried out by strictly adhering to the design. Once the earthing system is installed, it is important to carry out periodic inspections and testing and take remedial measures to maintain its performance. This will ensure that the earthing system shall continue to fulfill its objectives of providing safety and proper operation. In this chapter, various aspects related to construction and maintenance of earthing systems are brought out.

8.1 EXECUTION OF EARTHING SYSTEM

8.1.1 Introduction

A station earthing system is typically composed of five key components, namely (i) the soil, (ii) vertically installed bare metallic rods / pipes / plates and horizontally installed bare conductors in the soil, (iii) overhead shield wires and lightning masts, (iv) a layer of high resistivity gravel on top of the soil, and (v) bare / insulated conductors which connect all metallic structures, enclosures of all equipment including metallic conduits and cable trays, etc. with underground, buried vertical rods / pipes / plates and/or horizontal conductors. The underground buried vertical rods / pipes/ plates and horizontal conductors, to which all metallic structures, enclosures of all equipment including metallic conduits and cable trays, etc. in the switchyard are connected, form the grid earth electrode. The effectiveness of the earthing system depends on the condition of the buried conductors and the integrity of the connections between earth conductors and between earth conductors and the structures.

8.1.2 Construction of Grid Earth Electrode

8.1.2.1 The construction of earthing system depends on a number of factors, such as size of grid electrode, its depth of burial, size of earth conductor, type of soil, availability of equipment, cost of labour, and any physical or safety restrictions due to the presence of nearby, existing structures or energized equipment.

8.1.2.2 Construction Sequence for Earthing System Installation

An earth grid is normally installed after the yard is graded, foundations are laid, and deeper underground pipes and conduits are installed and backfilled. It may be prudent to wait until construction of plinths and other structures have been largely completed to avoid possible damage to earth conductors. The required connections to equipments and structures are made after the horizontal earth conductors are placed in trenches.

The security fence may be installed before or after the earth grid installation. In cases where deeper underground pipes and conduits are not installed before earth grid installation, an attempt should be made to coordinate the trenching procedure in a logical manner.

8.1.2.3 General Practices

- (a) The bare MS conductors forming grid electrode are generally laid at a depth of about 300 mm to 600 mm below ground level. The minimum depth is recommended for protection of conductors and connections against mechanical damage during subsequent excavation works. Actual depth of horizontal grid conductors should be in accordance with design calculations to keep dangerous voltages and EPR within acceptable limits.
- (b) At large substations, it will be advantageous if earth conductors are laid on one side of excavations made for cable trenches, field drains, and other civil works. However, spacing between horizontal grid conductors should be in accordance with design calculations to keep dangerous voltages and EPR within acceptable limits.
- (c) The conductors should be surrounded by 150 mm of non-corrosive soil of fine texture, firmly rammed [1].
- (d) The connection between vertical rods and horizontal conductors can be made using various methods. However connections between horizontal grid conductors should be welded/brazed / exothermic type, as assumed for calculation of their area of cross-section to carry the maximum fault current during earth fault conditions in the system. Bolted type connections are generally provided between earthing (lead) conductors and equipment / enclosure earthing terminals to facilitate the removal /replacement of equipment. Similarly, bolted type connections are also provided between earthing conductors and vertical rod / pipe /plate electrodes to facilitate testing / repair / replacement of vertical electrodes.
- (e) Where bare earth conductors cross over or are laid touching power or multi core cables, they should be insulated with PVC tape or sleeve to counteract possible puncturing of cable sheath arising from high voltage transients on earth conductors [1]. However metallic sheath / armour of cables are to be bonded with the earthing system in accordance with the recommendations given in the design and specifications for the earthing system of the stations.
- (f) Specific guidelines / recommendations for earthing of equipment / structures are given under section 8.3.

8.1.2.4 Gravelling and Antiweed Measures for Earthing System

In a grid earbth electrode, there are two aspects of the problem of ensuring safety with respect to touch and step voltages. Firstly, the spacing between earth conductors is chosen such that the estimated value of the touch and step voltages, which can appear at any point within the substation and around the perimeter, do not exceed the respective permissible values. Secondly, at most station sites it is possible to increase the magnitude of permissible touch voltage and step voltage by placing a high resistivity material, e.g. gravel, over the rough grade. The gravel, where required, is spread over the finished surface to a depth of about 100 mm to 200 mm. In a number of cases it

has been observed that effectiveness of the surface layer of gravel spread over the grid electrode is lost some years after installation due to growth of grass or weed. At most of the stations it has been very difficult to restrict the growth of grass / weed. In some cases termite growth has also created problems; it has been reported that termite growth has caused unwanted operation of equipment / tripping. In view of above, the following procedure for laying of the grid electrode is recommended in order to minimize this problem:

- (i) After all the structures and equipment are erected, antiweed treatment is to be applied in the switchyard wherever gravel is to be spread. The area is to be thoroughly de-weeded and all roots are to be removed. The recommendation of local agriculture or horticulture department is to be sought, if feasible, while choosing the type of chemical to be used. The antiweed chemical should be procured from reputed manufacturers. The type, dosage and application of chemical should be strictly done as per manufacturer's recommendation and should not accelerate corrosion of earth conductors,
- (ii) After antiweed treatment is complete, surface of the switchyard area is to be rolled/compacted by using half-ton roller, combined with water sprinkling, to form a smooth and compact surface. Due care should be exercised so that there is no damage to any foundations for structures or equipment during rolling and compaction,
- (iii) Over the prepared sub-grade, 75 mm thick base layer of cement concrete is to be provided. The areas for roads, drains, cable trenches etc. are to be excluded, and
- (iv) Finally, the layer of gravel/crushed rocks of specified size is to be spread uniformly up to specified depth over cement concrete layer after its curing is complete.

8.1.2.5 After an earth grid is laid, it is extremely difficult to test earth resistance of independent sections of the grid. If instead there are independent rod groups, links may be provided for testing independent groups[1].

8.2 MEASUREMENTS AND FIELD QUALITY CHECKS

Visual inspections, field tests and measurements should be carried out to ensure that the earthing system is installed in accordance with the applicable standard(s), design, technical specifications, and well accepted practices. For conducting field tests and measurements, proper equipment and facilities are required as discussed in Chapter 10.

8.2.1 Measurement of Substation Earth Resistance and Earth Impedance

8.2.1.1 Measurements shall be carried out after construction, where necessary, to verify adequacy of the design. Measurements may include earthing system impedance / resistance, prospective touch and step voltages at relevant locations and transferred potential, if appropriate, as per procedures given in Chapter 10. Although the measurements may pose some difficulties, if properly done, measured values are more exact than calculated values. When the soil is non-uniform and the earthing system is large and complex, measurements to check the theoretical calculations are advisable.

Measurements are also recommended after major changes affecting the basic parameters and as per the schedule of maintenance prescribed for power installations in this chapter.

Records shall be kept of the initial measured earth resistance of substation and/or generating station earth electrodes and of tests carried out subsequently.

Adequate safety and precautionary measures are to be taken during the test and measurements as discussed in Chapter 10.

8.2.1.2 All tests / measurements recommended under section 8.4 for periodic monitoring of earthing system / earth electrodes shall be carried out after the completion of respective construction / erection works. Results of these and all other tests / measurements shall be documented to serve as reference for (i) acceptance of design and construction of earthing system and (ii) monitoring and maintenance of earthing system.

8.2.2 Field Quality Checks / Inspections

All physical checks / inspections that are recommended under this section and section 8.4 for monitoring and inspection of earthing system / electrodes are to be carried out after the completion of respective construction / erection works. Results of all physical checks / inspections shall be documented to serve as reference for (i) acceptance of design and construction of earthing system and (ii) monitoring and maintenance of earthing system.

8.2.2.1 Field quality checks / inspection are to be carried out during the erection and construction activities to ensure that the following general and all other details are in accordance with design/ specifications of station earthing system and well accepted practices:

- (i) Material, dimension and physical condition of horizontal conductors and vertical electrodes,
- (ii) Layout, spacing and depth of horizontal conductors of earth electrode,
- (iii) Dimensions, locations and depth of vertical electrodes including construction of their chambers / pits, application and compaction of backfill around electrodes, watering arrangement and connections between vertical electrode and (a) main conductors of earth electrode and (b) earthing lead conductors from equipment /structures,
- (iv) All welded / brazed / exothermic connections between (a) horizontal grid conductors and (b) equipment / structure earthing lead conductors and horizontal conductors of main earth electrode,
- (v) Quality and reliability of all bolted connections between earthing lead conductors and earthing terminals of equipment / structures, and
- (vi) Quality and spacing of cleats for fixing of earth lead conductors on aboveground supporting structures.

8.2.2.2 Earthing and bonding connections to transformers, switchgear, cable sheaths, support frameworks, pillars, cubicles, metal clad chambers, bases of insulators and bushings and their associated metalwork etc. should be in accordance with the specifications / accepted practices and should be checked to ensure that they are properly made and are intact.

8.2.2.3 Material and size of flexible bonding braids or laminations should be in accordance with the specifications / accepted practices and also should be inspected for signs of fracture

and corrosion; these should be changed as required. Earth mat connections should be verified as secure and buried installations should be checked to ensure that they have not been disturbed.

8.2.2.4 On switchboards fitted with frame leakage protection, visual inspection should be carried out to ensure that the insulation segregating the switchgear frame from the main earth bar and the cable sheath is not short circuited by inadvertent paths.

8.2.2.5 Neutral Links / Connections

- (i) Neutral links should be checked to ensure that they are tight, the neutral earth connection is intact and, where appropriate, the value of resistance is correct.
- (ii) In substations where the neutral connections and cable sheaths are isolated from the substation earth, visual checks should ensure that this isolation is not short-circuited.

8.2.2.6 If there are any buildings within the earth grid area, earthing of such buildings is to be integrated with the earth grid as per design.

8.2.2.7 Ground Grid Integrity Test

Many times, protective relays, telephone equipment, power supply unit etc. in the control house get damaged due to lightning surge or fault if the substation has a poor earthing system. Typically, the earth grid integrity test is performed following such an event. Some times after installation of a large grid electrode, this test is performed to ensure the integrity before the substation is approved for operation. The integrity test may consist of one or more of the measurements like earth impedance, earth resistance, earth fault loop continuity, touch voltage and or earth resistivity in order to detect any open circuit or isolated structure or equipment or any other inadequacy of the earthing system in a substation. Procedure of such tests is given in Chapter 10.

8.3 FIELD PRACTICES AND TECHNIQUES FOR EQUIPMENTS

8.3.1 General

The main grid electrode is installed only after it is ensured by design that the attainable touch and step voltages are less than the respective permissible values. There are other important areas of concern in the substation earthing system which need special attention. These include the earthing practices for transformer neutral terminals, capacitive voltage transformer, lightning mast, lightning arrester, substation fence, switch operating handles, rails, pipelines, and cable sheaths. The effect of transferred potential shall also be considered. The basic objectives of proper equipment earthing have already been discussed in previous chapters.

8.3.2 Neutral Earthing of the Electrical System

There are three methods of earthing the neutral point in the electrical system:

- (i) Solid earthing,
- (ii) Earthing through a transformer, and

(iii) Earthing through a resistance.

The method is chosen as per design of the station.

8.3.3 Earthing of Capacitive Voltage Transformer

Capacitive voltage transformers which are generally connected between line and earth, present a relatively low value of impedance to steep fronted surges and would, as a consequence, permit high frequency currents to flow through them to earth. Unless a low impedance earth connection is provided for such items of the substation, the effectiveness of the arrester could be impaired and high transient potentials could appear on the earthing connections local to the equipment and on any other locally earthed plant. Steep fronted surges will rapidly attenuate in the earthing system away from the source resulting in possible large potential differences arising between locations on the same earthing system.

The earthing arrangement, shown in Fig. 8.1, is recommended for capacitive voltage transformer. Each capacitive voltage shall be earthed through a permanent independent earth electrode.

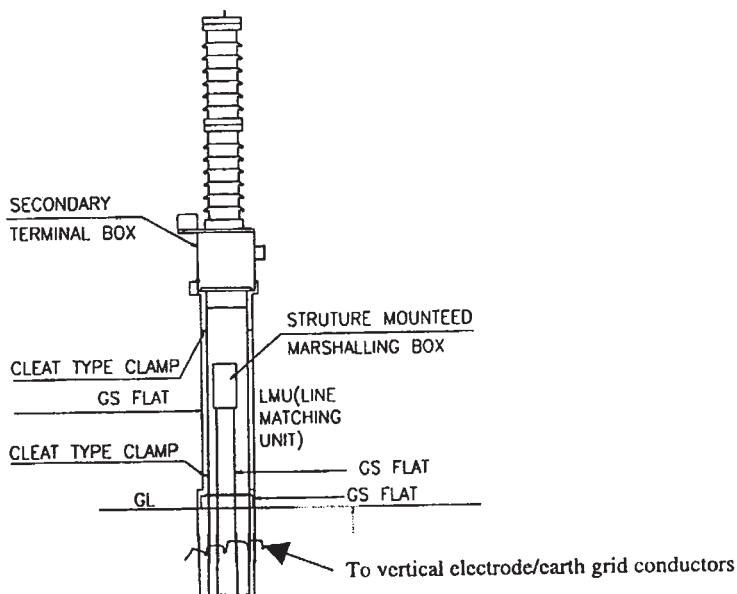


Fig. 8.1 : Earthing arrangement of capacitive voltage transformer

Earthing terminal of each capacitive voltage transformer shall be directly connected to a vertical rod electrode, which in turn shall be connected to the station earth grid. The detail of a typical vertical rod electrode with watering arrangement and soil treatment around the electrode is given in Fig. 8.2. In this arrangement, the size of hole in the earth is about 300 mm square. The rod or pipe is driven into earth in the centre of the hole and four PVC pipes for watering are positioned in four corners. The space in the hole is filled with a mixture of coke breeze, Bentonite etc.

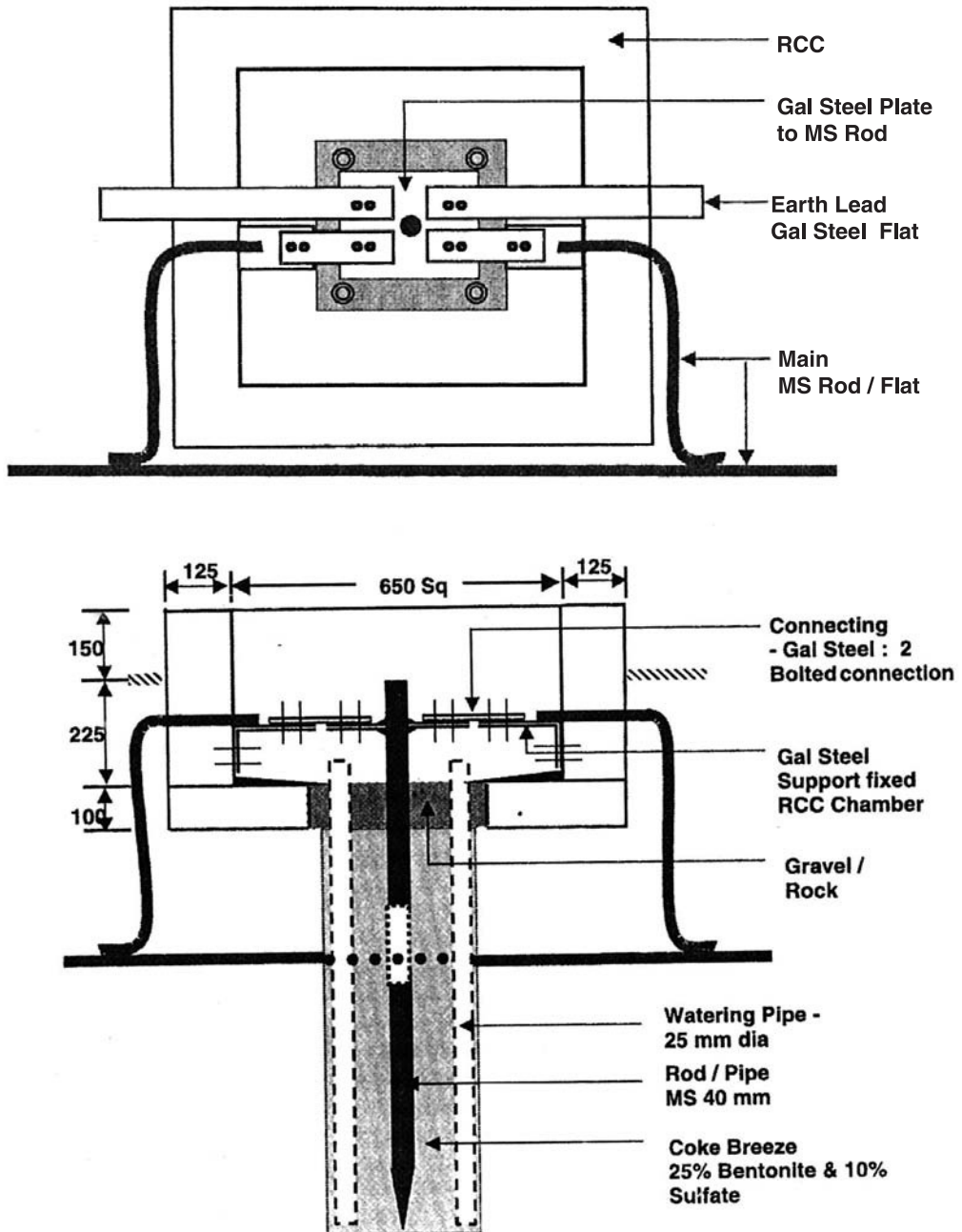


Fig. 8.2 : Plan and sectional view of vertical rod electrode without hinged cover of inspection and watering chamber

8.3.4 Lightning Mast & Tower with Peak Grounding

Lightning mast & the peak for towers are provided for protection against direct stroke lightning. Various literatures are available for direct stroke lightning protection calculations to decide the height and location of the lightning mast and tower with peaks.

The peaks of towers are normally connected with overhead earth wires of the overhead transmission lines. By connecting these earth wires to the station grid and by decreasing the tower footing resistances in the vicinity of the substation, a substantial portion of earth fault current is diverted away from the station earth grid. Hence the earthing of towers with peaks are very important from direct stroke lightning as well as the current diversion point of view.

Lightning masts and towers with peaks are to be provided with preferably low impedance path to the earth. Down conductors from the top of the lightning mast and peak of the tower are clamped down and connected through exothermic connection to the main earthing system of the substation through a circular/flat conductor without excessive bends in order to provide a low impedance path to high frequency lightning currents.

8.3.5 Lightning Arrester Earthing

Lightning arrester should always be provided with a reliable low impedance earth connection. It shall be connected as close as possible to the terminals of the apparatus to be protected and have as short and direct a path to the earthing system as practical. It is advised to provide separate earth connections from arresters mounted on metal structures to the separately provided earth pit which must also be connected to earth grid.

The statutory requirement of the Indian Electricity Rules shall be fulfilled. As per Indian Electricity Rules 1956 (as amended up to 25th Nov., 2000), the earthing conductor for any lightning arrester shall not pass through any iron or steel pipe, but shall be taken as directly as possible from the lightning arrester to a separate earth electrode and / or junction of earth grid provided at the station subject to the avoidance of bends wherever practicable and a vertical rod electrode shall be connected to this junction of the earth grid.

Therefore, the arrester should be connected with the shortest possible direct connection, on both the line and earth side, to reduce the inductive effects while discharging high frequency surge currents. All the connections should be firm and preferably exothermic connection and should not cause excessive mechanical stresses on the arrester/monitor. Use of flexible cable or lead and excessive bends is to be avoided in these connections.

A typical earthing arrangement of surge arrester is shown in Fig. 8.3.

8.3.6 Earthing of Substation Structures

For effective control of attainable touch voltage as well as to ensure that all earthed structures are uniformly at the potential of earth grid, all non-current carrying metalwork, i.e., steel structures of all kinds shall be bonded to the main earthing system in a reliable manner. The cross-sectional area of such bonding connections should be, where feasible, not less than 25 mm x 3 mm unless physical constraints dictate otherwise.

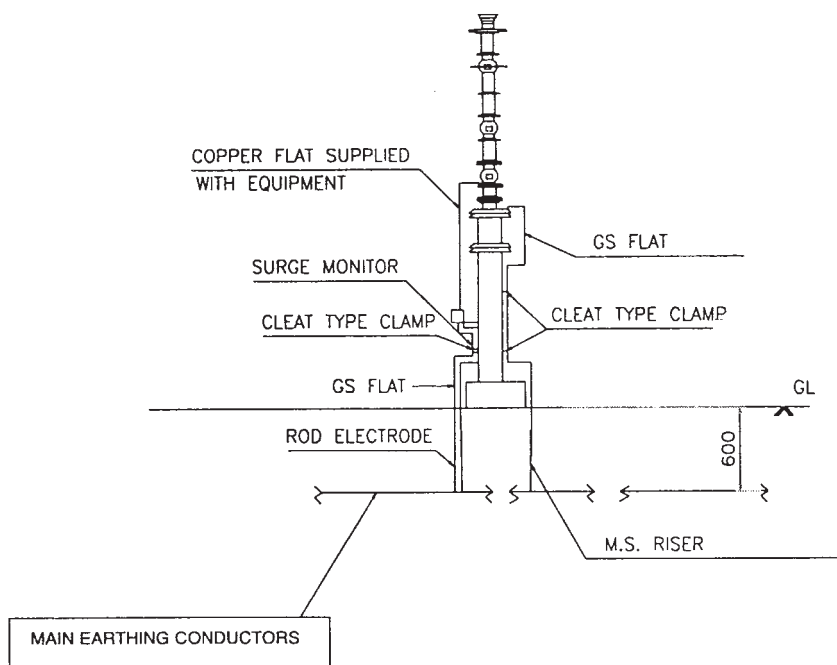


Fig. 8.3 : Earthing arrangement of surge arrester

The junction points of the metal frameworks shall be welded or have a bolted electrical connection. Measures are taken to ensure that the earthing of other parts is not disrupted if parts of the installation, which are detachable, are actually removed.

In reinforced concrete structures, earthing conductor may be embedded in concrete. They must have easily accessible junction points. The steel reinforcements required for the concrete construction may also be used as an earth conductor if they have adequate cross sections, are welded all through or are made electrically conducting in another manner.

8.3.7 Earthing of Substation Fencing

In order to keep step and touch potentials inside /outside the fence within permissible limits, all metallic elements of the station fence are made electrically continuous by bonding connectors and are connected to earthing system in accordance with recommendations based on results of design calculations and the considerations given in Section 3.12 . The earthing requirement of substation fence are described in Chapter 3. These may be accomplished by bonding the fence and its gate to the substation main earth grid.

The concept of earthing of metallic fence, provided around the periphery of a substation for security and safety considerations, is of vital importance since the methodology adopted and practice followed for the earthing of substation fence has a direct bearing on the touch and step potentials

outside the fence which is usually accessible to the general public, working personnel and cattle. The design of the earthing system ensures that the step voltage and touch voltage, likely to be encountered by a person outside the fence, does not exceed the permissible limit. The fence earthing and spreading of gravel near it should be carried out as per the design and specifications.

8.3.8 Earthing of Other Auxiliaries

It is to be ensured that all auxiliary metalwork associated with panels, cubicles, kiosks, LT equipments, cable sheath, water pipes, fire fighting pipes, motors, rails etc. are connected with the earthing system reliably with not less than 25 mm × 3 mm conductor.

8.4 MONITORING AND MAINTENANCE OF EARTHING SYSTEM

8.4.1 General

The earthing system of a HVAC substation of power installation or power plant is to be maintained as per the salient practices mentioned in Sec.34 of IS: 3043 which recommends periodical checks, annual measurements, value checks and testing of earth resistance and periodical verification of earth fault loop resistance. The general considerations / guidelines and specific monitoring / maintenance activities that are intended to provide information regarding the requirements for proper monitoring and maintenance of earthing systems are given in this section.

8.4.2 Monitoring and maintenance of earthing system generally involves the following basic activities:

- (i) **Periodic** visual inspection and physical checks of earthing conductors and connections that are provided (a) above the ground level, and (b) inside the pits / chambers of vertical electrodes and built-in cable trenches and ducts,
- (ii) **Periodic** visual inspection of (a) physical status of gravel / crushed rock layer, (b) growth of grass/weeds and (c) accumulation of water in station area and cable trenches and erosion of soil due to rains,
- (iii) **Periodic** test / measurements for the determination of (a) resistance of vertical earth electrodes, (b) continuity of earthing / bonding conductors for the flow of current during fault / abnormal operating conditions,
- (iv) **Periodic** remedial measures to maintain the integrity and performance of earthing system, as required, based on results of visual inspection / physical checks / tests and measurements, and
- (v) **Special** measures to ensure integrity and performance of earthing systems in specific cases such as (a) additions / alterations in electric system of the station (b) deterioration of earthing conductor/ vertical electrodes due to corrosion, aging etc.

8.4.3 Frequency of periodic visual inspection and physical checks, periodic tests / measurements, and periodic remedial measures should depend on local conditions, age and status of earthing system and the following considerations:

- (i) General inspection of all above ground earthing conductors and equipment earth connections should be carried out every month to ensure that all earthing connections are intact and

- properly fastened/welded and are not excessively rusted or corroded. Remedial measures such as tightening of loose connections, cleaning & painting / replacement of rusted / corroded connections should be taken whenever required but at least once a year,
- (ii) Physical status of (a) all earthing conductors and connections inside the pits / chambers of vertical electrodes and built-in cable trenches and ducts (b) physical status of gravel / crushed rock layer, (c) growth of grass / weeds and (d) accumulation of water and erosion of soil due to rains should be checked at least twice a year, once being after monsoon season. Remedial measures such as tightening of loose connections, cleaning and painting/ replacement of rusted / corroded connections, reconditioning of gravel layer, removal of grass / weed / water, restoration of soil cover should be taken whenever required and as early as possible,
 - (iii) Tests / measurements for the determination of resistance of vertical earth electrodes, should be carried out during dry soil conditions and after watering of electrodes. The results of these tests / measurements should form the basis for determination of the frequency of tests / measurements and watering of electrodes to lower their resistance. The results of tests / measurements before and after watering of electrodes should form the basis for the examination of physical status of the backfill and the electrode and the need for their replacement, and
 - (iv) Tests / measurements for the determination of continuity of earthing / bonding conductors for flow of current during fault / abnormal operating conditions should be carried out at least once in a year and remedial measures to ensure their proper performance should be taken immediately.

8.4.4 Special measures / investigations to ensure integrity and performance of earthing systems in specific cases such as mentioned under section 8.4.2(v) above should be decided by competent authority.

8.4.5 Specific Monitoring & Maintenance - Check List

- (i) Vertical Earth Electrodes
 - Periodic watering, as frequent as every fortnight during summer, of vertical earth electrodes,
 - Periodic cleaning of pits for vertical earth electrodes,
 - Periodic check for tightness of terminals in earth pits including their painting if required,
 - Visual inspection of all earth electrode connection, wherever applicable, shall be carried out to ensure their rigidity and detect any other signs of deterioration,
 - Where an earth pit is provided and its earth resistance is 50% more than the commissioning value, the pit is to be treated after re-filling salt and charcoal, as specified, and if required, damaged and corroded electrodes may be replaced/rectified. Special care is to be taken to physically examine and test the neutral earthing pit/electrode of power transformers,
 - Inspection of earth grid/vertical electrodes should be carried out on sample basis to ascertain corrosion level of earth conductors. Necessary rectification may be done where inadequacy is found,

- Each lightning arrester's earth pit / electrode should be interconnected to the nearest earth electrode of station earth grid by the shortest straight connection. Also it may be ensured during maintenance that earth conductor is shortest and straight connection from the lightning arrester to the earth pit, and use of flexible cable and excessive bends in connections is avoided. This measure is essential to maintain low earth impedance during lightning,
- (ii) Periodic check for rusting/corrosion/inadequacy of connections of bolts and washers,
- (iii) Periodic check for tightness of all the equipment earth connections including their painting if required,
- (iv) Periodic measurement of loop resistance on all equipments bay wise at earth terminals and verifying and confirming its continuity to earth mat,
- (v) Where earth-leakage circuit breakers are employed, a check shall be kept on the associated earth-electrode by periodically operating the testing device that is embodied in the earthed leakage circuit breaker,
- (vi) Measurement of earth resistance may be carried out preferably on un-charged bays of the yard,
- (vii) Where installations are earthed to a metal sheath of the supply cable, it shall be verified periodically that the earth fault loop is in a satisfactory state,
- (viii) Where installation is earthed to a cable sheath which is not continuous to the substation neutral (that is, there is an intervening section of overhead line without earth wire), a supplementary electrode system may be necessary. As such, the adequacy of the electrode system shall be checked initially by an earth-fault loop test,
- (ix) Tests of earth resistance, continuity of earth fault loop, and integrity of earthing system are to be carried out at vital/important locations on each bay of the station. The feedback of test results may be referred for major replacements/refurbishments if required,
- (x) Painting of earthing conductors and risers may be re-done wherever required. This work should be done on the basis of number of years in service. It is advised that after 15 years in service, at least 10% to 15% of earthing system should be examined physically. Necessary rectification may be done where inadequacy is found. Complete system is to be thus examined in rotation or in phased manner,
- (xi) If the earthing system at a station consists of copper strip or round conductor and has been in service for more than 15 years, then sample checks may be done on such a station. Sample inspection checks on switchgear bays should be carried out after excavating the earth and by exposing the electrodes / grid / flat to examine the status of corrosion / brazing / welds/ bolted connections. These connections are mostly corroded at both exothermal and bolted connection points. These checks may be carried out in rotation or phased manner in every subsequent year as per (x) above.
- (xii) Tightening of the earthing connections of CTs and PTs may be checked both in secondary and primary sides of the equipment.

- (xiii) The grit/gravel or crushed rock stones in the station yard should be re-dressed/replaced, if required. It is observed that in many old sub stations, gravel disappears over a period of time. Also gravel layer becomes thin and voids between gravel are filled with soil, grass, sand and other such material. This can significantly reduce the permissible step and touch voltages and thus the level of personnel protection.

8.4.6 Replacements and Refurbishment

The decision on whether to repair the damage to the earthing system or overlay a new earth electrode will depend on an analysis of the history of the earthing system, the design basis for the original earthing system, and the costs involved. In case the original design is no longer adequate and conductor cross-section, grid resistance, and conductor spacing need to be changed, it may be necessary to install new vertical rods and overlay a new earth grid. If the design is adequate but the system is damaged, repairs or replacements of the part of the system, the overlay of some new earth conductors, or a combination of the two may be appropriate.

If the fault level of the substation has increased much beyond the originally designed value and there exists inadequacy in design with existing earth grid, the decision to renovate the earth grid of particular substation may be considered. Refurbishment of earth grid may be considered as given below:

- (i) It is to be carried out at the substation, which is more than 20 years old or where fault level has exceeded the present value and the calculated grid current has considerably exceeded the original design value of grid current,
- (ii) For the substation, which is more than 20 years old and is directly connected to major generating stations replacement/refurbishment decision may be taken based on sample checking of conductors of earth grid,
- (iii) After ten years of installation, the treated earth pits with vertical rod electrodes are to be inspected by digging on sample basis. The damaged/broken electrodes need to be replaced, and
- (iv) Welded joints in corrosion prone areas need special attention. Anticorrosive paint may be applied on need basis.

8.5 SAFETY CONSIDERATIONS DURING EXCAVATIONS

During excavations after a station has been in operation, there are possibilities of snag in the connections of earth grid and earthing conductors. In such cases, a check should be made to determine if there is a break in the conductor and/or joints. A break in the conductor or joints, or both, must be immediately repaired. A temporary earth connection should be placed around the break before it is repaired. The temporary earth connection should be suitable for the application and installed according to safe earthing practices, because a voltage may exist between the two earth conductor ends.

Where construction works involves an existing earthing system and operating substation, adequate protective measures should be taken to ensure the safety of personnel during fault conditions as discussed in Chapter 10.

8.6 SUMMARY

- (a) Various steps and measures to be adopted during construction / execution of earthing system have been described.
- (b) Methods of earthing various types of equipment have been laid out.
- (c) Procedures for maintenance and monitoring of earthing system have been listed.

REFERENCES

- [1] Technical Specification 41-24, Guidelines for the Design, Installation, Testing and Maintenance of Main Earthing Systems in Substations, *Engineering & Safety Division, The Electricity Association, London, 1992.*
- [2] Indian Standard IS: 3043 - 1987, *Code of Practice for Earthing (First Revision).*
- [3] Indian Electricity Rules 1956 (as amended up to 25th Nov., 2000)
- [4] ANSI/IEEE Standard 80-2000, IEEE Guide for Safety in AC Substation Grounding, IEEE, New York, 2000.
- [5] International Standard IEC 61936-1. Power Installations exceeding 1 kV ac, *International Technical Commission, Geneva, Switzerland, 2002.*
- [6] CBIP Proceedings on “Design of Earthing Systems”, 18-19 December, Central Board of Irrigation and Power, New Delhi
- [7] CBIP Manual on Substation Earthing System, *January 1992*

CHAPTER - 9

Measurement of Soil Resistivity and Interpretation of Results

Synopsis : Soil resistivity is a major input for design of an earthing system. An important aspect of its measurement is the accuracy of the earth tester. A common test procedure for measuring soil resistivity is given in IS:3043-1987. However, its application becomes difficult at the site of many substations and generating stations. Proper interpretation of measured values of soil resistivity is required for determination of soil resistivity model for the design of an earthing system. Measurement of resistivity of gravel/crushed rock, used as surface material in switchyards, is important in view of possible wide variation in resistivity of samples from different places.

9.1 INTRODUCTION

9.1.1 General

An important parameter that affects establishing of an earthing system is soil resistivity. Measurement of soil resistivity will yield valuable information that will be very useful for planning and design of an earthing system. Soil resistivity in an area is not constant but varies with weather conditions as well with type and nature of soil. It can also vary with depth below earth surface. Given a choice, the site of a station may be chosen in area of low soil resistivity. Since an earthing system shall perform for many years under varying weather conditions, soil resistivity measurement may preferably be made during the year when soil is dry and temperature is low.

9.2 MEASUREMENT OF SOIL RESISTIVITY

9.2.1 Wenner Method

Methods of measuring earth resistivity are variations of a popular four-electrode method devised by Dr. F. Wenner [1]. Measurements are made with a four terminal earth tester. The earth tester is a source of current and measures voltage too. Basically, in a four-electrode method, illustrated in Fig. 9.1, four small electrodes or spikes or probes are driven into the ground. Current I is passed between the two outer probes from terminals 'C1' and 'C2' of the tester. The inner two probes are connected to the potential terminals 'P1' and 'P2' of the earth tester for measuring the voltage appearing at the earth surface between the inner two probes. The earth tester gives directly the ratio of potential difference between electrodes P1 and P2 and current I as resistance R . In the Wenner method, the probes are in a straight line and equidistant; as in Fig. 9.1, spacing between probes = $s = a$. When measuring resistivity at a location, probe spacing is increased in steps. The straight line on which the probes are located is called a radial.

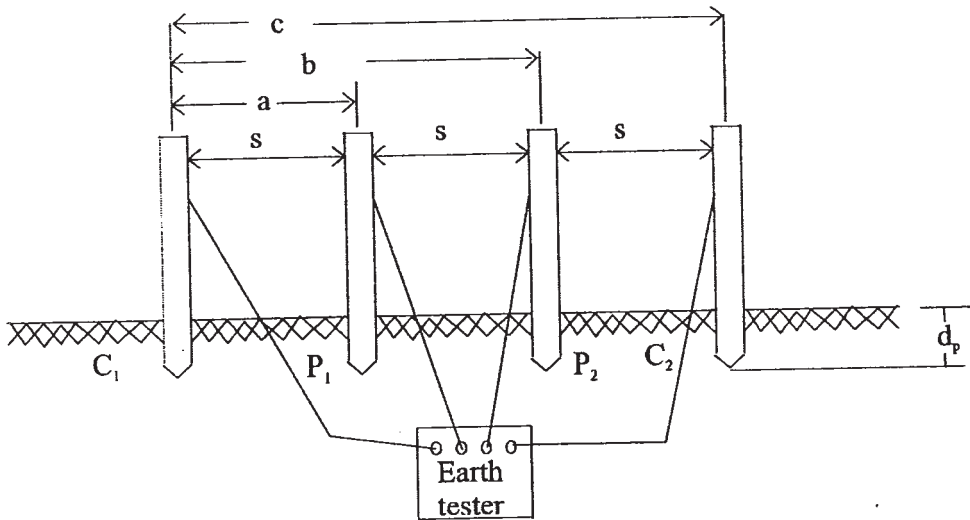


Fig. 9.1 : Connections of four electrode method of measuring soil resistivity

9.2.2 Procedure for Measuring Soil Resistivity

The following points may be kept in mind when making measurements:

- (i) For measuring soil resistivity at the site of a substation, measurements of resistivity are made along a number of radials at different locations in the station area such that the whole area in which the earth electrodes are to be laid is covered. There ought to be a minimum of two radials at one location,
- (ii) At large stations, roughly one location for each area of 100 m × 100 m should be chosen. Total number of locations may be chosen such that there are at least two locations in each of the areas for higher voltage bays, for lower voltage bays and for generator-transformer bays (if any). Besides locations may be chosen in the area for interconnecting transformers and in the area for control room.
- (iii) Spacing between the probes, which are hammered into the soil, should be varied from the smallest value of about 0.5 m or 1.0 m to large values depending on the extent of the earth electrode and the conditions on the ground. Typically, if the extent of the station is 100 m - 150 m in the direction of the radial, the readings of resistivity may be taken for probe spacing of 1 m, 2 m, 5 m, 10 m, 20 m, and 35 m - 50 m. Depending on the available space, the largest spacing may even be increased to 100 m or more.
- (iv) If resistivity variation is large, at least five progressively increasing probe spacings are necessary to get good estimate of deeper layer parameters.
- (v) A few spoonfuls of water may be poured around the probe, which has been hammered into ground, to get good conductive connection between probe and soil around it.
- (vi) The soil along the radials should be free from buried conductive pipes etc. and it should not be recently filled and therefore not yet compacted.

- (vii) If grid conductors have already been installed, resistivity measurements except those for small probe spacing in center of large meshes shall be affected. If soil is homogeneous, measurements may be made outside the grid.
- (viii) For convenience, one probe may be kept near the location of earth tester and the other three moved as required.
- (ix) In case the earth at the site of measurement is rocky, it may not be possible to hammer the probes into ground; if attempt is made to hammer a probe into ground, cracks may develop around the point of entry of the probe into ground. This results in high contact resistance in the current or the potential loop and shall result in erroneous results. A good digital earth tester shall have an indicator for high current loop resistance or high contact resistance at potential probes. If cracks develop around the probe, the hole should be filled with wet mud and the probe should be stood in the mud. In case probes cannot be hammered into ground, holes should be drilled into ground and these may be filled with mud or cement or Bentonite slurry into which the probes are erected.
- (x) Test wires should be insulated and should not have bare joints in between. These should be firmly connected to terminals of earth resistance meter bare and test electrodes.
- (xi) As far as possible wires from potential terminals may not run parallel to and near those from current terminals.
- (xii) Test electrodes should be clean and free from rust.
- (xiii) Hammering of electrodes should not result in loosening of connection between electrode and its test lead and thereby an increase of contact resistance between test lead and electrode.
- (xiv) Accuracy of earth resistance meter should be checked before and after the measurements as per procedure given under Section 9.5.
- (xv) Local soil condition such as surface rock, loose soil, water logging, roadside etc. at measurement points should be recorded in measurement book for ease of interpretation of measured data.
- (xvi) Resistivity value should be calculated after each observation by using (9.1). If there is an abrupt variation in measured resistivity, measurement for that probe spacing should be repeated after altering the probe location.

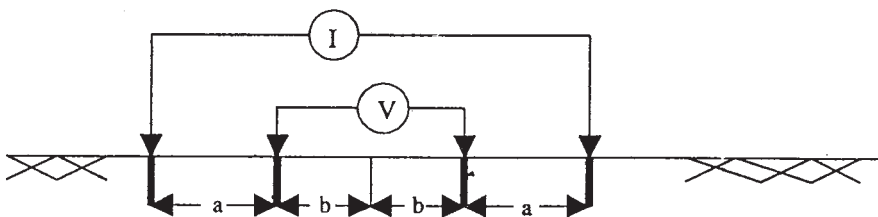


Fig. 9.2 : Schematic diagram of Schlumberger Palmer four-electrode method

When distance between the current electrodes is very large, the Wenner arrangement may result in very low resistance that is not measurable by the meter. To increase the measured value of resistance, in an alternate method, called Schlumberger-Palmer [1] method, the potential electrodes are placed closer to the outer current electrodes. In terms of distances indicated in Fig. 9.1, $(b-a) > a = (c-b)$. In one arrangement distance between potential electrodes is double the distance between adjacent potential and current electrodes this is illustrated in Fig. 9.2 in which $b = a$.

For small industrial and commercial, medium voltage installations, the soil resistivity value may be obtained from the utility operating in the area. For this purpose it is necessary that the utility carries out resistivity surveys of the area under its jurisdiction and provides the required information to its customers.

9.2.2.1 Shortcoming of IS:3043 Procedure

IS:3043 [2] recommends measurement of resistivity at one location along at least eight radials. In any modern substation the earth conductors are not concentrated at one location but spread out throughout the area of the station, therefore, it is not enough to measure resistivity at one location. The procedure specifies that the probe spacing be increased, along each radial, till measured value of soil resistivity becomes constant with change in probe spacing. It is necessary to clarify that Earth Tester measures usually the resistance R , and resistivity is calculated by equation (9.1) or (9.2). As such, only at sites usually the soil is homogeneous, no change in calculated values of resistivity with increasing depths is observed.

9.3 INTERPRETATION OF MEASURED DATA

9.3.1 Application of Four-Electrode Method

The Wenner method is an accurate method and because of its simplicity and ease of calculations is the most common method. When the depth of insertion of each probe below earth surface, d_p , is less than $1/20^{\text{th}}$ of the distance between the adjacent probes, the apparent measured soil resistivity is

$$\rho_a = 2\pi s R \quad \dots(9.1)$$

where the earth tester reading is $R \Omega$. In some situations it may not be possible to install electrodes at large enough spacing $s \gg d_p$. When the depth of electrode, d_p , is greater than $1/20^{\text{th}}$ the spacing between adjacent electrodes the soil resistivity value is calculated by using the formula [3,4]

$$\rho_a = \frac{2\pi d_p R}{\{2 \ln[2 + E]/(1 + F)\} + 2F - \frac{s}{d_p}} \quad \dots(9.2)$$

$$E = \sqrt{4 + \left(\frac{s}{d_p}\right)^2} \quad \dots(9.3)$$

$$F = \sqrt{1 + \left(\frac{s}{d_p}\right)^2} \quad \dots(9.4)$$

In (9.2), (9.3) and (9.4) d_p = depth of electrode, m.

If, as illustrated in Figure 9.2, Schlumberger-Palmer arrangement of electrodes is used, the apparent resistivity is obtained from

$$\rho_a = 2\pi Ra (a + 2b)/(2b) \quad \dots(9.5)$$

9.3.2 Interpretation of Measurements

In (9.1), (9.2) or (9.5), ρ_a , called apparent measured resistivity, represents true resistivity of the soil at the site of measurement only if the soil formation is homogeneous and isotropic (having same properties in all directions) in nature. Usually, resistivity variation is not very pronounced in lateral direction and is gradual. Resistivity is more likely to vary along depth of soil below surface. The soil may consist of two or more layers of different resistivities. In that case ρ_a is a measure of weighted average of true resistivities of different layers. The effective depth of current penetration below earth surface is dependent on distance between current electrodes. Apparent measured resistivity ρ_a , obtained by using Wenner method, is a measure of resistivity up to a depth equal to one third of the distance between current electrodes i.e., depth equal to distance 's' metres [1,5]. As magnitude of 's' is increased from a small value to larger values, the measured resistivity reflects the effect of soil at greater depth. This is the reason that a layered model can be used to reflect the variation in measured resistivity along depth below earth surface as 's' is varied.

From the soil resistivity measurements, the data becomes available in the form of a table of values of apparent measured soil resistivity and corresponding probe spacing. Soil model, which is to be used for designing the earthing system for a station, is to be obtained from the measured data. Two commonly used soil models are (i) the uniform soil model and (ii) the two-layer model. Soil models with more than two layers are possible; however, as the number of layers is increased, analysis of an earth electrode becomes very complex. Algorithms for interpretation of measured soil resistivity data to select the best-fit soil model are available.

If any observed soil resistivity for a probe spacing is found to be too high or too low compared with resistivities for the next smaller and next larger probe spacing along that radial, it may be judiciously ignored when determining the soil model.

9.3.3 Uniform Soil Model

The soil is assumed to have uniform resistivity ρ to a very large depth below earth surface. Actually the soil is rarely homogeneous in all directions; nevertheless this approximate representation is used when non-uniformity is small. An arithmetic average value, $\rho_{a(av)}$, of resistivity is determined as [6]

$$\rho_{a(av)} = \frac{\sum_{i=1}^n \rho_{a(i)}}{n} \quad \dots(9.6)$$

where $\rho_{a(1)}$, $\rho_{a(2)}$, ..., $\rho_{a(i)}$, ..., $\rho_{a(n)}$ are values of apparent measured resistivity in Ω -m obtained by Wenner method for n measurements with various values of probe spacing along different radials. If the measured soil resistivity values vary within about $\pm 30\%$ of the arithmetic average value, it would be appropriate to choose a uniform model. Another way of specifying the conditions of uniform soil model is that each of the data points satisfies the following conditions [3]:

$$\left| \rho_{a(av)} - \rho_{a(i)} \right| \leq 0.3 \rho_{a(av)} \quad \dots(9.7)$$

$$\left| \rho_{a(av)} - \rho_{a(i)} \right| \leq 3\sigma \quad \dots(9.8)$$

or

$$\sigma \leq 0.1 \rho_{a(av)} \quad \dots(9.9)$$

where σ is the standard deviation of the measured apparent resistivity values $\rho_{a(i)}$, $i = 1, 2, \dots, n$. If the variation is more than the above, and a definite trend of values is established, a layered model may be adopted. If one or two measurements in a large data set vary considerably from the average value, those values may be discarded as bad data points.

9.3.4 Two-layer Soil Model

A two-layer soil model is shown in Fig. 9.3. It consists of an upper layer of depth h (m) and resistivity ρ_1 Ω -m, overlaying a lower layer of infinite depth and resistivity ρ_2 Ω -m. Both the layers are of very large extent in the transverse direction. Though it may be possible to obtain the most accurate representation of the actual variations of soil resistivity at the site of a substation; it may not be technically feasible to model all the variations.

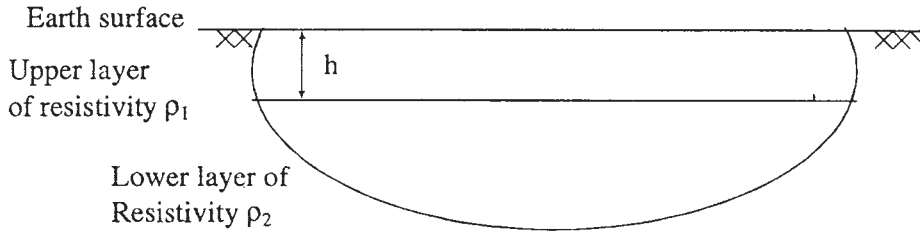


Fig. 9.3 : Two layer soil model

Use of uniform soil model for the site where the apparent soil resistivity changes significantly with the probe spacing may lead to pessimistic or optimistic designs. It is necessary that a layered model may be adopted when uniform model does not fit the measured values [3,4,6,7]. In most cases, an equivalent two-layer model is sufficient for designing a safe earth electrode.

Before generating the model the arithmetic average resistivity corresponding to each probe spacing is determined from the measurements made along different radials at the substation site. Thus a table of values of probe spacing, s_i , and average measured apparent resistivity, $\rho_{a,i}$ is made. A layered model can be obtained by using the master curves of Sunde [8] reproduced in Subsection 9.3.4.2, but it is best generated by using computer software. Amongst graphical methods, a method called Inverse Slope Method is given in the next Subsection.

9.3.4.1 Inverse Slope Method to Determine Layered Soil Model

Based on an analysis of layered formations and empirical studies, Sanker Narayan & Ramanujachary

[9] have proposed a graphical procedure for computing the true resistivity of various layers. The analysis, called Inverse Slope Method, is as follows:

- (i) Plot electrode spacing ' s_i ' versus ' s_i / ρ_{ai} ' (ratio of electrode spacing to average apparent resistivity for that spacing).
- (ii) On drawing the best fitting straight-line segments through the points, the electrode spacings at intersections of straight-line segments are read off for depths.
- (iii) The reciprocals of the corresponding slopes of the segments give the absolute resistivities of the layers directly.

The method gives approximate results. Its application is possible in the cases where maximum values of probe spacing are larger than the depth of layers. The method is illustrated in Figs. 9.4 and 9.5; the graph of Fig. 9.4 is drawn for the two-layer model with $\rho_1 = 100 \Omega\text{-m}$, $\rho_2 = 1000 \Omega\text{-m}$, and $h = 10 \text{ m}$ and that of Fig. 9.5 for the two-layer model with $\rho_1 = 100 \Omega\text{-m}$, $\rho_2 = 10 \Omega\text{-m}$, and $h = 10 \text{ m}$. The smooth curve in each figure is drawn through data points of Table 9.1.

The straight-line graph of Fig. 9.4 is obtained by joining two lines of slope $1/100$, $(1/\rho_1)$, and $1/1000$, $(1/\rho_2)$, meeting at the point corresponding to electrode spacing of 10 m . It is seen that the curved graph has initial slope of about $1/105$ between the points corresponding to $s = 1$ and $s = 4$; also between $s = 20$ and $s = 50$, the slope is about $1/1121$; the two lines shall meet at a value of s which is less than 10 m . Similarly in Fig. 9.5 the straight-line graph is obtained by joining two lines of slope $1/100$, $(1/\rho_1)$ and 1710 , $(1/\rho_2)$, meeting at the point corresponding to electrode spacing of 10 m ; the curved graph of Fig. 9.5 has an initial slope of $1/96$ between points corresponding to $s = 1$ and $s = 4$, between $s = 20$ and $s = 50$ the slope is about 7.8 ; the two lines shall meet at a value of s that is greater than 10 m . Thus the two-layer model obtained from the inverse slope method is only approximate.

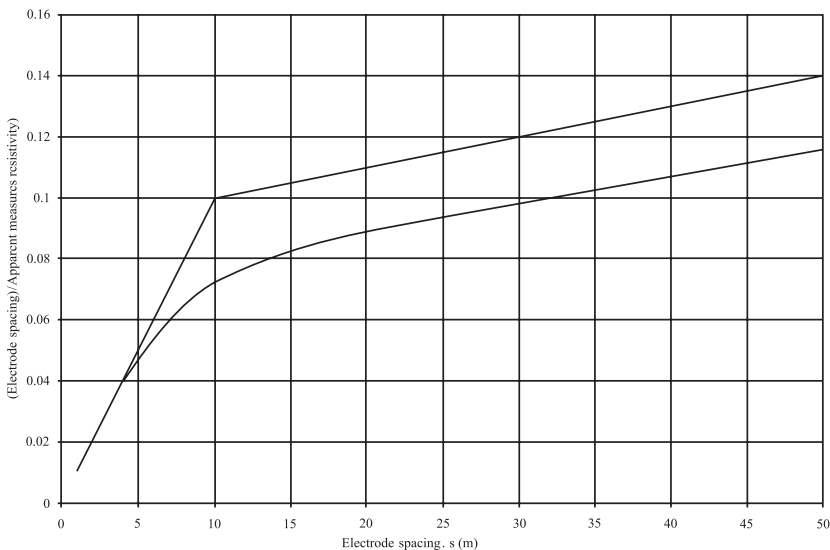


Fig. 9.4 : Illustration of inverse slope method to determine two-layer soil model

Table 9.1 : Data for graph of Figs. 9.4 and 9.5 to apply inverse slope method

Sl. No.	Electrode spacing 's _i ' (m)	$\rho_1 = 100 \text{ } \Omega\text{-m}, \rho_2 = 1000 \text{ } \Omega\text{-m},$ and $h = 10 \text{ m}$		$\rho_1 = 100 \text{ } \Omega\text{-m}, \rho_2 = 10 \text{ } \Omega\text{-m},$ and $h = 10 \text{ m}$	
		Apparent resistivity generated from two-layer model, $\rho_{a,i} \text{ (}\Omega\text{-m)}$	$s_i/\rho_{a,i}$	Apparent resistivity generated from two-layer model, $\rho_{a,i} \text{ (}\Omega\text{-m)}$	$s_i/\rho_{a,i}$
(1)	(2)	(3)	(4)	(5)	(6)
1	1	100.07	0.00993	99.9443	0.010006
2	2	100.54	0.01989	99.5675	0.020087
3	4	103.96	0.03848	96.9046	0.041278
4	5	107.24	0.04662	94.4067	0.052962
5	6	111.62	0.05375	91.161	0.065818
6	8	123.33	0.06487	82.9211	0.096477
7	10	138.03	0.07245	73.3903	0.136258
8	15	181.04	0.08285	50.4316	0.297433
9	20	225.29	0.088794	33.8671	0.590544
10	25	267.10	0.093598	23.7152	1.054176
11	30	305.75	0.09812	17.9049	1.675519
12	35	341.36	0.10253	14.664	2.386798
13	40	374.21	0.10689	12.8603	3.110347
14	50	432.75	0.11554	11.2549	4.442509

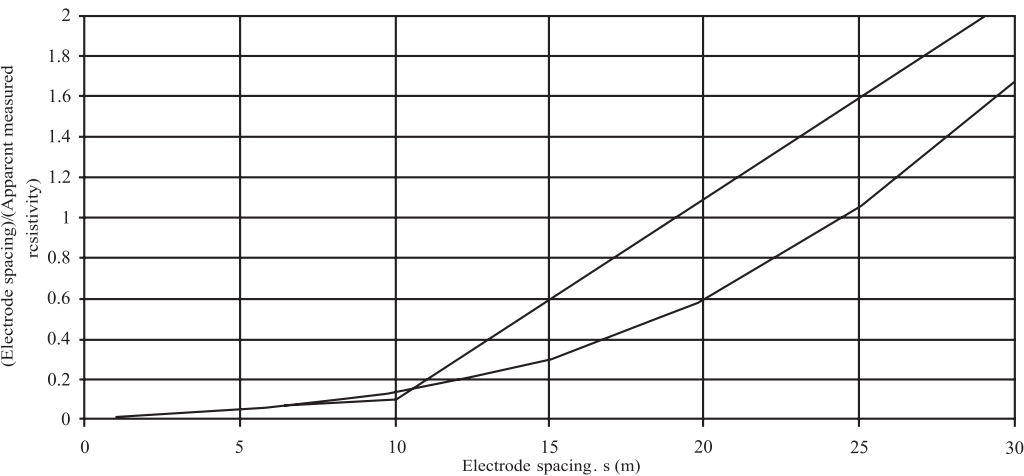


Fig. 9.5 : Illustration of inverse slope method to determine two-layer soil model

Since it is a graphical method, the model obtained by this method is dependent on the person analyzing the data. Therefore the method is not recommended for determining a soil model for non-homogeneous soil; it can be used to obtain initial input data for the computer software to determine two-layer soil model. Since use of computer software is essential to design an earthing system in non-homogeneous soil, computer software should be used for determining the two-layer soil resistivity soil model too.

9.3.4.2 Two-layer Soil Model by Sunde's Graphical Method [8]

In this method the graph shown in Fig. 9.6 is used to approximate a two-layer soil model from measured resistivity data. The graph, which is based on the Wenner four-pin test data, is reproduced from Fig. 2.6 of Sunde. The steps for determining ρ_1/ρ_2 and h by using the graph of Fig. 9.6 are as follows:

- (i) Draw ρ_a versus s curve on a logarithmic graph using the same length of the cycle of the logarithmic scale for ρ_a and s as for ρ_a/ρ_1 and s/h respectively in Fig. 9.6
- (ii) Value of ρ_1 is obtained by matching ρ_a versus s graph with one of the curves of Fig. 9.6. Since this figure is drawn for discrete values of ρ_2/ρ_1 some interpolation is usually required. The value ρ_a on the resistivity curve, that corresponds to $\rho_a/\rho_1 = 1$ line in Fig. 9.6 is the value of ρ_1 .
- (iii) Value of h is equal to that value of s on ρ_a versus s curve that corresponds to $s/h = 1$ in Fig. 9.6.
- (iv) The value ρ_2/ρ_1 can be read off from the curve of Fig. 9.6 with which the actual resistivity curve is matched or may have to be obtained by interpolation between two curves.

For the purpose of matching, the actual curve may be moved vertically or laterally but the two axes should remain parallel. Value of ρ_1 can be determined sometimes either from horizontal portion of the resistivity curve for small values of s or by extrapolation of the curve to $s = 0$ axis. The range of values of s in actual resistivity curve must be more than one decade for ease of matching.

9.3.4.3 Comparison of Results Obtained for Two-layer Model by Inverse Slope Method

The two-layer soil models obtained by the Inverse Slope method for the data given in columns (3) and (5) of Table 9.1 are $\rho_1 = 105 \Omega\text{-m}$, $\rho_2 = 11121.7 \Omega\text{-m}$, and $h = 8.2 \text{ m}$, and $\rho_1 = 96 \Omega\text{-m}$, $\rho_2 = 7.8 \Omega\text{-m}$, and $h = 16.76 \text{ m}$, respectively. If a uniform soil model is attempted, the average of the apparent resistivity values in the columns (3) and (5) of Table 9.1 are $\rho_{av} = 208 \Omega\text{-m}$, and are $\rho_{av} = 57.36 \Omega\text{-m}$, respectively. These soil models and the true soil model given in sub-section 9.3.4.1 are used to compute values of earth resistance R_G and step and mesh voltages E_s and E_m for a $50 \text{ m} \times 50 \text{ m}$ grid. This grid has 16 equal sized meshes and its depth of burial is 0.5 m . The conductor radius is 0.01 m and grid current is 1000 A . The values obtained for various soil models are given in Table 9.2 for comparison.

Table 9.2 : Comparison of earth resistance, and step and touch voltage

Parameter	Case of $\rho_1 < \rho_2$				Case of $\rho_1 > \rho_2$			
	True soil model	Inverse slope model	Uniform Soil model		True soil model	Inverse slope model	Uniform soil model	
			$\rho = 208 \Omega\text{m}$	$\rho = 100 \Omega\text{m}$			$\rho = 57.36 \Omega\text{m}$	$\rho = 100 \Omega\text{m}$
Earth resistance (Ω)	2.95	3.48	2.07	0.995	0.505	0.572	0.571	0.995
Step voltage (v)	178.7	200.9	274.6	132.0	107.0	112.9	75.7	132.0
Mesh voltage (v)	271.0	283.8	537.9	258.6	250.6	242.7	148.3	258.6

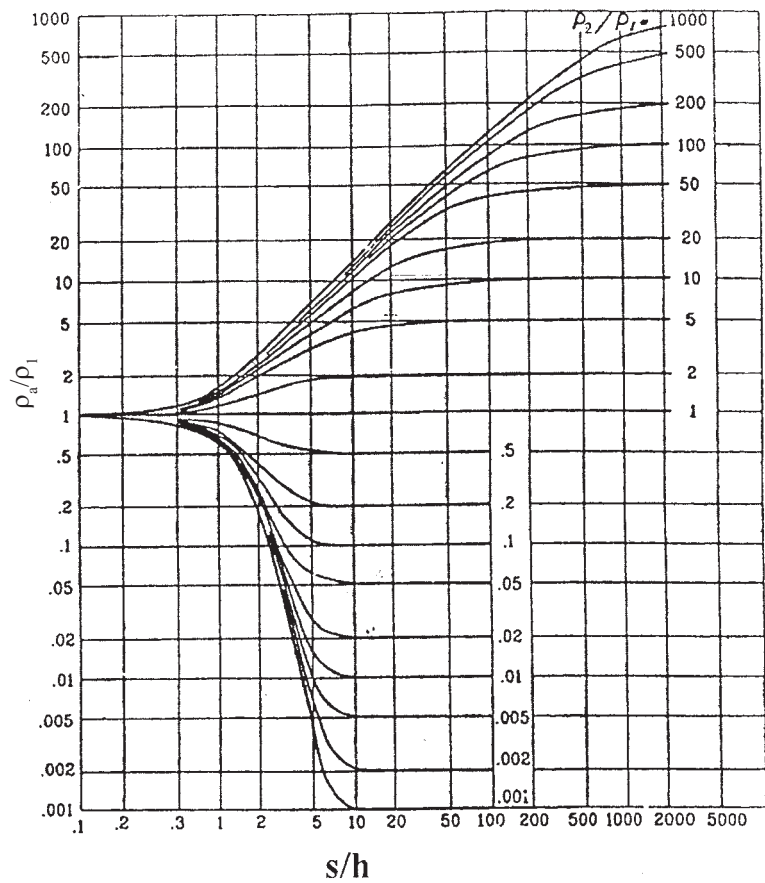


Fig. 9.5 : Apparent resistivity for two-layer soil model from Sunde

9.3.4.4 Two-layer Soil Model with Computer Software

In this method the values of parameters h , ρ_1 , and ρ_2 are obtained by an iterative search process. The values are determined as the best estimates by minimizing the objective function

$$f(\rho_1, \rho_2, h) = \sum_{i=1}^k \left[\frac{\rho_i - \rho'_i(\rho_1, \rho_2, h)}{\rho_i^2} \right]^2 \quad \dots(9.10)$$

where it is assumed that resistivity has been measured for k values of electrode spacing. The average of the apparent measured resistivity, ρ_i is determined for each of the k values of electrode spacing, ρ'_i is the expression for resistivity in terms of ρ_1 , ρ_2 , and h for the i th value of electrode spacing. This is an un-constrained least squares minimization problem. Values of ρ_1 , ρ_2 , and h are obtained iteratively starting from initial estimates of their values ρ_1° , ρ_2° , and h° . The method would usually converge to the best possible values of three parameters for the specified values of satisfaction criteria. Use of computer software to obtain two-layer soil model has been reported in [3,7,10].

9.4 MEASUREMENTS AT A SITE IN HILLY TERRAIN

9.4.1 Problems of Measurement in Hilly Terrain

At a site in hilly terrain, such as that of a hydroelectric project, usually a large flat area where soil resistivity measurements may be made is unavailable except if a flat site is available for the pothead yard. If an area, which has been made flat to prepare a site for construction works, is available it can also be used for measuring soil resistivity. If the earth structure is homogeneous, even a spacing of up to about 10 m may give the resistivity of the earth/rock, which extends to a large distance in all directions. However, if a flat area is unavailable, the measurements may be made on hillside, on the side away from the gorge or valley, along an unmetalled road or bench. The electrode spacing may be made fairly large if straight stretch of road is available. However, it is to be realized that the formula (9.1) assumed that current flows radially in all directions. This is not possible if measurements are made on a narrow road/bench flanked by a hill on one side and a valley on the other, because current cannot flow on the valley side. In such a case it is preferable if the spikes are driven into the hill surface on the side of the road. Another problem that arises is that the road is usually curved along the hillside. It is then not possible to position four equidistant spikes in a straight line. A different version of the four-electrode method, the central electrode method, described in Sub-section 9.4.2, can then be employed.

9.4.1.1 Choice of Locations and Electrodes

In case of a hydroelectric project, terrain is generally rocky. Soil resistivity is usually such that earth resistance shall be more than a desirable value. If the penstock and pressure shaft are buried in soil, these can form part of earthing system. Further earth conductors may have to be installed alongside the penstock if it is above ground, inside underground cavities and headrace tunnel/channel. Resistivity of the medium in which the earth conductors are to be installed should be determined. It is possible that the measurements may be made inside a tunnel/adit in which excavation work has already been started. Usually the floor of the excavated portion is covered with muck, but the measurements made by inserting electrodes in the walls of the excavated portion give a very good measure of the resistivity of the kind of rock strata into which the current will flow in case of earth fault. For making resistivity measurements, use can be made of any rock bolts of known length if these have been installed for strengthening the walls. Otherwise, 25 mm diameter holes may be drilled in the walls to a depth of 1 m and after putting mud paste into

these holes 20 mm diameter and 1 m long MS rods may be hammered in. These electrodes can be installed at suitable locations. Four such electrodes are used at a time for making resistivity measurements. The resistivity is determined with a computer program or with the formula, which takes into account depth of buried portion of electrodes [3].

At any site where electrodes cannot be hammered into rock, pneumatic rock drill is needed to make small holes for inserting them into ground. The electrodes are installed after drilling holes on one day and measurements are made the next day.

9.4.2 Central Electrode Method

An alternate method of measuring soil resistivity, which is another form of the four-probe method, is the central electrode method. In this method the two current electrodes are buried a large distance apart. The two potential electrodes are placed at distances 'a' m and 'b' m from one of the current electrodes as shown in Fig. 9.1. The distance 'c' between current electrodes should be about 10 times the distance 'b' or more. The expression for determining soil resistivity is obtained in Annexure A and is given by [5]

$$\rho = 2\pi \frac{ab}{(b-a)} R \quad \dots(9.11)$$

where R in ohm is the quotient V/I as given by the four-electrode earth tester. In this method only the current electrode and the two potential electrodes buried near it are to be in a straight line; the far current electrode is buried at a radial distance 'c' from the first current electrode and need not be in a straight line with the other three electrodes. The soil resistivity is obtained to a depth of approximately (a+b)/2 m, from the surface where the first three electrodes are buried.

9.5 ACCURACY OF EARTH TESTERS

9.5.1 Requirements

Power frequency as well as harmonic leakage currents normally flow in the earth due to several reasons such as neutral connections of the power system, intentional use of earth as a conductor, unbalanced operation of power system and capacitive coupling between earth and different components of power system. Such currents will produce extraneous voltages between the probes connected to P_1 and P_2 . It is important that earth testers are able to distinguish between the extraneous voltage thus appearing between P_1 and P_2 and that due to the current injected into the earth by the earth tester. If the meter used for measuring soil resistivity is not sufficiently immune to such effects, it shall not give consistent values of resistivity. Now-a-days, good, easily portable, battery operated digital earth resistivity testers with inbuilt capability to filter out noise signals and indicate presence of abnormally high resistance in either current or potential loop are available. Besides four electrodes and stranded copper core PVC insulated connecting wires, hammer etc. are needed for making measurements. The meter should be dependable such that resistivity values obtained are consistent and repeatable.

9.5.2 Testing of Earth Tester

If an accurate earth tester is tested with the test circuit shown in Fig. 9.7, it gives correct value of the unknown resistance [11]. In this method of testing an earth tester, a known standard resistance R is

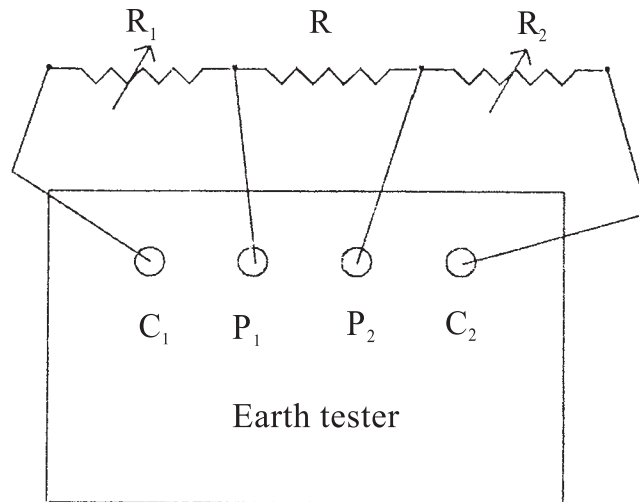


Fig. 9.7 : Circuit for testing earth tester in the laboratory

connected between terminals P_1 and P_2 . Resistances, R_1 and R_2 , of different values are connected between P_1 and C_1 and between P_2 and C_2 terminals of earth tester, respectively. The ratio R_1/R_2 is varied between 0.2 and 5. The reading of the meter should not change when ratio R_1/R_2 is changed. Test may be repeated for several different values of R . It has been observed that in the procedure commonly adopted for testing earth testers, terminal P_1 is shorted to C_1 and terminal P_2 to C_2 . A meter calibrated with this method gives correct reading only when resistances R_1 and R_2 both are made zero. This is not consistent with actual conditions obtained in the field. Even if the meter is calibrated with resistance $R_1 = R_2$ it may not give correct reading under all conditions of measurements at site. As a result many of the earth testers widely in use give incorrect values of resistivity.

9.6 MEASUREMENT OF RESISTIVITY OF GRAVEL

9.6.1 General

Resistivity of gravel can vary from $1000 \Omega\text{-m}$ to $10000 \Omega\text{-m}$ depending on the type of parent rock. Gravel or crushed rock is often used as surface material to cover the natural soil in substations for various reasons one of which is to increase the permissible magnitude of step voltage and touch voltage [Equations (9.5) and (9.6) in Chapter 3]. These values will be high for dry gravel and will be reduced for moist gravel. For estimating the permissible magnitude of step voltage and touch voltage, it is advisable to determine resistivity of the type of gravel or crushed rock to be used. The resistivity should be determined under conditions of wetness of gravel as is usually obtained at site.

Resistivity of gravel is the lowest when wet; water on the surface of rock and in between the pieces of rock forms the main conduction path for electric current. Conduction through the rock pieces will depend on the porosity and chemical composition of rock and will be usually much reduced.

Size of the rock pieces is important as larger aggregate will have fewer contact points and a higher wet resistivity than smaller aggregate of the same material.

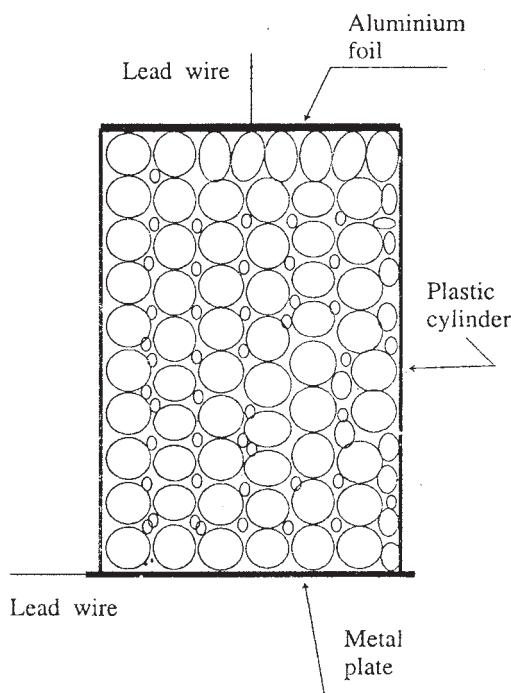


Fig. 9.8 : Set-up for measurement of resistivity of gravel for use as surface layer

9.6.2 Method of Measurement

The set-up for measuring resistivity of gravel/crushed rock is shown in Fig. 9.8 [12, 13]. A plastic or glass cylinder of diameter 'd' meter and height 'l' meter is used as container for test sample. It is placed on a flat perforated metal plate forming its base. The plate could be MS galvanized flat or some other metal. An insulated wire lead is attached to the plate for passing current through the test sample. The diameter of cylinder and height are of the order of 0.15 m to 0.30 m. The container is filled with the test sample up to its level brim. The top of the sample is covered with several layers of aluminium foil or steel wool, forming a pad with which an even connection with test sample can be ensured. A weight of 25 kg is to be placed on top of the aluminium/steel wool pad. Test sample is then removed from the container and immersed in tap water for 10 minutes after which the water is drained off and gravel sample is lightly sponged dry. It would be preferable if resistivity of water is about 100 ohm-m. The sample is then filled back in the container. The aluminium foil/steel wool and weight are then placed back on top.

In an alternate procedure, first the container is filled with sample and aluminium foil/steel wool and weight are put in place. Then after removing the weight and aluminium foil/steel wool pad from the top the container with test sample is placed in a shallow tub and water is poured on the sample from

top. The water will seep through sample and collect in the tub; this water is poured back in from the top. This is continued for 10 minutes. Then the container is removed from the tub and water drained off completely. The aluminium foil/steel wool and weight are then placed back on top.

Insulated wire lead is connected to the aluminium foil/steel wool pad also for completing the electrical circuit. Resistivity is obtained by measuring resistance of the column of test sample. For this purpose, electric current is passed through the sample with a variac and 230 V ac supply. Resistance is obtained from observation of current passing through the sample and voltage between metal electrodes at the top and bottom of the container. If resistance of the sample is R ohm, the resistivity ρ is obtained from the relation

$$\rho = \frac{\pi d^2 R}{(41)} \quad \dots(9.12)$$

It is recommended that enough gravel/crushed rock should be obtained from source so as to be able to perform the test on three samples of the same batch. Average of the three measurements should be taken as resistivity of the sample. If necessary, the test can be performed by using water of different conductivities, to determine the effect of different types of impurities in water. For this same sample can be used but starting first with water of the least conductivity.

9.7 SUMMARY

The chapter deals with the following topics:

- (i) Common methods of measurement of soil resistivity are given.
- (ii) Interpretation of measured data for determining either single layer or two-layer soil model is described.
- (iii) Procedure for ascertaining accuracy of earth tester is given.
- (iv) A procedure for determining resistivity of gravel aggregate under field conditions is described.
- (v) A case study of evaluation of soil resistivity and effect of soil model on earthing system parameters is given in the Section 11.6.

REFERENCES

- [1] IEEE Std 81-1983, *IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System*, and IEEE Std 81.2-1991, *IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems*.
- [2] Indian Standard Code of Practice for Earthing (*First Revision*), IS: 3043 - 1987.
- [3] Seedher Hans R. and Arora, J. K. "Evaluation of Soil Resistivity Parameters from Resistivity Measurements," Proc. All India Seminar on Electrical Grounding Systems, pp. 1-11, Bihar Section of I.E. (India), Patna, 1987.
- [4] Dawalibi F. and Blattener, C. J. "Earth Resistivity Measurement Interpretation Techniques," IEEE Trans, on Power App. and Systems, vol. PAS-103, pp. 374-382. Feb. 1984.
- [5] Tagg, G. F. *Earth Resistances*, George Newnes Ltd., London, 1964.

- [6] IEEE Guide for Safety in AC Substation Grounding, *ANSI/IEEE Std. 80-2000*.
- [7] Seedher H. R. and Arora, J. K. "Estimation of Two Layer Soil Parameters Using Wenner Resistivity Expressions," *IEEE Trans. On Power Delivery*, vol. 7, pp. 1213-1215, July 1992.
- [8] Sunde, E. D. *Earth Conduction Effects in Transmission Systems*, New York, *McMillan*, 1968.
- [9] Sanker Narayan, P.V. and Ramanujachary, K.R., "An Inverse Slope Method of Determining Absolute Resistivity," *Short note, Geophysics*, XXXII (6), pp. 1036 - 1040, 1967.
- [10] Meliopoulos A. P. and Papalexopoulos, A. D. "Interpretation of Soil Resistivity Measurements: Experience with the Model SOMIP," *IEEE Trans, on Power Delivery*, pp. 142 -151, Oct. 1986.
- [11] Seedher H. R. and Arora, J. K., "Review of Current Earthing Practices and Recommendations," *Jour, of the Institution of Engineers (India)*, vol. 82, pp. 213-219, December 2001.
- [12] Abledu K. O. and Donald M. Laird, "Measurement of Substation Rock Resistivity," *IEEE Trans. on Power Delivery*, vol. 7, pp. 295 - 300, January 1992.
- [13] Report on Measurement of Soil Resistivity and its Interpretation for the Site of 400 kV Substation of Power Grid Corporation of India Ltd. at Nalagarh, *Department of Electrical Engineering, Punjab Engineering College, Chandigarh*.

ANNEXURE A

9.A.1 Expression for Resistivity in Central Electrode Method

In all four-electrode methods of measuring soil resistivity, size of the current electrodes is much smaller in comparison with the inter-electrode distance. As a result, the current distribution in the earth at a distance from a current electrode may be considered to be radial. Figure 9.1 shows four electrodes of four-electrode method. During resistivity measurement the current discharged into earth from electrode C_1 is I and that from the electrode C_2 is $-I$. As a result the voltages at electrodes P_1 and P_2 and the difference between the two voltages are given by

$$\begin{aligned} V_3 &= \frac{I\rho}{2\pi} \left(\frac{1}{a} - \frac{1}{c-a} \right) \\ V_4 &= \frac{I\rho}{2\pi} \left(\frac{1}{b} - \frac{1}{c-b} \right) \\ V_{3-4} &= \frac{I\rho}{2\pi} \left[\left(\frac{1}{a} - \frac{1}{b} \right) - \left(\frac{1}{c-a} - \frac{1}{c-b} \right) \right] \end{aligned} \quad \dots(9A.1)$$

In these equations V_3 is the voltage at potential electrode P_1 , V_4 is the voltage at potential electrode P_2 and V_{3-4} is the difference of voltage between electrodes P_1 and P_2 . The earth tester measures voltage V_{3-4} and divides it by I to give the resistance R . Thus we get

$$R = \frac{\rho}{2\pi} \left[\left(\frac{1}{a} - \frac{1}{b} \right) - \left(\frac{1}{c-a} - \frac{1}{c-b} \right) \right] \quad \dots(9A.2)$$

If $a < b < 0.1 c$, $\left[\frac{1}{c-a} - \frac{1}{c-b} \right]$ can be neglected. Thus the apparent measured resistivity of soil is given by $\rho = 2\pi R \frac{ab}{(b-a)}$. This expression can thus be used to calculate measured value of soil resistivity by using the measured value of resistance R and the values of distance 'a' and distance 'b'.

CHAPTER - 10

Field Measurement of Erected Earthing System

Synopsis : *Measurement of surface potentials and earth resistance of an installed earth electrode / earthing system is important for testing integrity of its design and construction. The techniques and limitations of commonly used tests / measurement should be properly understood for proper evaluation of performance of earthing systems. User institution can choose the practice most suitable to it depending on the system conditions, availability of equipment and its current practices.*

10.1 INTRODUCTION

10.1.1 Measurement of Performance Criteria of an Earthing System

Performance of an earthing system can be evaluated by measurement of earth resistance of the earthing system and the maximum touch and step voltages that are created inside and around the earthing system during fault conditions in the electric system. Results of measurements of an earth electrode / earthing system can be used not only for confirming the adequacy of its design and construction but also for determination of additions / modifications to be carried out as and when the electric system is modified in future (the terms earth electrode and earthing system have both been used as sometimes measurements are made without isolating an earth electrode from the earthing system).

Practical determination of earth resistance of an earth electrode/earthing system and the maximum touch and step voltages requires measurement of potential differences that are created on earth surface during the flow of current between the earth electrode / earthing system and soil. At a station, the measurements are made initially when the station is not energized to determine the earth resistance and step and touch voltages for comparison with the design values. During the life of the station, measurements are made at the energized station, from time to time, to monitor the condition of the earthing system.

10.1.1.1 Problems of Staged Earth Fault Testing

It can be theorized that magnitude of touch voltage and step voltage and earth resistance may be determined by a staged earth fault [1,2]. However, it is a difficult proposition because of the following reasons:

- (i) It shall be difficult for system administrators to agree to a staged fault, as it shall disrupt supply of power.
- (ii) The current during staged fault is of transient nature and therefore elaborate recording techniques will be required for simultaneous measurements of (a) potential difference between earth electrode / earthing system and earth surface at a number of locations between earth electrode / earthing system and remote earth due to the reason that location of the saddle point of fall-of-potential graph, which will decide the value of earth resistance, is not known in advance and is to be determined as a result of the test, and (b) touch and step voltages at a large number of locations inside and around earthing system due to the

reason that exact locations where the maximum touch and step voltages will occur are not known in advance and are to be determined by the test.

- (iii) Planning and implementation of requirements to ensure safety of personnel and equipment during the test may present difficulties.

10.1.2 Measurements under Simulated Earth Fault Condition

A convenient method of measuring earth surface voltages at the site of an earthing system is by simulating an earth fault by the current injection method. In this method, a test current is impressed between the earth electrode / earthing system and an auxiliary (current collecting) electrode. The resulting potential differences between the earth electrode / earthing system and points on earth surface are measured for determination of performance of earth electrode / earthing system.

The earth resistance of earth electrode / earthing system is measured by fall of potential method. However, measurement of earth resistance of large earthing systems is subject to limitations due to several considerations including the requirement of installation of a low resistance auxiliary electrode at sufficiently large distance from the earthing system.

Similarly, the touch and step potentials that will occur inside and around earthing system during faults in electric system are estimated by proportionally extrapolating the results obtained after impressing a test current between earth electrode / earthing system and an auxiliary electrode. Estimation of touch and step potentials by this technique is also subject to several limitations including the requirement of installation of a low resistance auxiliary electrode at sufficiently large distance from the earthing system.

The earth testers comprising a built in source of power, meter for measurement of resistance and device for filtering of interfering currents / voltages that may affect accuracy of measurements are specially made for measurement of earth resistances. Therefore, these testers are commonly used for measurements for determination of performance of earth electrodes.

For those measurements, which require the application of much higher test current than that can be supplied by commonly available 4-terminal earth testers, an external source of power is required to impress test current between earth electrode / earthing system and auxiliary electrode.

10.2 BASIC TECHNIQUES AND TEST CIRCUITS

10.2.1 Current Injection Method (Fig. 10.1)

A convenient method of measuring earth surface voltages at the site of an earthing system is by simulating an earth fault by the current injection method. Current is injected between the earth electrode / earthing system G and an auxiliary / remote electrode A that is installed at a remote location with respect to G. The power supply circuit includes :

- (i) Voltmeter for measurement of potential difference,
- (ii) Shunt / Ammeter for measurement of impressed current,
- (iii) Fuses / protective devices for over current / voltage protection in test circuits, and
- (iv) Filtering device to remove voltages other than that of test frequency.

When the test system is switched on for measurements, the test voltage is impressed between earth electrode G and auxiliary test electrode A, a test current (I) flows between electrode G and A.

through the soil. Test voltage magnitude equals the product of test current and impedance of the current loop. Earth surface voltage at location of measurement P with respect to the earth electrode G is measured by the voltmeter connected across earth electrode G and potential probe at P.

The potential differences (V_{x_n}) between earth electrode G and earth surface at locations x_n ($n=1,2,3, \dots, N$) of probe P are measured by the voltmeter and magnitude of impressed current (I) is measured by shunt / ammeter. The resistance R_x for the location x of probe P is determined as $R_x = V_x / I$

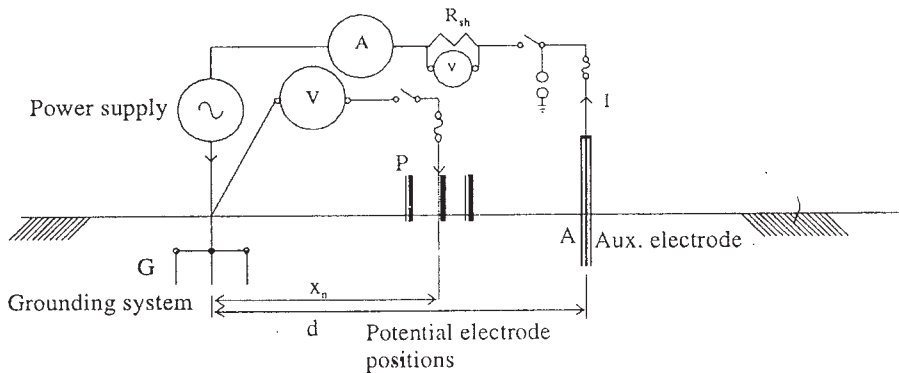


Fig. 10.1 : Current Injection method (Using external source of power)

10.2.2 Power Supply Systems for Current Injection

10.2.2.1 AC Power Supply

(a) AC induced interferences at power supply frequency

In any energized substation or power station some power frequency current is always present in earth due to unbalance of phase to earth capacitance and leakage between phases and earth, and phases and shield wire. Part of unbalance line current can also flow in the earth. Besides these, currents induced in shield wires of loaded lines, residual current due to difference in magnetization currents of individual phases of a transformer, third and other harmonic currents arising from power-line corona, induced currents and high frequency currents due to communication circuits, harmonic currents due to non-linear loads also flow in the earth. The ac stray and leakage currents can affect the measured values substantially. Currents in live circuits can also induce voltages in test circuit leads during the measurements. The effect shall appear as noise voltage between potential terminals.

(b) Injection of power frequency current

If the injected test current is of power frequency, it has to be sufficiently large so that the effect of interfering potential may be negligible. In the report of Task Force 36.04.01 [3] it is stated that the injected current be preferably more than 50 A, and earth potential rise be limited to 100 V from safety considerations. IEEE Std 81.2-1991 also suggests current magnitude to be 10 to 100 A. The lower magnitude of current is to be used at an unenergized station. The magnitude requirement of power frequency supply current can make the test voltage itself a safety hazard; if the impedance of the test loop is more than 2Ω , the applied

voltage would have to be more than 100 V. Installation of auxiliary electrode of sufficiently low resistance to keep the applied voltage below the specified safe limit of 100 V may not be possible in high resistivity soils.

(c) AC power supply at other than power frequency

Test current of a frequency different from the power frequency can be used for eliminating interference due to power frequency currents.

The frequency of ac test current has to be close to frequency of ac power system so that the magnitude of reactance offered to the flow of test current in the electric system shall be close to actual value. The measured signal has to be conditioned with a filter to recover the signal of only test frequency. In such a method, test currents of 0.1 - 10 A may be used [2,4]. Thus the equipment needed is a generator rated at 100 - 200 V, 0.1 - 10 A. The system frequency being 50 Hz, a generator generating at 40 - 60 Hz can be used. It is expected that the background noise at the chosen frequency will not be significant or that its magnitude will be much less than that of measured signal. The highest frequency of this range, 60 Hz, may be chosen as a higher frequency often, reduces size of equipment. Together with this appropriate filter preferably very narrow bandwidth type, resistance shunt for measuring current, and multi-range digital voltmeter of very high input impedance etc. are required. Alternatives for filter are spectrum analyzer or oscilloscope with built in FFT analyzer.

If a frequency, higher than 60 Hz is used, size of the equipment can be reduced even further. Even though the higher frequency affects the magnitude of all mutual reactances and hence it affects the magnitude of measured impedance to some extent, commercial earth testers often operate at higher frequencies.

(d) Injection current sources

A battery powered earth tester has an in built current source. Alternately, alternating current for current injection method can be supplied by one of the following:

- (i) System frequency current from power system station service supply with auxiliary transformer (1 - 100A) if the current reversal method (described in Section 4), is used;
- (ii) Portable engine driven generator with governor to control the speed (frequency) such that the output is of 60 Hz, rated at 0 - 200 V, and 0.1 - 10 A.
- (iii) A solid-state inverter powered either by batteries or from 50 Hz power supply or oscillator with amplifier of suitable rating.

It may be mentioned that two prototype equipments that incorporate solid-state sine-wave generators, one rated at 0 - 100 V, 60 Hz, 1 A, and the other at 0 -100V, 60 Hz, 0 -10 A, together with the signal conditioning modules have been fabricated and tested in the field [5,6]. A battery powered solid state generator rated at 0 - 100 V, 0 - 1 A, and 120 Hz was also fabricated. However, commercially designed and fabricated equipment is needed for field measurements. Besides the generator, narrow bandwidth filter and voltmeter or frequency selective voltmeter or spectrum analyzer and other associated equipments are also needed.

10.2.2.2 DC Power Supply

Direct current is not used for measuring earth resistance of an earth electrode because of the following reasons:

- (i) The electrode that discharges direct current (dc) into earth, anode, is subject to corrosion due to electrolysis.
- (ii) Conduction of dc through soil causes gases produced during electrolysis to cover the cathode. The effect called polarization introduces errors in measurement.
- (iii) Earth impedance effect cannot be measured in case of large electrodes by using dc for tests/measurements.

DC testing is useful when electrolytic potentials are not present, e.g. in measuring earth electrode/earthing system continuity. The effects due to electrolytic flow of current in soil are greatly reduced when alternating current is used.

10.2.3 4 - Terminal Earth Tester (Fig. 10.2)

10.2.3.1 A 4 - Terminal Earth Tester (Earth Resistance Meter) can be used for measurements to determine performance of earth electrodes. As shown in Fig. 10.2, the connections with 4 terminals of the tester are as follows:

- Terminals C_1 and P_1 are connected to earth electrode G
- Terminal C_2 is connected to auxiliary test electrode A
- The terminal P_2 is connected to potential probe P

By using separate leads for connection between earth electrode G, and C_1 and P_1 terminals of the tester, voltage drop in the resistance of the current lead is not included in the measured potential values. If a 3-terminal earth tester is used, terminals C_1 and P_1 are shorted together in the meter. The test circuit includes fuses / protective devices for over current / voltage protection as shown in Fig. 10.2.

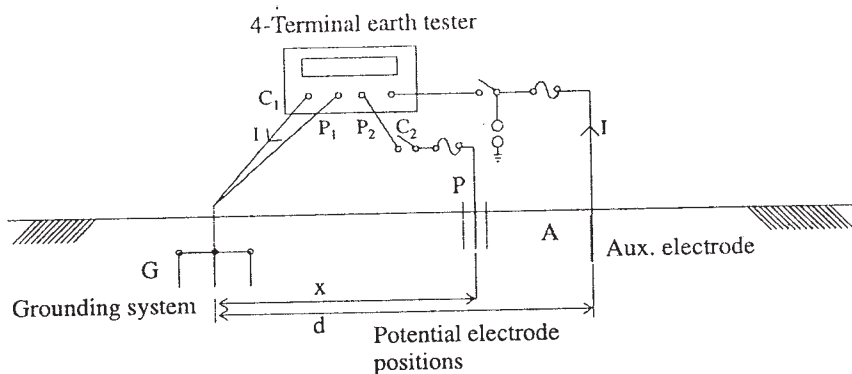


Fig. 10.2 : Four Terminal Earth Tester (Earth Resistance Meter)

10.2.3.2 When switched on for measurements, the test voltage is impressed across terminals C_1 and C_2 and the test current (I) flows between earth electrode G and auxiliary test electrode A through soil. The potential difference (V_{x_n}) between earth electrode G and earth surface at locations X_n ($n=1,2,3, \dots, N$) of probe P are measured by the tester. Resistance $R_x = V_x / I$ for a location x is displayed on the meter of the tester. The instrument reading is quotient of voltage between the electrode G and potential probe at P and the current flowing in current loop.

A typical commercial tester would have maximum output voltage in the range 50 - 200 V at a frequency which can be anywhere between 90 Hz to 130 Hz, and maximum output current of about 10 - 50 mA. Earth testers capable of higher output current may be available. The test frequency is higher than the range 60 Hz mentioned in sub-section 10.2.2.1 and shall affect the result when measuring earth impedance of a large earthing system. The meter should have built-in noise eliminator. The measured signal is filtered to recover the signal of test frequency. It should also have appropriate circuitry to prevent damage to the meter from measured signal. A digital earth tester has digital display.

For measuring low-impedance, of the order of 0.5Ω or less, of an earthing system that covers a large site, direct reading earth testers may not be very suitable. Injected current has to be higher than the test current provided by built-in power source of common earth testers, usually less than 50 mA. If the test current is less than 1 A, increasingly sophisticated filtering is needed [2]. In such cases, one of the current injection methods using a current source capable of supplying 100 mA or more, mentioned in 10.2.2.1(d), is to be employed.

10.2.4 Auxiliary test Electrode and Test Lead Cables

The earthing system / electrode under test, the auxiliary test electrode, the test leads between them together with the earth form the loop through which the test current flows. A number of factors affect choice of auxiliary test electrode and test leads.

10.2.4.1 Purpose of Auxiliary Test Electrode

The condition of flow of earth fault current from the earth electrode / earthing system at the location of fault to the remote earth electrode / earthing system of equipment that supplies the fault current, is simulated by impressing the test current between earth electrode / earthing system (to be tested) and the auxiliary electrode.

10.2.4.1.1 Type

The auxiliary test electrode is required only for conducting the test / measurement and is not required as a permanent installation. Any of the following can serve as auxiliary electrode:

- (i) A number of MS rods / pipes / angles, each at least 1 m long, can be driven in earth and interconnected by cables to serve as auxiliary earth electrode system as per requirements of the measurements.
- (ii) A metallic water pipeline, if available at desired location and fulfilling requirements of measurements, can be used as an auxiliary earth electrode
- (iii) It may be possible to use the earth electrode at the far end of a low voltage line as an auxiliary test electrode if it meets the requirements of the measurements. The line has to be shut down for the duration of the test. The phase conductors of the line can be shorted together at the two ends to reduce the impedance and used as conductors between test and auxiliary electrode. Even an unused transmission line, if available, can be used.

10.2.4.1.2 Requirements

The accuracy of earth resistance/impedance measurement depends on locating the auxiliary electrode remote from the earthing system under test. The distance of auxiliary test electrode from the test electrode should preferably be about 10 times the extent of test electrode. The minimum

distance to potential/test electrode, that will have an approximate accuracy of 95%, may be estimated by 6.5 times the extent of the earthing system [2]. The extent of an earthing system for an isolated grid is its maximum diagonal distance.

In the fall of potential method, the potential of earthing system is measured with reference to the test/potential electrode placed at increasing distances from the earthing system until the difference between two or three successive voltage readings is negligible, assuming the test current is constant. If the difference does not become negligible, the distance of auxiliary electrode from the earth electrode / earthing system under test is increased and measurements are repeated till results of the test confirm the remoteness of auxiliary test electrode with respect to earth electrode / earthing system under test.

The current carrying capacity of the auxiliary electrode should be such that it does not cause excessive temperature rise of earth leading to moisture evaporation and increased electrode resistance.

Continuous current rating of a 1.0 m rod of 15.9 mm diameter, and a 3.0 m long rod of 19.1 mm diameter is given by $14.4/\sqrt{\rho}$ A and $36.8/\sqrt{\rho}$ A, respectively, where ρ is soil resistivity in $\Omega\text{-m}$ [2]. Alternately, current rating is $12.0\sqrt{R}$ A and $11.8\sqrt{R}$ A where R is earth resistance of rod. The earth resistance of an auxiliary electrode consisting of four 3-metre rods driven into ground at the corners of a 10 m square is $9\ \Omega$ when soil resistivity is $100\ \Omega\text{-m}$. Resistance of auxiliary electrode should be sufficiently low to keep the magnitude of applied test voltage within safe limits.

10.2.4.2 Test Lead Cables

Test leads cables shall be insulated copper conductor cables, rated to carry test current and withstand test voltages without damage of conductors and their insulation. The connection point on the earth electrode / earthing system should be chosen in the main body and not on some peripheral conductor. The terminal of test current supply equipment / earth tester should be connected to a riser of earth electrode / earthing system. The surface of the riser of earth electrode / earthing system and auxiliary earth electrode should be properly cleaned with emery paper before making the cable connections. Connections between test cables and riser of earth electrode / earthing system and auxiliary earth electrode should be of bolted type and should be firmly made to minimize contact resistances.

The connection between the earth electrode / system under test and the auxiliary electrode can be made with an out of service transmission line or distribution line. Sometimes an abandoned pair of telephone line can be used.

The leads from the tester to the probe P_1 and P_2 , or P as the case may be should not be run parallel to the leads carrying current. To minimize measurement errors due to ac mutual coupling, the test potential conductor should be routed at 90° to the test current conductor and as far as possible from each other. This is done so as to minimize the inductive coupling between the current loop and the potential loop. In large earthing systems, in order to avoid mutual coupling with extended-earth conductors and in-service transmission lines, it may be necessary to route at angles other than 90° .

10.3 TEST-CURRENT-REVERSAL METHOD [2]

10.3.1 This is a power frequency current injection method. The measurement of earth impedance with test currents derived from a substation low-voltage source (Subsection 10.2.2.1) in the

presence of an energized power system will add significant levels of fundamental and harmonic frequencies to the measured quantities. If the system conditions do not change during the test period, the interference will not change in magnitude, time, or phase relationships. Then, constant levels of background fundamental and harmonic frequencies present in the measured voltage and current can be cancelled out with the test-current-reversal method.

10.3.2 As shown in Fig. 10.3, test equipment used for this method consists of the substation service source (SOURCE), an auxiliary adjustable matching transformer (T_x), an optional series capacitor (C_x) used to reduce current-circuit reactance, an out-of-service transmission line with either one phase used separately or three phases connected in parallel for impedance reduction, and an arrester or protective gap (gp) adjusted for 2-3 kV. The remote / auxiliary current electrode can be either the line termination grid or a low-resistance tower footing. Impedance magnitude and its resistance-reactance components can be calculated from measurements made with a wattmeter (W), ammeter (A), and voltmeter (V) of the electrodynamic type. A current transformer (CT) is used to reduce the test-current magnitude to within meter current coil ratings. These meters will give the true rms readings of waveforms containing harmonics. If the current in the wattmeter current coil has no distortion, only the fundamental frequency component of the potential waveform will produce active Power readings. Even if the current waveform has a slight (<5%) distortion, the active power produced by the harmonic content of the voltage will not significantly affect final results. Electrodynamic instruments of the moving-coil type are quite rugged; however, the input resistance of their potential circuits is low. If the resistance of the potential probe and the test lead, R_{probe} , is not at least 1/100 of the parallel voltmeter and wattmeter potential circuits, R_{meters} , then the voltmeter and wattmeter readings will be low and will require a correction multiplier: $(R_{meters} + R_{probe})/R_{meters}$. Meter potential circuit loading of the remote potential electrode circuit can be eliminated with a high input-impedance, fixed-ratio amplifier (not shown in Fig. 10.3) interposed between the meters and the test probe circuit. The optimum meter accuracy will be obtained if the amplified potentials are at least 50% of coil ratings. Then the actual active power and voltage will be found by dividing the measured values by the amplification factor.

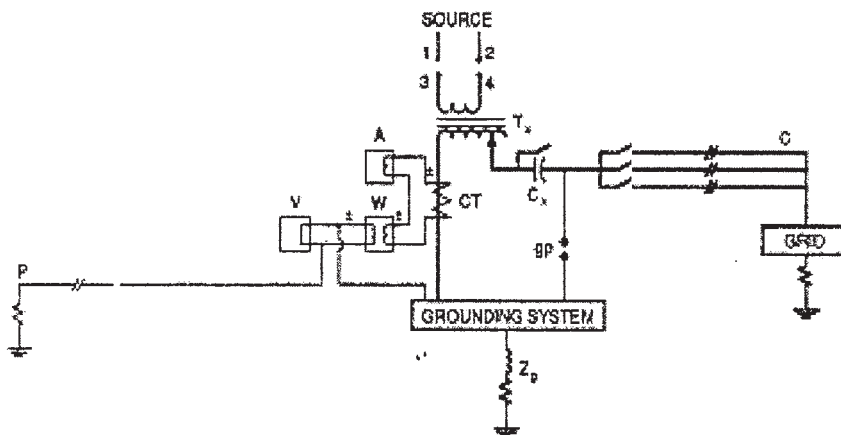


Fig. 10.3 : Power frequency current injection with current reversal for impedance measurement

10.3.3 In the test-current-reversal method, referring to Fig. 10.3, V_{sa} , I_{sa} , and P_{sa} are measured for connection 1 to 3 and 2 to 4; V_{sb} , I_{sb} , and P_{sb} are measured for connections 1 to 4 and 2 to 3; and with 3 connected to 4 (1 and 2 open), V_i , I_i , and P_i are measured. If an initial current, I_i , exists in the injection line when the source of I_s is short-circuited (3 to 4), there will be a corresponding grid-rise voltage, V_i . To minimize errors caused by I_i and V_i these quantities should be measured before and after the current injection test-current-reversal method. Then, I_s , V_s , and P_s can be calculated with the following equations:

$$I_s = \sqrt{\frac{I_{sa}^2 + I_{sb}^2}{2} - I_i^2} \quad \dots(10.1)$$

$$V_s = \sqrt{\frac{V_{sa}^2 + V_{sb}^2}{2} - V_i^2} \quad \dots(10.2)$$

$$P_s = \frac{P_{sa} + P_{sb}}{2} - P_i \quad \dots(10.3)$$

and the impedance magnitude, resistance, reactance, and phase angle from:

$$Z_G = \frac{V_s}{I_s} \quad \dots(10.4)$$

$$R_G = \frac{P_s}{I_s^2} \quad \dots(10.5)$$

$$X_G = \sqrt{Z_G^2 - R_G^2} \quad \dots(10.6)$$

$$\cos \phi_s = \frac{P_s}{V_s I_s} \quad \dots(10.7)$$

where ϕ_s is the angle between V_s and I_s

10.3.4 The advantages of using the power-system low-voltage source are:

- (i) Impedance is measured at power system frequency,
- (ii) Equipment used for measurement is generally available in the utility, and
- (iii) Sufficient test current is used to overcome background voltages and any circuit nonlinearities such as connection resistances.

10.4 MEASUREMENT OF EARTH RESISTANCE

10.4.1 The test current is supplied by current injection technique or from an earth tester. Fall-of-Potential-Method is usually used for determination of resistance of earth electrode / earthing system.

10.4.2 As shown in Figs. 10.1 and 10.2, the test current I (A) is passed between earth electrode / earthing system G and auxiliary electrode A through the surrounding soil. V_{x_n} (V), the voltage drops from earth electrode / earthing system G to points P at distances x_n , ($n = 1, 2, 3, \dots, N$), from G , are measured with a potential probe. Voltage drops V_{x_n} are measured at regular intervals in a straight line between G and A .

10.4.3 During measurements, the distance of potential probe from the edge of electrode G in the direction of auxiliary test electrode is varied in steps.

10.4.4 If the current in the loop is I (A), the quotient $R_{x_n} = V_{x_n} / I$ is an apparent resistance. R_{x_n} , ($n = 1, 2, 3, \dots, N$), are measured directly by an earth tester. A particular R_{x_n} for some value of n can be the true earth resistance R_G of the earthing system under certain conditions described under sub-section 10.4.7.

The voltage drops V_{x_n} or the resistances R_{x_n} , measured for N values of distance x_n as the case may be, are plotted as function of distance x_n between the earthing system and potential probe to obtain the fall-of-potential graph. Fall-of-potential plots are illustrated in Fig. 10.4.

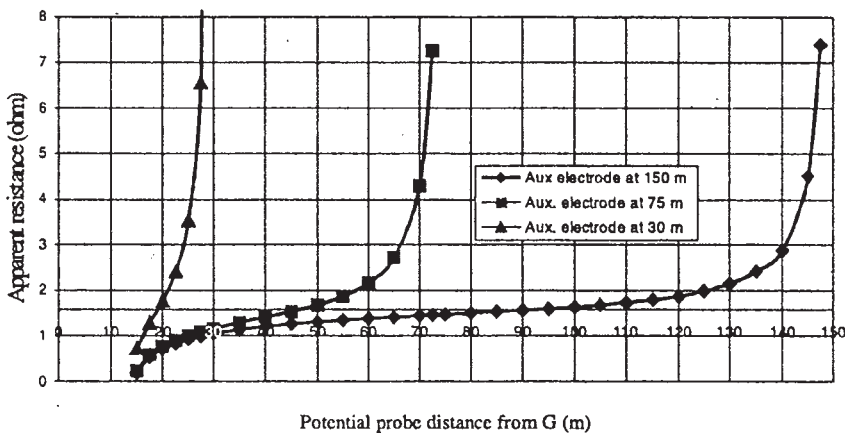


Fig. 10.4 : Effect of electrode spacing on fall-of-potential curves

10.4.5 Figure 10.4 shows the plot of R_{x_n} (Apparent resistance) versus x_n when the grid size is $30 \text{ m} \times 30 \text{ m}$ and grid conductor radius is 0.01 m . The grid consists of 16 meshes, buried at a depth of 0.6 m in soil of resistivity $100 \Omega \text{m}$. The auxiliary electrode is 1 m long vertical rod of 0.01 m radius and buried with its top 0.2 m below earth surface. Plots for three different values of distance between center of grid and the auxiliary test electrode, namely 30 m , 75 m and 150 m are shown. The effect of variation of distance between G and A on the shape of the fall of potential graph is apparent.

10.4.6 If the distance 'd' between the earthing system and auxiliary test electrode is much larger than the dimensions of the earthing system, of the order of 10 times the equivalent diameter of earthing system, a portion of fall-of-potential curve may appear to be parallel to x-axis. The point at which slope of the graph changes from +ve to -ve is the saddle point. It is accepted that the saddle point or the flat part of the curve gives true resistance R_G of the earthing system.

If the resistance R_{x_n} versus distance x_n plot does not have a part parallel to x-axis, the auxiliary test electrode is installed at larger distance/s and measurements are repeated, as described in sub-section 10.4.2, to obtain resistance R_{x_n} versus distance x_n plot in accordance with requirement for determination of correct value of R_g . In case distance cannot be increased to such an extent that a horizontal portion is obtained, it may be difficult to determine R_g accurately.

10.4.7 Analytical Considerations for 61.8 % Distance Rule

In Figure 10.2 if V_G^G and V_G^P are the voltage of earthing system G and the voltage at point P, respectively, due to current I flowing from the earthing system into the soil, and V_A^G and V_A^P are the voltage at G and the voltage at point P, respectively, due to the current -I flowing from the auxiliary electrode into the soil, then the resistance R_x is given by

$$R_x = (V_G^G - V_A^G - V_G^P + V_A^P) / I \quad \dots(10.8)$$

As shown in Fig. 10.2, point P is between G and A. V_A^G is a function of distance d; V_G^P is a function of distance x, and V_A^P is a function of distance (d-x). Also $V_G^G / I = R_g$. Therefore $R_x = R_g$ if

$$V_A^P - V_G^P - V_A^G = 0 \quad \dots(10.9)$$

In case the earthing system and auxiliary electrode are assumed to be hemispheres buried in homogeneous soil and radii of the two electrodes are $\ll$ distances d and x both, equation (9) reduces to

$$\frac{\rho I}{2\pi} \left(\frac{1}{d-x} - \frac{1}{x} - \frac{1}{d} \right) = 0 \quad \dots(10.10)$$

Distances are measured from center of respective hemisphere. Solution of (10.10) gives the solution $x = 0.618 d$. This is the well-known 61.8% rule [7,8]. Thus when the above conditions, namely (i) earth electrode and auxiliary electrode are assumed to be hemispheres buried in homogeneous soil, and (ii) radii of the two electrodes are $\ll$ distances d and x both, hold, only one measurement is enough to determine the earth resistance.

If point P is beyond the electrode A, the distance (d-x) is replaced by (d+x) in (10.10). This results in the solution $x = 1.618 d$. If d is large, 1.618 d may be too large to be practical. In case (i) the soil is non-homogeneous, or (ii) electrodes cannot be assumed to be hemispheres of radii $\ll$ d or x, or (iii) the electrical center point of electrode G cannot be identified, the point at which (9) holds good cannot be ascertained empirically.

10.4.8 In case fall of potential method is not used but the 61.8% rule is to be applied, meter reading of resistance $R_x = R_g$ is obtained When point P is located at $x = 61.8\%$ of the distance between electrical center of G and A. Three distances of auxiliary electrode are chosen, namely, 'd' m, (d-10) m, and (d+10) m. The desired distance 'x' of potential probe in each case is obtained by calculation and the resistance R_x is measured. The three measured values of earth resistance should be close to each other. If the electrode is odd shaped and the 61.8% rule cannot be applied, the required distance 'x' of P from edge of the earth electrode can be determined by computer simulation.

10.4.9 If the auxiliary electrode is installed close to the earth electrode / earthing system under test, the reading of earth tester may bear no relation to the earth resistance being measured. The measured value shall be much smaller than actual earth resistance.

10.4.10 For grid earth electrodes of large size and in case the earth electrode is in an inhabited area, sometimes it may be difficult to locate the auxiliary electrode at a distance equal to 10 times the extent of electrode under test. In that case initially the auxiliary electrode may be placed at a distance of about 3.5 times the extent of test electrode. Three measurements are made with potential electrode at 61.8% of the distance between test electrode and auxiliary electrode and at a point 1 m towards earth electrode and at another point 1 m away towards auxiliary electrode. If the three measurements are close together, the first value is taken as earth resistance, otherwise the distance between test electrode and auxiliary electrode needs to be increased [9].

10.4.11 When the measured earth resistance is very low, the potential probe P is moved along a traverse that is at 90° to the line from G to A [10]. However the graph of apparent resistance versus distance of potential probe from G is only asymptotic to the actual value of earth resistance.

10.4.12 If measurement is made by current injection method at an unenergized station, the current magnitude is between 0.1 – 10 A. At an energized station, if injected current is of frequency other than power frequency, magnitude of current can be 0.1 — 10 A; if power frequency current is injected, magnitude of current shall be 50 - 100 A.

10.5 MEASUREMENT OF STEP AND TOUCH VOLTAGES

10.5.1 Step Voltage

Step voltage is measured between two points on earth surface that are one meter apart. The maximum value of step voltage is expected at a corner of the grid earth electrode, between a point on earth surface above a corner of the perimeter conductor of grid earth electrode and a point that is one meter away from grid earth electrode along the diagonal of corner mesh. If the perimeter conductor is under the fence, one point is just outside the fence and the second is outside the fence 1 m away.

Current is injected into earth between the earth electrode, G, and the test electrode, A, either with a power supply or from terminals C_1 and C_2 of an earth tester; the set-up is the similar to the one described for measuring earth resistance. Step voltage can be measured in two ways. In one method two probes are hammered into ground one meter apart. Instead of installing two probes in the earth, it is possible to use two metallic circular discs, each of 0.16 m diameter placed at two points, one meter apart, between which the step voltage is to be measured. To ensure good contact with the earth underneath, a sponge can be on one face of the disc. The sponge is moistened prior to making measurement. If making measurement on gravel, water may be pored over gravel to mimic post rain condition. A person wearing rubber-insulating shoes stands with one foot on each disc or a weight of about 20 kg may be placed on each disc.

In case a power supply is used the step voltage V_s corresponding to the injected current I is measured with a digital voltmeter after conditioning the measured signal with a filter. The step voltage is $E_s = V_s \times I_g / I$, where I_g is the grid current.

In case of earth tester the probes or the metallic circular plates are connected to terminals P_1 and P_2 with the probe nearer to C_1 being connected to P_1 . The meter will indicate a resistance value R_p . For

the measured resistance (R_p) by the earth tester, the step potential is determined as $E_s = R_p \times I_G$, where I_G is the grid current.

10.5.2 Touch Voltage

Touch voltage is measured between the electrode G and a point on earth surface. The points on earth surface where the maximum value of touch voltage is expected are marked on earth surface beforehand. One such location, at which touch voltage is measured, is the point one meter outside the corner of the fence if the fence is earthed to grid earth electrode. Other locations are along the diagonal of meshes near the corners of grid earth electrode.

Measurement procedure is similar to that in case of step voltage except that either one probe or two circular metallic discs, placed near each other and connected in parallel, are used. In case of discs, a weight of about 20 kg is to be placed on each disc. Alternately a person wearing insulated shoes can stand on the discs. Voltage is measured between the probe or disc and conductor of the earthed fence or a riser connected to a metallic earthed structure near the point, where the touch voltage is desired, as the case may be.

In case a power supply is used the touch voltage V_t corresponding to the injected current I is measured with a digital voltmeter after conditioning the measured signal with a filter. The mesh voltage is $E_t = V_t \times I_G / I$, where I_G is the grid current.

In case of earth tester, the meter will indicate a resistance value R_p . For the measured resistance (R_p) by the earth tester, the mesh voltage is determined as $E_t = R_p \times I_G$, where I_G is the grid current. E_m is the largest value of E_t inside the grid area.

10.6 MISCELLANEOUS REQUIREMENTS / CONSIDERATIONS

10.6.1 Measurements ought to be made on a newly laid earth electrode with all components of the earthing system connected [2]. Earth resistance may be determined both with the shield wires of the overhead transmission lines connected with the station grid and also the armour of cables connected to the station grid if any, and after disconnecting the shield wires and the armour. For this purpose the shield wire and the riser for it from the earth electrode may be terminated on insulators with removable links between them. Similar arrangement may be made for cables. It has also been suggested that the component of current diverted by shield wires of transmission lines may be measured by using CT's around the connection of shield wire and the earth electrode.

There should be electrical continuity between different earthed structures / enclosures and the earth electrode. The continuity should be tested by passing 10 -100 A dc current between two points that are connected to the earth electrode and resistance between them is measured by using a dc micro/mili-voltmeter or with a micro-ohmmeter. In case of an old station, low resistance connection may have been destroyed by corrosion or by system faults. In such a case voltage drop between injection point and the nearest point 2 to 10 m away should be comparable with the estimated voltage drop of the tested section obtained from the size and length of conductor material between the points of measurement [2].

10.6.2 General Precautions

A high degree of exposure to atmospheric disturbances or power system line-to- earth faults and earth potential rise (EPR) is possible during the tests/ measurements. The following precautionary measures are recommended [2]:

- (i) Do not schedule field measurements of either the power system earthing, during periods of forecast lightning activity, in areas (determined by conditions at each utility) that encompass the station being measured or of the power network connected to the station being measured.
- (ii) Do not lay out test leads or connect test leads to out-of-service transmission lines during a period when lightning is prevalent.
- (iii) When test procedures, are not in progress, externally routed test leads should be disconnected and isolated from the grid and treated as being energized.
- (iv) In the event lightning appears in the zone defined above when test procedures are underway, stop all testing, open the test connection to the out-of-service transmission line, and isolate from the grid any temporarily installed test conductors routed externally to the grid.

10.6.3 Safety Aspects of Test Preparations [2]

Field measurements of earthing system leave participating personnel vulnerable to exposure caused by (i) faults at the station where the earthing system is under test or (ii) faults in which power flows through that earthing system, transferred potentials from remote test earth electrodes, and inadvertent line energizations. While the probability of the occurrence of one of these events is low, personal safety will, nevertheless, be enhanced by :

- (i) Using high-voltage rated insulated gloves and boots, eye protection, and hard hats during setting up connections and measurements,
- (ii) Working on clean, dry crushed rock or an insulating blanket,
- (iii) Avoiding bare hand-to-hand contact between equipment and extended test leads,
- (iv) Sufficiently insulating the voltage or current probe test conductor within, the station and its close neighbourhood,
- (v) Ensuring that the cable reel is well insulated or mounted on an insulated platform,
- (vi) Connecting safety earths (sized for fault levels) to all equipment frames,
- (vii) Making connections to instrumentation only after cable-pulling personnel are in the clear (radio communication recommended),
- (viii) Before starting measurement, check the continuity of neutral of Power /Instrument Transformer or earth conductor of Lightning Arrester to earth mesh/grid on low resistance range of multimeter,
- (ix) Removing working earths on the test circuit last,
- (x) The neutral of Power Transformer/Voltage Transformer/CVT or earth conductor of Lightning Arrester should not be touched by bare hands, when the equipment is live,
- (xi) The personnel should not open any earth connection or handle the old corroded connections involving live equipment in service. Any earth connection required to be made during measurements should be in addition to the connection already in service,
- (xii) The personnel should be aware that during the measurement if an electrical fault is experienced by the station, the instrument and the personnel are likely to be influenced and hazardous voltages can develop at measurement points or at instrument,

- (xiii) The instrument in use should have a facility to eliminate and cancel the interference of all frequencies other than the instrument frequency,
- (xiv) It is advisable to take measurements with the main equipment under shutdown in case any evident abnormality or discontinuity in earthing is observed or suspected, and
- (xv) The operating personnel should ensure that the instrument being used is compliant to safety standards suitable for electrical/electronic instruments (EEC-61010 or equivalent) and EMI/EMC immunity (IEC-61000 or equivalent) before taking up the measurements.

It is recommended that test procedures, hazardous conditions, and the responsibilities of each person be discussed and understood by everyone taking part in the test. Safety can be heightened by the use of a disconnect or switch to isolate the current source and the voltage-probe circuit when no measurement is being made. When grid rise exceeds several hundred volts, the measuring instrument should, if possible, be connected through instrument transformers or resistance voltage dividers. If a capacitor in series with the current circuit is employed, it should be located at the line entrance. A current-injection high-voltage line must be earthed at both ends when the test is under preparation. The injection end cannot be earthed during the actual measurement. However, a safety spark gap or arrestor with a spark-over voltage of 2 to 4 kV is advisable at the line entrance, in view of possible atmospheric over-voltages, fault-related earth potential rise, or inadvertent energizing of the line. Moreover, the circuit should not be touched after removal of the temporary earthing,

10.6.4 Safety Aspects of Test Measurements

After completion of the test set-up, it is essential that one person (usually the test supervisor) coordinate all switching operations, maintain control of connections made to all externally routed circuits, and authorize all test energizations. No personnel shall be permitted to work on or touch the test circuit without clearance from the test coordinator. During modifications of the test circuit, it is recommended that all safety practices outlined in 10.6.3 and 10.6.4 be followed along with those additional rules instituted by each utility. From the standpoint of safety rules, a test that applies the 10 to 100 A current injection method should be considered as corresponding to a prolonged earth fault; and an earth-fault test should be considered as corresponding to a fast tripped earth fault. Thus, the test currents should be such that the rules with regard to the touch voltage, transferred potential, and induced-potential limits for earth faults are respected. It is recommended that all personnel present in the substation under study be informed of the nature of the tests, in particular of the consequences of current circulating in the earth. Measurement of an earthing system with low impedance will require higher magnitude test currents to have an adequate signal-to-noise level and improved sensitivity. When tower footings, guy anchors, or vertical earth rods are used as auxiliary / remote electrodes, the possibility that their potentials could be hazardous must be considered. Selection of higher test currents (above 40 mA) raises the questions of safety for measurement personnel, the public, and domestic animals that could come in contact with auxiliary/ remote electrode potentials. Where temporary vertical earth rods are used, every effort should be made to reduce the electrode resistance, e.g., paralleling several rods, salting, and using longer rods. Nevertheless, in high-resistivity earth, it may not be possible to reduce the current-loop resistance to less than 200 Ω . Even at 0.5 A, this would result in a 100 V probe rise. For auxiliary / remote electrode voltages above some minimal value (20–40 V), it is recommended that a safety watcher and temporary fencing be provided during test energization.

If measurements are made at an energized station, precautions for safety of personnel and equipment must be taken. If an earth fault occurs during the measurements, the grid earth electrode will be raised to the level of grid potential rise. As per design, the personnel within the station should be safe against step and touch voltages, but because the auxiliary electrode is at a distance from the station grid earth electrode, problem of transferred potential can arise. Under this condition, test current (I_T) will flow between earth electrode under test and auxiliary electrode and earth fault current (I_F) can flow between earth electrode under test and the earth electrode / earthing system supplying fault current. The total EPR of earth electrode under test will be $R_G \times (I_T + I_F)$ and measured voltages V_{x_n} will be due to current $(I_F + I_T)$. Voltage impressed by external power source is sum of total earth potential rise of auxiliary test electrode and earthing system / electrode under test.

Transferred potential presents danger to personnel making measurements outside the station area for determining earth resistance. A safety measure is to provide a switch and a fuse both in the lead to the auxiliary electrode and to the potential probe [2,11]. Both the switches should be in off position except when an observation is being taken. Also the personnel, handling the equipment during testing should use insulated shoes and gloves. Use of a safety spark gap or arrestor as shown in Figs. 10.1 and 10.2, with a spark-over voltage of 2 - 4 kV, is advisable if an overhead line is being used as current path to the auxiliary electrode. Working personnel should stay on dry crushed rock

10.7 EARTHING AUDIT

10.7.1 Introduction

A pressing issue that is engaging attention of managers of electric systems these days is assessment of quality and capability of earth electrodes. This is called performing complete earth grid audit. The tasks to be performed in a complete audit are as follows:

- (i) To check the continuity of all connections to the earth electrode
- (ii) To perform the fall of potential test on the electrode
- (iii) Where there are a number of separate earth electrodes connected together, each of them is to be tested for its individual resistance

10.7.2 Methods

To test the continuity of a composite earth electrode, a micro-ohmmeter is used to measure resistance between the points between which continuity is to be checked. Alternatively, a dc current of 10 A or more is passed between the points and the resistance between them is determined by measuring the voltage between them with a micro-voltmeter. If the length and area of cross section of conductors between the two points is known, the measured value can be compared with the expected value.

In another method, an earth tester with two clamp type current transformers is used around an earthing conductor or lead. One CT is used to inject current into the loop formed by earthing conductor or lead with the rest of earth electrode. The second CT measures the current flowing in earthing conductor or lead. The meter is said to directly measure resistance of the earth conductor to which the earthing conductor or lead is connected. The meter reading is said to be earth resistance of the particular earth conductor. This is useful in a system where there are a number of earth

electrodes in parallel. Use of such a meter is possible if the earthing conductors are laid such that use of clamp type transformers is facilitated.

As mentioned above, Instruments are required for performing audit tasks. EPRI of USA had developed a Smart Ground Meter for this purpose. It has now undertaken the work of improving the hardware and developing a Ground Grid Evaluator.

10.8 SUMMARY

- (i) Basic techniques and considerations for measuring parameters of earthing system / earth electrode are described.
- (ii) Procedures for measurement of earth resistance and step and mesh voltage are discussed. The precautions to be observed during measurements are given.

REFERENCES

- [1] Romuaid Kosztaluk, Mukhedkar Dinkar and Gerais, Yvon "Field measurement of Touch and Step Voltages," *IEEE Trans, on Power App. and Systems*, vol. PAS-103, pp. 3286-3294, November 1984.
- [2] IEEE Std.81.2-1991, IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems.
- [3] Seljeth H. and Feist, K.H. "Final Report of Task Force 36.04.01 (Station Earthing), Station Earthing Safety and Interference Aspects." No. 71, pp. 47 - 69, Electra, July 1980.
- [4] Pillai PR. and Dick, E.P. "A Review on Testing and Evaluating Substation Grounding Systems," *IEEE Trans, on Power Delivery*, vol.7, pp. 53-61, January 1992.
- [5] Arora, J.K. Completion Report on the Problem 'Ground Potentials in High Voltage Substations', CBI&P, New Delhi, 1993.
- [6] Arora, J.K. Bisht V.K. and Jain, R.K. "Surface Potential Measurement by Current Injection Method," "Proc. 55th R&D Session of CBI&P, TS-2, pp. 15-19, July 1989.
- [7] IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System, (Part I), IEEE Std., 81-1983.
- [8] Dawalibi F. and Mukhedkar, D. "Resistance Measurement of Large Grounding Systems," *IEEE Trans, on Power App. and Systems*, vol. PAS-98, pp. 2348-2354, Nov ./Dec. 1979.
- [9] Electrical Grounding Techniques, LEM Instruments Inc., USA.
- [10] IS: 3043 - 1987, India Standard Code of Practice for Earthing (First Revision).
- [11] A Simple Guide to Earth Testing, *Published by AVO International Limited, Dover, Kent CT17 9EN, 1986.*

CHAPTER - 11

Typical Examples

Synopsis : *In this chapter a number of examples illustrating different aspects of the procedure for designing earth electrode for a substation are presented. The relevant data for carrying out calculations, by using the procedures described in this manual, are also given. A number of examples that demonstrate the effect of varying the soil model, the grid conductor spacing and the location of fence are given. In all these cases results are obtained by analyzing the design data with software.*

11.1 CALCULATION OF EARTH FAULT CURRENT AND GRID CURRENT

Importance of earth fault current and grid current in design of earth electrode for a station is brought out in Section 3.7. The details of a method of calculating grid-current are presented in Chapter 4. In this Section two examples of calculation of fault current and grid current are presented.

11.1.1 Example 1: A 33 kV Generating Station System

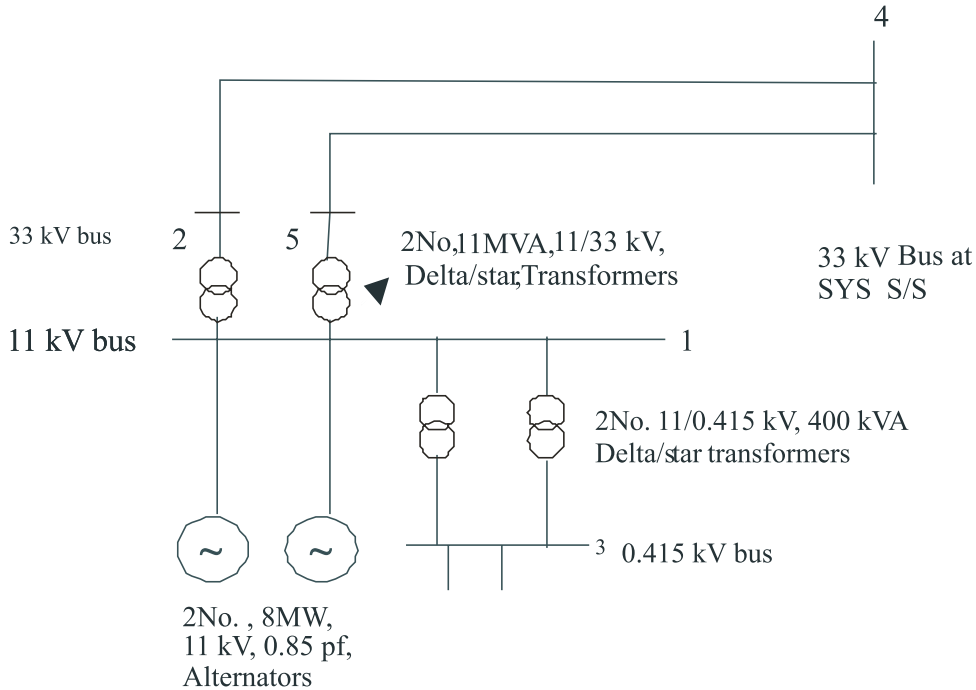
Single line diagram of a hydroelectric generating station evacuating power to 33 kV bus of electric power system is shown in Fig. 11.1. The hydroelectric plant (HEP) has two units rated at 8 MW, 11 kV and 0.85 pf. Each unit is connected to 33 kV bus through a three-phase transformers of 11 MVA, 11/33 kV, in delta/star connection. The 33 kV bus is evacuating power to electric power system through two 12 km long, single-circuit lines. Phase conductor on each transmission line is ACSR Dog. There is no earth/shield wire. The 33 kV line terminates at 132/33 kV transformer at SYS station. For estimating the fault current for fault at the HEP, it is assumed that the 33 kV bus at SYS is an infinite bus. It shall give an upper limit of the fault current.

(a) System data

The system data is as follows. Ohmic values are referred to 33 kV side.

- (1) Generator sub-transient reactance = 0.15 pu = 17.3589 Ω .
- (2) Generator negative sequence reactance = 0.17 pu = 19.67 Ω .
- (3) Generator zero sequence reactance = 0.05 pu = 5.7853 Ω .
- (4) 11 MVA Transformer +ve, -ve and zero sequence reactance each = 0.0835 pu = 8.2665 Ω .
- (5) Single circuit, 33 kV line +ve & -ve sequence impedance = 0.2745+j0.35104 Ω /km
- (6) Single circuit, 33 kV line, zero sequence impedance = 0.42254+j 1.5197 Ω /km.
- (7) 400 kVA Transformer +ve, -ve and zero, sequence reactance each = 0.05 pu

(b) Single Line to Earth Fault Study with Computer Software

**Fig. 11.1** : Single line diagram of SYS - HEP system

The study can be carried out by simulating the system network with digital computer software. The single line diagram on a simulator is reproduced in Fig. 11.2. Bus voltages and bus numbers are shown on the diagram. Bus 4, which is the SYS bus, is the infinite bus of the equivalent system. Reactances of the generator at this bus are assumed such that the short circuit currents at this bus are as follows: (i) three phase short circuit at bus 4 = 1.7492×10^7 A, (ii) single line to earth fault at bus = 2.2526×10^7 A

(i) Single line to earth fault on 33 kV bus at HEP

For fault on either 33 kV bus at HEP, the fault current is found to be $4485.1 \angle -74.48^\circ$ A. The three phase currents supplied from the SYS system, represented by an infinite generator, are $2530.37 \angle -62.09^\circ$ A, $574.5 \angle 118.92^\circ$ A, and $583.12 \angle 120.61^\circ$ A, respectively. The earth return current is three times the zero sequence current and is 1373 A. This is the magnitude of current fed from substation at SYS to a single line to earth fault at 33 kV bus at HEP. Since there is no earth/shield wire on the line, this current returns through earth and is the grid current. The current fed to the fault from generator-transformers does not return through earth; the zero-sequence component is zero, as it cannot flow through the delta-connected winding.

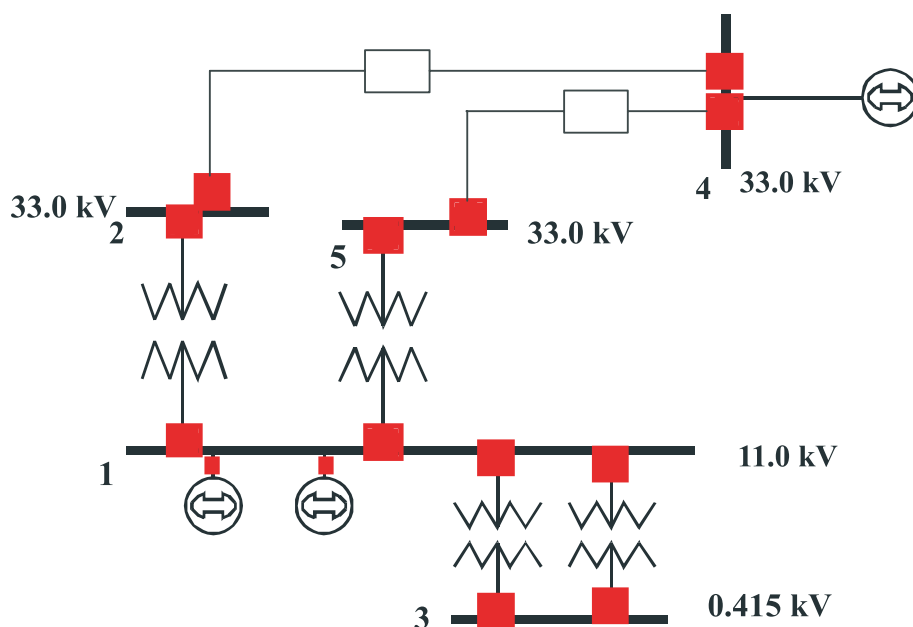


Fig. 11.2 : HEP single line diagram on digital computer simulator

(ii) Single line to earth fault on 0.415 kV bus at HEP

The fault current for a single line to earth fault at 0.415 kV bus is also calculated with the simulator, It is found to be 22892.3 A. No part of this current flows into earth.

Maximum earth fault current = 22892.3 A say 22892 A

Maximum symmetrical grid current = 1373 A say 1373 A

(c) Fault Study - Sequence Diagrams

The fault current calculations can be carried out by making sequence impedance networks and thereby the Thevenin equivalent networks for the three sequences. The three sequence networks are shown in Fig. 11.3. The equivalent networks for the three sequences for calculation of sequence components of fault current on 33 kV bus at the HEP station are shown in Fig. 11.4.

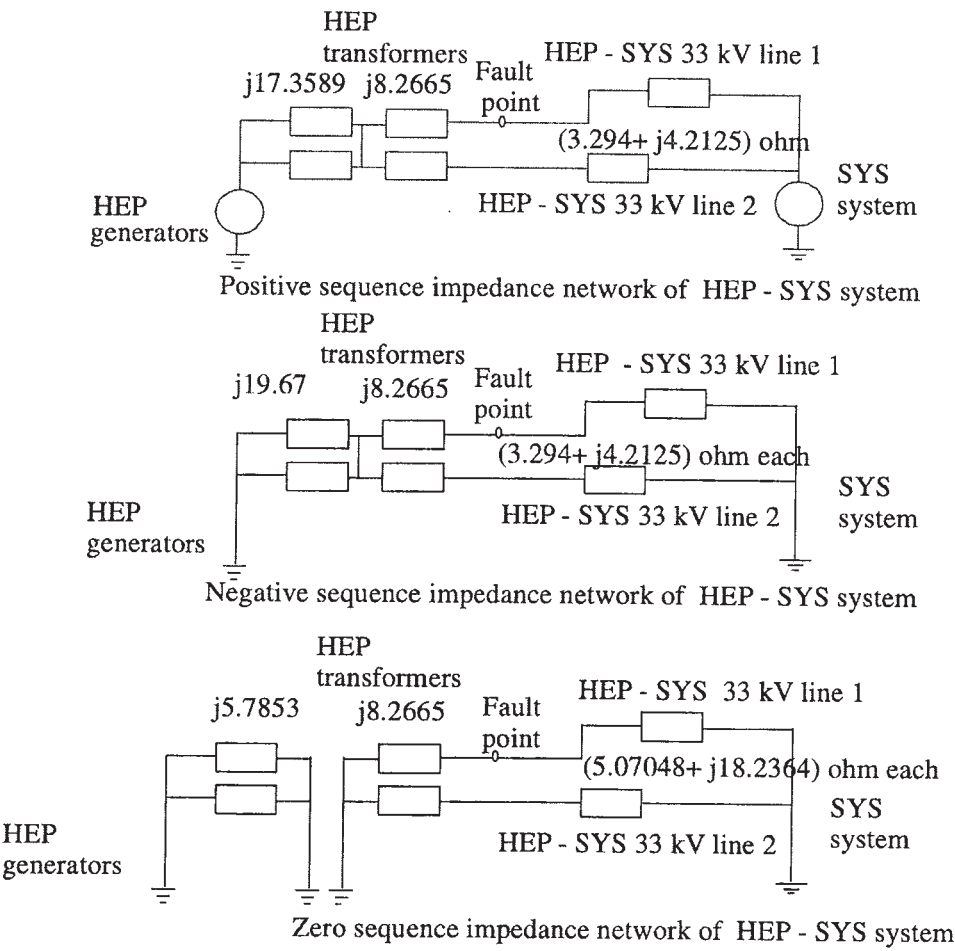
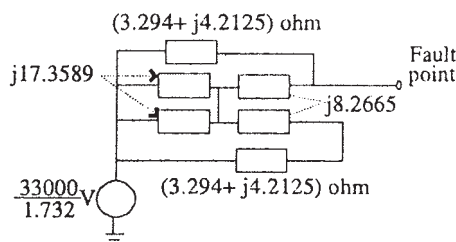
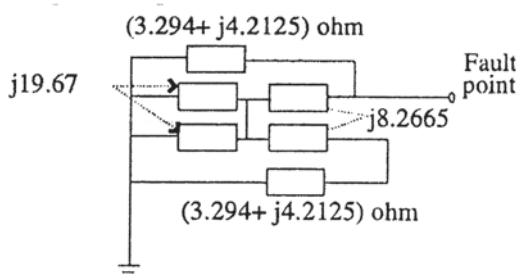


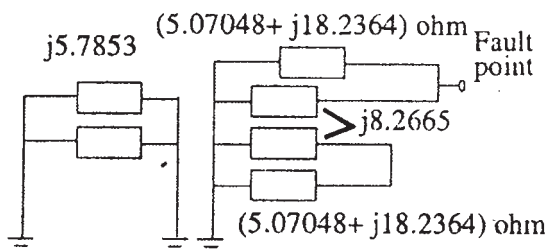
Fig. 11.3 : Positive, negative and zero sequence networks for fault at 33 kV bus of HEP station



Positive sequence impedance network of HEP - SYS system for fault current calculation



Negative sequence impedance network of HEP - SYS system for fault current calculation



Zero sequence impedance network of HEP - SYS system for calculation of fault current

Fig. 11.4 : The sequence networks for calculation of fault current at 33 kV bus of HEP station

11.1.2 Example 2: 132 kV Substation of Electric Power System

Single line diagram of a 132 kV substation is shown in Fig. 11.5. The station is connected to the rest of electric power system through two, 100 km long, 132 kV single circuit lines. Four, 10 km long each, 66 kV, single circuit lines also leave the station. Transmission line phase conductor is ACSR Panther 30/7/3 mm. The earth wire conductor is 7/3.15 mm steel. The 132 kV and 66 kV buses are connected through two 50 MVA interconnecting auto-transformers. Both transformers have grounded-wye / grounded-wye connection. Station transformer is 400 kVA, delta/star, 66/0.415 kV. For estimating the upper limit of fault current for faults at the station buses, it is assumed that the 132 kV lines as well as 66 kV lines terminate at infinite buses. Earth resistance of the station earth electrode is 0.5Ω

(a) System data

The system data is as follows:

- (1) 132 kV line +ve, & -ve sequence impedance = $(0.09803 + j0.22699)$ pu
- (2) 132 kV line zero sequence impedance = $(0.240071 + j0.835629)$ pu

- (3) 66 kV line +ve, & -ve sequence impedance = $(0.03921 + j0.08301)$ pu
- (4) 66 kV line zero sequence impedance = $(0.1001151 + j0.348026)$ pu
- (5) 50 MVA autotransformer +ve, -ve and zero sequence reactance = 0.18 pu
- (6) Base MVA = 100
- (7) 400 kVA transformer +ve, -ve and zero sequence reactance = 12.5 pu

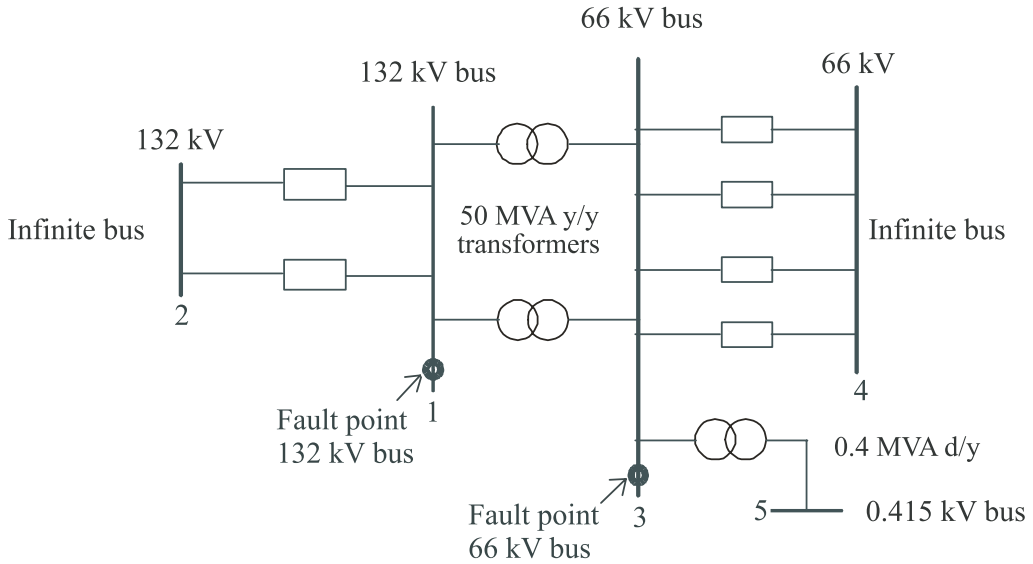


Fig. 11.5 : Single line diagram of 132 kV substation

(b) Single Line to Earth Fault Study

Single line to earth fault can be determined either with computer software or with the help of sequence impedance networks. Bus voltages and bus numbers are shown on the diagram. The bus 2 and bus 4 are assumed infinite buses. The reactances of the Thevenin equivalent generators at these two buses are assumed and the short circuit currents at these buses are: (i) three phase short circuit at bus 2 = 4.3756×10^6 A, (ii) single line to earth fault at bus 2 = 5.7077×10^6 A, (iii) three phase short circuit at bus 4 = 8.7512×10^6 A, and (iv) single line to earth fault at bus 4 = 1.293×10^7 A.

- (i) Single line to earth fault current for fault on 132 kV bus

The single line to earth fault current on 132 kV bus is $5344.7 \angle -78.02$ A. The contribution $3I_0$ from 132 kV generator is $(473 - j 1487.0)$ A and it flows on the two 132 kV lines to the faulted station bus. The current $3I_0$ from the 66 kV generator is $(1273.8 - j 7482.2)$ A and it flows towards the faulted bus over the four 66 kV lines.

- (ii) Single line to earth fault current for fault on 66 kV bus

For a single line to earth fault on the 66 kV bus at the station, the magnitude of fault current is $22152.6 \angle -89.98$ A. The currents $3I_0$ supplied by the 132 kV and 66 kV generators are $(459.1 - j 1572.5)$ A and $(6142.6 - j 17836.9)$ A respectively.

- (iii) Single line to earth fault current for fault on 0.415 kV bus

Single line to earth fault current for the fault on 0.415 kV bus is $11118.4 \angle -89.97$ A. However the zero sequence current out of each generator is zero for single line to earth fault at this bus.

- (c) Earth Wire Currents and Grid Current

To determine the current diverted by earth wires and hence the grid current the method of Chapter 4 is used. To apply the method the self impedance Z_e of the earth wire and the mutual impedance Z_m between earth wire and the phase conductors of each transmission line / feeder is required. The number of spans of each 132 kV line and 66 kV line is more than 30. The values of the impedances Z_e and Z_m have been determined for the 132 kV line as well as 66 kV line for sample geometrical configuration data of phase conductors and earth wire of each transmission line. The values are given below:

Self impedance Z_e of 132 kV line = $(5.88318 + j0.70269) \Omega$

Mutual impedance Z_m of 132 kV line = $(0.13122, + j0.55259) \Omega$

Self impedance Z_e of 66 kV line = $(5.32604, + j0.63166) \Omega$

Mutual impedance Z_m of 66 kV line = $(0.1266, + j0.57475) \Omega$

Using the values of self and mutual impedances, for the fault on 132 kV bus, the current diverted by the earth wires of the two 132 kV lines is found to be $(159.6 - j 977.8)$ A and that by the earth wires of 66 kV lines is $(845.6 - j 2284.0)$ A. Thus, for single line to earth fault, the current flowing towards the earth, i.e., the symmetrical grid current is 5755.4 A.

For the fault on 66 kV bus, the current diverted by earth wires of 132 kV line is $(470.2 - j 2169.4)$ and that by earth wires of 66 kV lines is $(2768.4 - j 4776.4)$ A. The magnitude of current flowing towards the earth i.e. symmetrical grid current is 12924.7 A. Thus for an earth fault at the station, the larger value of 12924.7 A would be used.

11.2 DESIGN OF GRID EARTH ELECTRODE FOR A STATION

11.2.1 Philosophy of earth grid design for a HVAC substation has been brought out in Chapter 3 of this publication. Various formulas used in design are reproduced in Chapter 5. In this section an example of earth grid design is presented to illustrate the techniques described in the earlier chapters.

11.2.2 Data Required-for the Design of Earthing System of a Substation

- (i) Soil resistivity model for the site of the station or soil resistivity test data
- (ii) Electrical circuit single line diagram for the station
- (iii) Layout map of the station showing the locations of buildings, roads, trenches, railway line etc. and the fencing line or boundary line of the station
- (iv) Layout of the equipment in the station
- (v) Single line to earth fault current on the buses in the station
- (vi) If there is local generation then contribution of local generation to the fault current
- (vii) Earth wires connected to station earth grid or not
- (viii) Magnitude of Grid current - if it is not available then the fraction of the total single line to earth fault current contributed by various transmission lines:
 - Number of transmission line and feeders leaving/entering the station
 - For each aerial line/feeder configuration, number and size of phase conductors and earth wire/s (configuration means typical distances between phase conductors and earth wire/s and from earth)
 - GMR of earth wire and its resistance per km
 - Length of each transmission line and feeder up to next station
 - Average span length
 - Average tower footing resistance
 - Average resistivity of soil along the right of way of lines/feeders
- (ix) Preferred material and preferred shape or size of conductors of electrode conductors if any
- (x) Time of operation of fault clearance to be used (i) for determining size of conductor and (ii) for determining permissible values of step and touch voltages
- (xi) Preferred depth of laying the earth electrode if any

- (xii) Specified depth of crushed rock or gravel layer in the station
- (xiii) Specified resistivity of crushed rock or gravel
- (xiv) Any restrictions on spreading gravel outside the fence or making fence inaccessible from outside if necessary
- (xv) Type of fence or the boundary wall etc

11.2.3 Data for Design Calculations

(a) Soil resistivity data

Soil resistivity has been measured at a number of locations in the switchyard area corresponding to 10 different electrode spacings with Wenner method. From the measured data, measured average apparent soil resistivity, for each electrode spacing, has been determined and presented in Table 11.1.

Table 11.1: Measured average apparent soil resistivity

Sl. No.	Probe spacing (m)	Apparent soil resistivity (Ωm)
1	1	65
2	2	60
3	3	50
4	4	44
5	5	38
6	6	39
7	8	35
8	12	48
9	15	56
10	20	65

The average of ten measurements is 50.0 $\Omega\text{-m}$. The percent difference between the average value and the minimum and the maximum measured values is -30 and, +30; these numbers are such that the soil at station site may be assumed to be uniform soil of resistivity 50 $\Omega\text{-m}$.

(b) Single line circuit diagram

Single line circuit diagram of the lines interconnecting the substation to the electric power system of the area is shown in Fig. 11.6. The power system feeding the transmission lines is represented by equivalent generators at the far end of transmission lines.

There are four 220 kV lines and four 132 kV lines connecting the station to the electric power system. The 220 kV buses and 132 kV buses are connected through two, 100 MVA, 220/132 kV grounded wye/delta transformers.

Length of 220 kV lines between bus No. 1 and 3 is 38 km each and that of lines between bus No. 2 and 3 is 2 km each. The line conductors are ACSR Zebra and earth wire is 7/3.66 mm steel wire. The span length is 250 m and tower footing resistance is 10 Ω . Length of each of the four 132 kV lines is 25 km, phase conductor is ACSR Panther and earth wire is 7/3.66 mm steel.

The symmetrical earth fault current at the station for a single line to earth fault at 220 kV bus is 31500 A. Contribution of fault current of each of 38 km line is 3666 A, that of each 2 km line is 9351 A and of each 132 kV line is 1369 A.

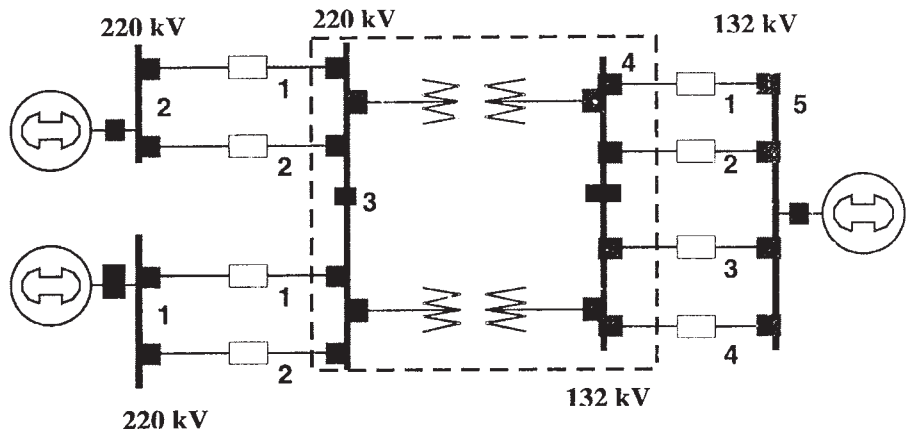


Fig. 11.6 : Single line diagram of the 220/132 kV system for substation

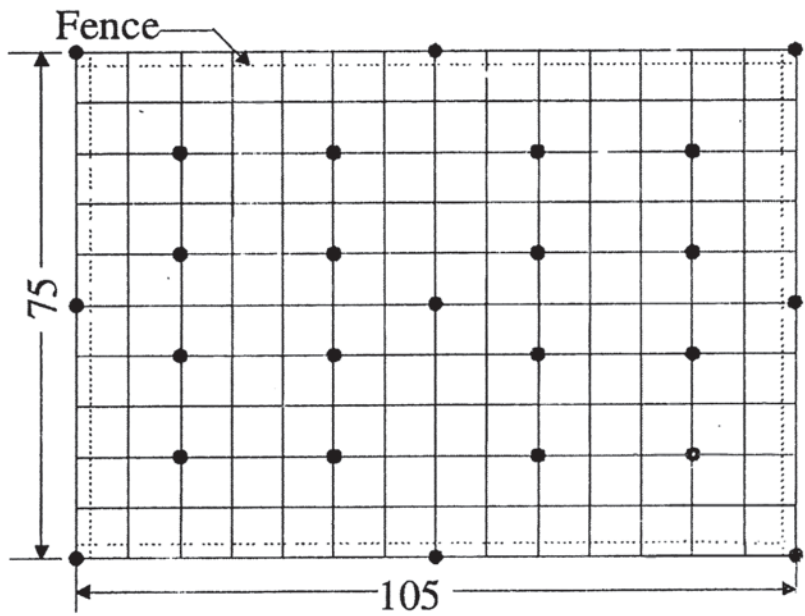


Fig. 11.7 : Configuration of station showing in layout of equi-spaced grid

(c) Station layout showing fence

Station size is 105 m × 75 m. The detailed layout and layout of electrical equipment of the station is not reproduced in this example. Configuration of earth conductors is shown in Fig. 11.7. Conductors are spaced at 7.5 m each. The fence is shown 2 m inside the outermost conductor of the earth grid electrode.

(d) Configuration of transmission line conductors

Configuration of phase conductors and shield/earth wire of 220 kV and 132 kV transmission line conductors is shown in Fig. 11.8. Similar towers are assumed for both the lines. Magnitude of various distances marked on Fig. 11.8 is given in Table 11.2.

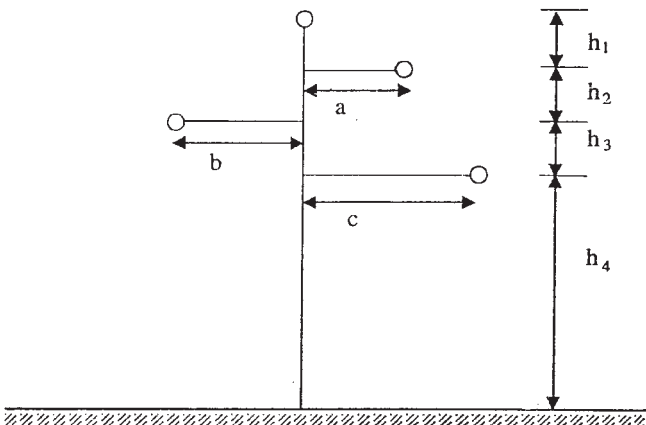


Fig. 11.8 : Configuration of phase conductors and earth wire of 220 kV and 132 kV tower

Table 11.2 : Geometry of phase conductors and earth wire on tower

Tower symbol	Distance (m)
h_1	5.84
h_2	1.94
h_3	1.94
h_4	15.015
a	3.25
b	3.25
c	3.385

(e) Single line to earth fault current and other available data

Symmetrical earth fault current I_f = 31500 A

Duration of fault duration for sizing conductor t_s = 1 sec

Duration of shock for determining allowable body current t_s = 0.5 sec

Available grounding area. A_c	=	105 × 75 m
Crushed rock resistivity ρ_s	=	3000 Ω .m
Thickness of crush rock h_s	=	0.1 m
Depth of laying of grid h	=	0.6 m
Number of incoming lines (220 kV) with shield wire	=	4
Number of outgoing lines (132 kV) with shield wire	=	4
Tower footing resistance of incoming line	=	10 Ω
Tower footing resistance of outgoing line	=	10 Ω
Fence location	=	2 m away towards inside from peripheral conductor

11.2.4 Design Calculations with Empirical Formulae

The soil model has been determined from the measured soil resistivity data.

The magnitude of single line to earth fault current and fault current contributions of various lines have been determined from the network fault study. Since there is no generation at the substation, all of the fault current supplied by 220 kV and 132 kV lines, is returned through earth and earth wires.

Approximate earth resistance $R_g = \rho / (4\pi r) = 0.25 \Omega$, where $r = \sqrt{(105 \times 75 / \pi)}$. This value is used along with data of four, single-circuit, 220 kV lines each with one shield wire and four single circuit 132 kV lines also each with one earth wire, to calculate grid current with program **gridi**, a Visual Basic version of PAG. Approximate magnitude of grid current is found to be 19461 A.

Thus the four important data for earth grid design are:

- (i) Average soil resistivity = 50 Ω m
- (ii) Fault current = 31500 A
- (iii) Grid current = 19461 A = 20000 A
- (iv) Size of grid electrode = 105 m x 75 m
- (a) *Size of earth conductor*

Cross-section area $A_c = 12.15 I \sqrt{t_f} = 12.15 \cdot 31500 \sqrt{1} = 382.7 \text{ mm}^2$

With an allowance of 15.0% for corrosion, area of conductor = 440.1 mm^2

If round conductor is chosen, MS conductor size = $d = 25.0 \text{ mm}$ diameter = 0.025 m

If rectangular conductor is chosen, conductor size = 10 mm x 45 mm MS strip

- (b) *Permissible dangerous voltages*

$$K = (\rho - \rho_s) / (\rho + \rho_s) = (50 - 3000) / (50 + 3000) = -0.96721$$

Magnitude of C_s as per approximation of IEEE Std. 80 is

$$C_s = 1 - \frac{0.09(1 - (\rho / \rho_s))}{2h_s + 0.09} = 1 - \frac{0.09(1 - (69.1/3000))}{2.0.1 + 0.09} = 0.6961$$

The corresponding permissible voltages are:

$$E_{\text{step}} = (1000 + 6C_s \rho_s) \frac{0.116}{\sqrt{t_s}} = (1000 + 1.5 \cdot 0.6961 \cdot 3000) \frac{0.116}{\sqrt{0.5}}$$

$$= 2215.79 \text{ V}$$

$$E_{\text{touch}} = (1000 + 1.5C_s \rho_s) \frac{0.116}{\sqrt{t_s}} = (1000 + 1.5 \cdot 0.6961 \cdot 3000) \frac{0.116}{\sqrt{0.5}}$$

$$= 676.98 \text{ V}$$

The value of C_s as per formulas given by HRS and JKA is

$$C_s = 1 - \frac{1.369b}{1.952h_s + 0.608b} \ln(1 - K) = 1 - \frac{1.369 \cdot 0.08}{1.952 \cdot 0.1 + 0.608 \cdot 0.08} \ln(1 - (-0.96721)) = 0.6961$$

Corresponding permissible voltages - $E_{\text{step}} = 2219.54 \text{ V}$ and $E_{\text{touch}} = 677.92 \text{ V}$.

In areas where there is no gravel, with surface soil resistivity as $50 \Omega\text{m}$, arid $C_s = 1.0$, permissible magnitude of E_{step} and E_{touch} is 213.26 V and 176.35 V , respectively.

(c) *Preliminary layout of earth conductors and earth resistance*

Preliminary layout of earth conductors is shown in Figure 11.7. To start with grid conductors are placed at regular spacing = $D = 7.5 \text{ m}$. The number of conductors is as follows:

$$\text{Number of conductor along the length (long conductors)} = 11$$

$$\text{Number of conductor along with width (short conductors)} = 15$$

In preliminary layout of grid electrode 25 vertical rods are placed as shown in Fig. 11.7. Thus

$$\text{Number of vertical ground rods } N_r = 25$$

$$\text{Length of each vertical ground rod } = l_r = 3\text{m}$$

$$L_R = \text{total length of vertical earth rods} = 75 \text{ m}$$

$$\text{The total length of horizontal conductors} = L_c = (105 \times 11 + 75 \times 16) = 2280 \text{ m}$$

Other values are as below :

$$L_p = 360\text{m}$$

$$L_x = 105 \text{ m}$$

$$L_y = 75\text{m}$$

$$D_m = 129.03 \text{ m}$$

$$L_t = L_c + L_r = 2355 \text{ m}$$

$$A = 7875 \text{ m}^2$$

The earth resistance with IEEE formula is obtained as :

$$R_G = \rho \left[\frac{1}{L_t} + \frac{1}{\sqrt{20A}} + \left(1 + \frac{1}{1 + h\sqrt{20/A}} \right) \right]$$

$$= 50 \left[\frac{1}{2355} + \frac{1}{\sqrt{20 \cdot 7875}} + \left(1 + \frac{1}{1 + 0.6\sqrt{20/7875}} \right) \right] = 0.2695 \, \Omega$$

However, with formula given by Thapar et al, the earth resistance = 0.2478 Ω .

(d) *Grid current*

With new value of earth resistance the grid current is calculated as 18900 A. However the rounded off value of 20000 A is used in further calculations. This takes into account a factor for future growth of fault current.

(e) *Actual maximum mesh voltage and step voltage*

Actual maximum mesh voltage and step voltage are calculated by using IEEE Std. 80 formulas.

$$K_{ii} = 1$$

$$K_h = (1+h)^{0.5} = 1.2649$$

$$n_a = 2 L_c / L_p = 2 \cdot 2280/360 = 12.6667$$

$$n_b = [L_p / (4\sqrt{A})]^{0.5} = [360 / (4\sqrt{7875})]^{0.5} = 1.007$$

$$n_c = 1 \text{ (for square and rectangular grid electrode)}$$

$$n_d = 1 \text{ (for square and rectangular and L- shaped grid electrode)}$$

$$n = 12.7557$$

The mesh voltage is calculated from the expression

$$E_m = \rho K_m K_{im} I_G / L_m$$

$$\text{Effective length for } E_t = L_m = L_c + \left[1.55 + 1.22 \left(\frac{I_r}{\sqrt{L_x^2 + L_y^2}} \right) \right] L_r = 2398.9 \text{ m}$$

$$K_m = \frac{1}{2\pi} \left[\ln \left[\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d} \right] + \frac{K_{ii}}{K_h} \ln \left[\frac{8}{\pi(2n-1)} \right] \right] = 0.61122$$

$$K_{im} = K_{is} = 0.644 + 0.148 n = 2.531845$$

$$E_m = 645.11 \text{ V}$$

The step voltage is calculated from the expression

$$E_s = \rho K_s K_{is} I_G / L_s$$

$$K_s = \frac{1}{\pi} \left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D} (1 - 0.5^{n-2}) \right] = 0.34697$$

$$\text{Effective length for } E_s \text{ is } L_s = 0.75 L_c + 0.85 L_r = 1773.75 \text{ m}$$

$$E_s = 495.27 \text{ V}$$

$$\text{EPR} = R_G \times I_G = 0.2695 \times 20000 = 5390 \text{ V}$$

A more realistic value is obtained by using value of R_G from Thapar's formula and it is $= 0.2478 \times 20000 = 4956 \text{ V}$.

(f) *Safety analysis*

The maximum mesh voltage that may occur in the grid electrode is 645.11 V; this is less than the permissible touch voltage of 676.98 V on gravel and is safe. The maximum step voltage that may occur near a corner of grid electrode is 495.27 V; it is also less than its permissible value of 2215.79 V on gravel. The permissible magnitude of step voltage if earth surface is not covered with gravel is 213.26 V, which is more than 495.27 V. It is therefore necessary that gravel layer of 100 mm thickness be spread and maintained to a distance of 1 m outside the fence. The IEEE method does not calculate the touch voltage from outside the fence. This information is presented in tabular form in Table 11.3.

Table 11.3 : Safety check table in the switch yard

Voltage	Permissible value on gravel (V)	Permissible value without gravel (V)	Attainable value (V)
Touch Voltage	676.98	176.35	645.11
Step Voltage	2215.79	213.26	495.27

(g) *Effect of increase in depth of outermost conductor*

If the depth of the outermost conductor is increased, it decreases the factor K_s . Thus the actual step voltage is reduced. In this example if the depth of outermost conductor is increased from 0.6 m to 2 m, calculation of factor K_s is modified with $2h = 2 \times 2 = 4$ as

$$K_s = \frac{1}{\pi} \left[\frac{1}{2.2} + \frac{1}{7.5 + 0.6} + \frac{1}{7.5} (1 - 0.5^{12.7557-2}) \right] = 0.16129$$

$$\text{This makes } E_s = 230.23 \text{ V}$$

This value is still larger than 213.26 V, the permissible value of step voltage on natural soil. But it demonstrates the effect of increase of depth of burial of the outermost conductor of grid electrode on actual step voltage.

11.2.5 EARTHING DESIGN FOR A 33/11 KV SUBSTATION

11.2.5.1 A case study of the earthing design of a 33/11 kV substation is presented in this section. The station is fed with two 33 kV lines from a grid substation. A single line diagram of the station is shown in Figure 11.9. At the feeding station, the 33 kV bus is connected to 132 kV bus through 2 Nos. 132/33 kV star/star transformers. The system behind the 132 kV bus is represented by a generator such that the three-phase short circuit current on 132 kV bus is 31 kA as obtained from system studies. Approximate length of 33 kV lines is 34 km.

At the station under consideration 33 kV is transformed to 11 kV through 2 Nos. 33/11 kV, delta/star transformers. A number of 11 kV feeders emanate from the station. Layout of the station is given in Figure 11.10.

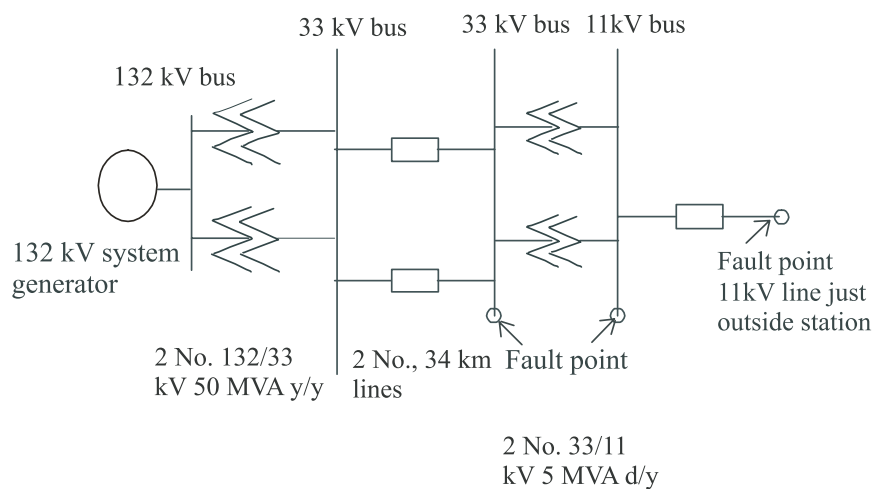


Fig. 11.9: Single line diagram representation of the station of case study

11.2.5.2 Soil Resistivity Data

Measurements of soil resistivity were carried out at the station site with the Wenner four electrode method. The soil is rocky and measurements could be made only with a few electrode spacings. The average values of measured resistance obtained for various spacings and the computed values of apparent soil resistivity are given in Table 11.4.

Table 11.4: Apparent measured soil resistivity

Sl. No.	Electrode spacing (m)	Measured resistance (Ω-m)	Apparent resistivity (Ω-m)
1	1.0	47.5	298.5
2	2.0	27.1	340.5
3	4.0	13.0	326.7
4	8.0	7.2	361.9
5	10.0	4.8	301.6

The average of the five measurements is 325.84 Ω-m. It is rounded off to 326.0 Ω-m. The percent difference between the average value and the minimum and the maximum measured values of

apparent resistivity is -8.4 and $+10.9$; these numbers are such that the soil at station site may be assumed to be uniform soil of resistivity $326 \Omega\text{-m}$.

11.2.5.3 Phase to Earth Short Circuit Current and Grid Current

Phase to earth short circuit current and the grid current are estimated with the data given below. Spacing between conductors of 33 kV line is 1.525 m and geometric mean radius of conductor 0.01278 m. All reactance values are on 100 MVA base. All resistances except that of earth electrode are neglected.

1. Reactances of source generator = 0.014 pu
2. 50 MVA transformer +ve, -ve, and zero sequence reactance = 0.25 pu
3. 33 kV +ve, and -ve sequence reactance of each line = 0.98712 pu
4. 33 kV line zero seq. reactance (assumed 3 x +ve sequence value) = 2.96136 pu
5. 5 MVA transformer +ve, -ve, and zero sequence reactance = 1.43 pu
6. Earth resistance of grid earth electrode assumed 3Ω = 2.4793 pu
7. For fault on 11 kV line just outside the station, line reactance = 0.001 pu

11.2.5.4 Fault Current Calculations

(a) Fault on station 33 kV bus

$$\begin{aligned} \text{Total reactance of the circuit} &= (+\text{ve seq. reac.}) + (-\text{ve seq reac}) + (\text{zero seq. reac}) \\ &= (0.014 + 0.125 + 0.49356) \times 2 + (0.014 + 0.125 + 0.49356 \times 2) \\ &= 2.8848 \text{ pu} \end{aligned}$$

$$\text{Single phase to earth fault current} = 3 \times (1/2.8848) = 1.0399 \text{ pu} = 1819.4 \text{ A}$$

$$\text{Two-phase to earth fault current} = 1355.6 \text{ A}$$

$$\text{Grid current} = 1819.4 \text{ A} \approx 1820 \text{ A}$$

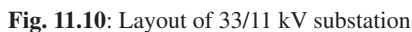
(b) Fault on station 11 kV bus

$$\begin{aligned} \text{Total reactance of the circuit} &= (+\text{ve seq. reac.}) + (-\text{ve seq reac}) + (\text{zero seq. reac}) \\ &= (0.014 + 0.125 + 0.49356 + 0.715) \times 2 + 0.715 \\ &= 3.41012 \text{ pu} \end{aligned}$$

$$\text{Single phase to earth fault current} = 3 \times (1/3.41012) = 0.87972 \text{ pu} = 4617.4 \text{ A}$$

$$\text{Two-phase to earth fault current} = 5669.0 \text{ A}$$

$$\begin{aligned} \text{Grid current (delta winding on} &= 0.0 \text{ A} \\ \text{11 kV side)} & \end{aligned}$$



The maximum value of grid current = 1924.1 A $\approx$ 1925 A

(d) Grid Current and Fault Current

The values selected for earth grid design are as given below:

Short circuit current for conductor size = 6000 A

Grid current = 1925 A

11.2.5.5 Area of Grid Earth Electrode

Even though the station covers an area of about 57 m x 37 m, the utility authorities wished to restrict the grid to an area of 48 m x 28 m. However in view of the high soil resistivity and restricted area, it is advisable to enclose the maximum area in the grid. Therefore both options are tried.

11.2.5.6 Other Data

The fault current duration is taken as 3 seconds and the shock duration is assumed to be 1 second. MS steel conductor of round cross section of 0.032 m diameter is to be used. The same conductor may be used for vertical rods as well as horizontal earth conductors. Depth of burial of earth conductors is 0.6 m. The length of vertical rod is restricted to 3.0 m because of the difficulty of installing rods in rocky soil.

Gravel is spread in the station areas where required. Its resistivity is 3000 Ω -m and its depth is assumed to be 0.15 m.

11.2.5.7 Permissible Step and Touch Potential and EPR

Permissible values of step and touch potential are calculated as per the formulas given in IEEE Std 80 – 2000 and this CBIP Manual. As is the practice in most design offices an EXCEL program has been written for earthing design calculations.

$$E_{\text{step}} = (1000 + 6\rho_s \cdot C_s) \cdot 116/\sqrt{t_s}$$

$$E_{\text{touch}} = (1000 + 1.5\rho_s \cdot C_s) \cdot 116/\sqrt{t_s}$$

After substituting for various values we get

$$E_{\text{step}} = 1774.5 \text{ V}$$

$$E_{\text{touch}} = 530.6 \text{ V}$$

The maximum earth potential rise (EPR) may be restricted to less than $11000/\sqrt{3}$ V. This works out to be 6350 V. If earth resistance is approximately 3 Ω , the maximum EPR shall be shall have to be 5775 V for grid current of 1925 A. If earth electrode resistance is about 4 Ω , then the maximum grid current shall be that for fault on 33 kV bus i.e. 1820 A. This gives an unacceptable EPR of 7280 V.

11.2.5.8 Possible Design Solutions**(a) First Solution**

Initially a program in EXCEL which is based on empirical formula given in IEEE Std 80-2000 is used to obtain the design results. As configuration of earth grid conductors is changed to one where empirical formulas are not applicable, results are obtained with software. An initial layout

of earth grid conductors with rods is shown in Figure 11.11 (a). There are 8 parallel conductors in one direction and 13 in the other. There are 28 vertical rods each of 3 m length. As given above radius of earth conductors as well as of rod conductors is 0.016 m. There are 18 vertical rods near the periphery.

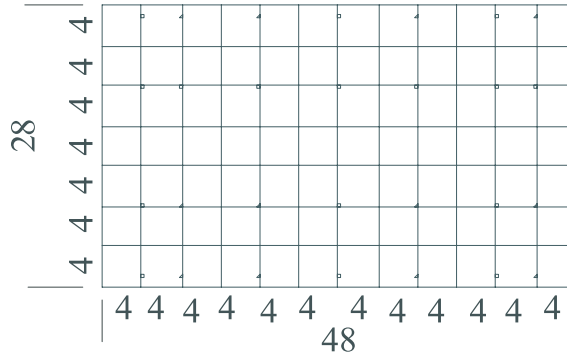


Fig. 11.11 (a) : Equispaced conductors of 48 m x 28 m grid electrode.

The results obtained with this data are:

$$\begin{aligned} R_G &= 3.94 \, \Omega \\ E_s &= 873.2 \, \text{V} \\ E_m &= 957.7 \\ \text{EPR} &= 7170 \, \text{V} \end{aligned}$$

If soil enhancement measures are adopted, it may be assumed that effective conductor radius becomes 0.1 m. With this value of conductor radius, the earth resistance and step voltage values do not change as radius of conductors does not appear in the expressions for earth resistance. The touch voltage changes as below:

$$E_m = 442.1 \, \text{V}$$

Even though this value is less than the permissible, EPR of 7170 V is not acceptable.

(b) Second Solution

In case of the first solution, out of the results obtained with conductor radius of 0.016 m, clearly the touch voltage as well as EPR exceed the permissible values. So this design is unacceptable. To reduce the earth resistance of the grid the area of the grid is enhanced to 57 m x 37 m by enclosing all of the available area. The layout of grid conductors and vertical rods is shown in Figure 11.11 (b). In this layout there are 35 vertical rods, each of length = 3 m. When all conductors are assumed to be of 0.016 m radius, the calculated values are

$$\begin{aligned} R_G &= 3.12 \, \Omega \\ E_s &= 673.4 \, \text{V} \\ E_m &= 677.5 \, \text{V} \\ I_g &= 1925 \, \text{A} \\ \text{EPR} &= 6063.75 \, \text{V} \end{aligned}$$

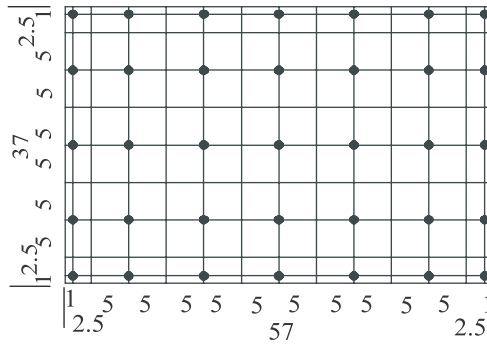


Figure 11.11 (b): Earth grid conductor layout for 57 m x 37 m grid area

In fact EPR value will be less than 6063.75 V because, grid current is obtained as 1925 A with earth resistance of 3.0Ω . In these values the touch voltage is more than the permissible value of 530.6 V. In this case too, soil enhancement material may be tried. The conductor radius is then assumed to be 0.1 m after use of such material. With this value, we get $E_m = 284.5$ V. Thus the calculated values of step and touch voltages are within the permissible range but EPR is on higher side.

11.2.5.9 Results with Software

The data of grid earth electrode of Figure 11.11 is simulated on the software that has been written as per Heppe's algorithm. The results obtained are given below:

Case 1. Conductor radius = 0.016 m

Radius of vertical rod conductor = 0.016 m

$$R_G = 3.09 \Omega$$

$$E_s = 636.6 \text{ V}$$

$$E_m = 605.7 \text{ V}$$

$$I_g = 1925 \text{ A}$$

$$\text{EPR} = 5948 \text{ V}$$

Case 2.

Conductor radius = 0.016 m

Radius of vertical rod conductor = 0.1 m

$$R_G = 3.02 \Omega$$

$$E_s = 618.5 \text{ V}$$

$$E_m = 487.7 \text{ V}$$

$$I_g = 1925 \text{ A}$$

$$\text{EPR} = 5813.5 \text{ V}$$

Case 3

Conductor radius = 0.1 m

Radius of vertical rod conductor = 0.1 m

$$R_G = 2.985 \, \Omega$$

$$E_s = 646.1 \, \text{V}$$

$$E_m = 268.2 \, \text{V}$$

$$I_g = 1925 \, \text{A}$$

$$\text{EPR} = 5775 \, \text{V}$$

11.2.5.10 Conclusions

Thus it is seen that a design that is workable and satisfies the safety criteria is possible. It may be kept in mind that results obtained with software may differ up to 20% from those obtained with empirical formulas. However, the design may not be as per specifications laid down by utility authorities. It was specified that the earth design would give earth resistance of 2 Ω or less. There is not a great advantage in attaining 2 ohm earth resistance. The grid current goes up to 2620 A and the EPR is the 5240 V. But to attain an earth resistance of 2.0 ohm in the area of the substation is not easy. It would require some very deep earth wells of 40 m depth .and several vertical rods of 10 m depth. The costs may be prohibitive.

11.3 ANALYSIS OF GRID USING EARTHING ANALYSIS SOFTWARE

Results of design of earth grid, presented in Section 11.2.3 are compared with the results of design with software based on algorithm given in literature [1]. It has been brought out in Section 3.11 that earth grid design, except for the case of uniformly spaced grid buried in uniform soil, has to be carried out with software. Necessity and effect of use of non-uniformly spaced grid on grid design is also presented in this section.

11.3.1 Uniformly Spaced Grid Conductors

Using computer software based on average potential method, the equally spaced grid of Fig. 11.7 was modeled. This is done in order to compare results of simplified equation of IEEE Std. 80 with results of more rigorous algorithm on which the software is based.

The computer calculated values are compared with IEEE Std. 80 empirical equation in Table 11.5. The plot of touch voltage and of step voltage can be seen in Figs. 11.12 and 11.13, respectively.

It can be determined from Fig. 11.12, that the maximum touch voltage occurs at coordinate X=3 m, and Y=3 m, that is, near the center of corner mesh. Figure 11.13 shows that the maximum step voltage occurs outside the grid approximately over 1 m distance in a diagonal direction away from the grid corner.

It can be seen from the touch and step voltage plots that the presence of gravel is absolutely necessary both inside and outside the fence yard. However, it is seen from Fig. 11.14 for step

voltage inside the fence yard that the maximum step voltage is less than the permissible step voltage without use of gravel. This suggests that in areas of switchyard without presence of any metallic equipment e.g. future extension, gravel is not necessary from step potential point of view. Also, gravel can be laid in patches, just surrounding metallic object (e.g., equipment, tower, lighting post, sign board etc) instead of laying gravel throughout the grid area or equipment area.

Table 11.5 : Comparison of results or software analysis with IEEE Std. 80 formulas

Parameter	IEEE Std. 80 empirical equations	Computer results
Earth resistance	0.269 Ω	0.250 Ω
Maximum touch voltage	645.11 V	741V
Maximum step voltage	495.27 V	443 V
Maximum step voltage inside fence yard	Not possible to estimate	174V
Applicable area for gravel spreading beyond perimeter conductor in order to protect humans from step voltage	Not possible to estimate	3 m from perimeter conductor
Fence contact voltage	Not possible to estimate	Refer Fig. 11.12

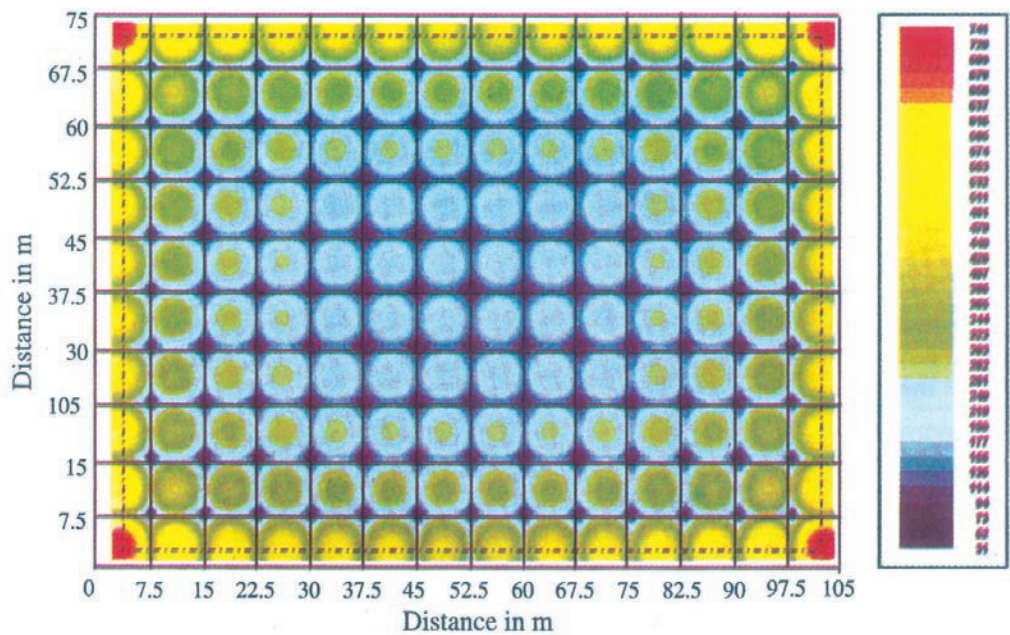


Fig. 11.12 : Touch voltage plot for uniformly spaced grid conductors

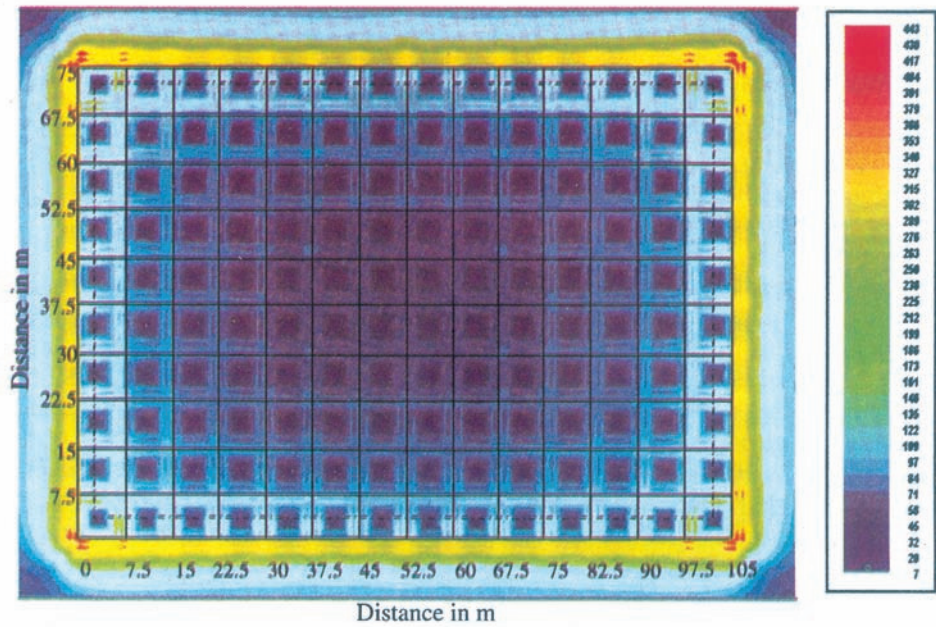


Fig. 11.13 : Overall Step Voltage plot for uniformly spaced grid conductors

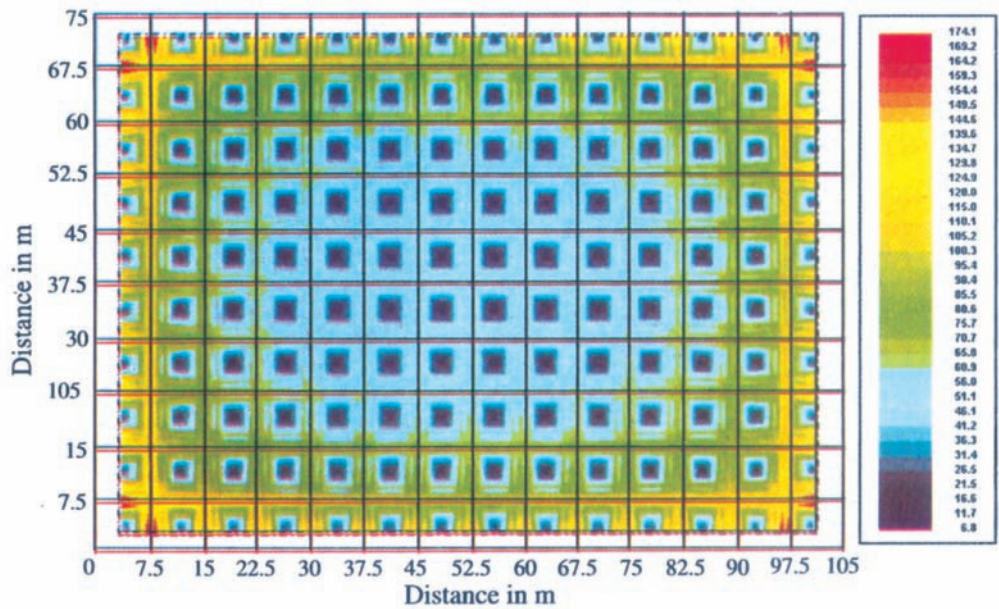


Fig. 11.14 : Step voltage inside switchyard fence for uniformly spaced grid conductors

11.3.2 Non-uniformly Spaced Grid Conductors

It can be seen in Fig. 11.12 that touch voltage is the maximum in meshes near corners and decreases in meshes that are towards the center. To make optimum use of earth conductors, the touch voltage must be equalized. This can be achieved to some extent by suitably rearranging the earth conductor.

In an earth grid the current discharged in to the earth by the grid conductors is nonuniform. A larger portion of the current is discharged into the soil from the outer grid conductors rather than from the conductors at or near the center of the grid. Also on any individual conductor, current dissipation per meter is larger towards the ends compared to that towards the middle. When grid conductors are uniformly spaced, this results in much higher touch voltage on the corner of the grid than those in center. An effective way of making the touch voltage more uniform is to employ a non-uniform conductor spacing as shown in Fig. 11.15. The conductor spacing is larger at the center of the grid and smaller toward the perimeter. However, analysis of grids with this type of spacing cannot be accomplished using the empirical equations of IEEE Std. 80. Analysis is possible with software that is based on specific algorithms, which can determine distribution of current dissipation from earth conductors into soil.

Figure 11.16 refers to the distribution of current density of current, dissipated by uniformly spaced grid conductors into soil, for the six conductors as marked in Fig. 11.15. It can be seen from Figure 11.13 that current density is highly non-uniform along the length of conductor. Current density is also highly non-uniform as we move from periphery to the center area of grid. This suggests that conductors located inside the grid are not utilized effectively.

Figure 11.17 refers to the current density of dissipated grid current from non-uniformly spaced conductors for the six conductors marked in Fig. 11.15. In this arrangement of grid, current density is fairly uniform over the conductor length as well as throughout the grid. This results in drastic

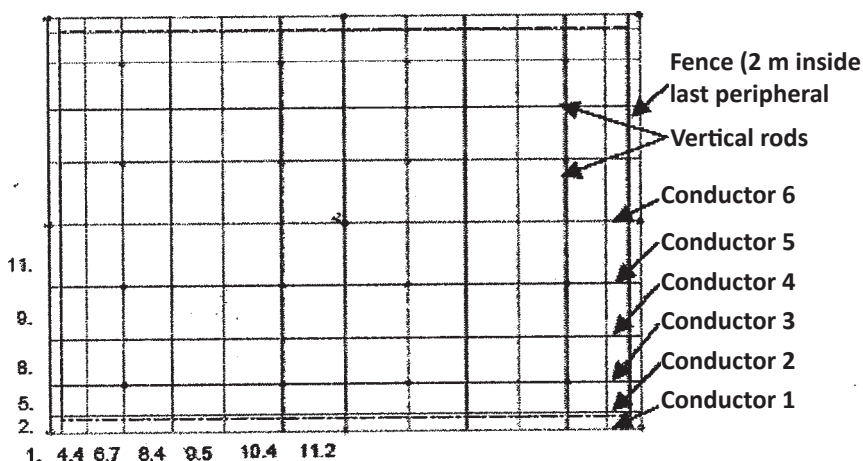


Fig. 11.15 : Non-uniform spacing arrangement of grid conductors

reduction in maximum value of touch voltage, Fig. 11.18, as compared to Fig. 11.12. Here, the maximum touch voltage is reduced to 417 V compared to the maximum value of 741 V in grid with uniform spacing. The maximum value of step voltage, from Fig. 11.19, is also marginally reduced to 423 V against 443 V. Fig. 11.20 shows the fence contact voltage from outside along the 105 m side for uniform and nonuniform spacing grid. It is evident that in case of non-uniform case, fence contact voltage is significantly reduced compared to uniformly spaced grid.

Important parameters of grid with uniformly spaced conductors and those obtained for grid with non-uniformly spaced conductors are summarized in Table 11.6.

Table 11.6 : Comparison of results with software for equi- and unequally spaced grid conductors

Parameter	Uniform spacing grid	Non-uniform spacing grid
Ground Resistance	0.250 Ω	0.249 Ω
Maximum touch Voltage	741V	417V
Maximum Step Voltage	443 V	423 V
Maximum Step Voltage inside fence yard	174 V	110V
Fence contact voltage	Refer Figure 11.20	Refer Fig. 11.20

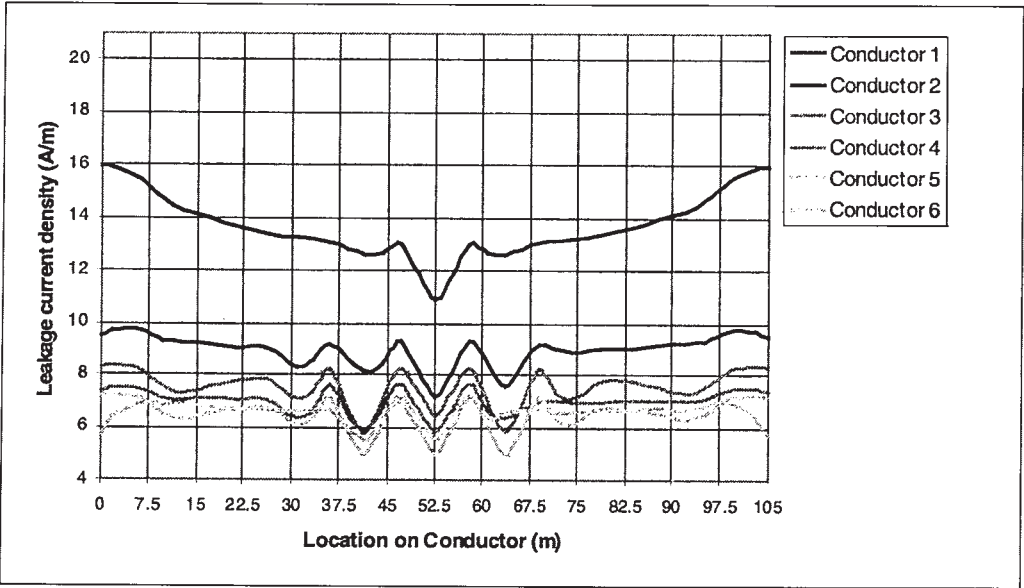


Fig. 11.16 : Leakage current density from conductors of uniformly spaced grid

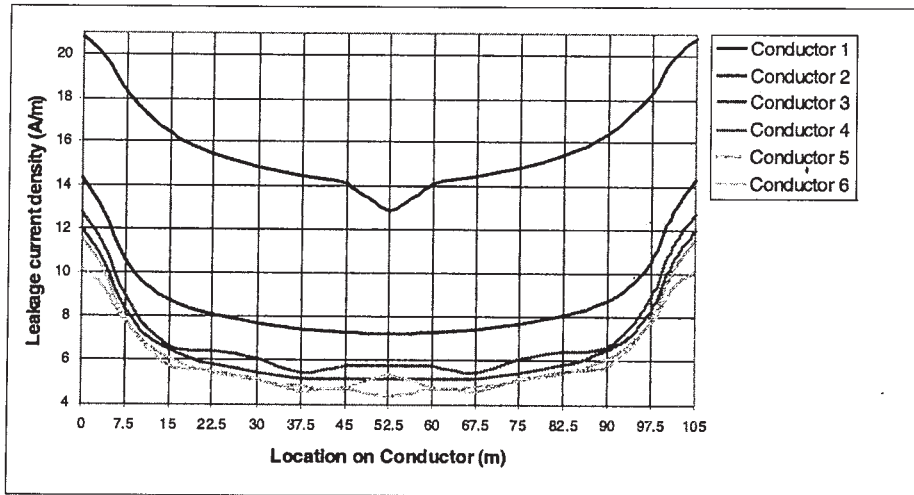


Fig. 11.17 : Leakage current density from conductors of non-uniformly spacing

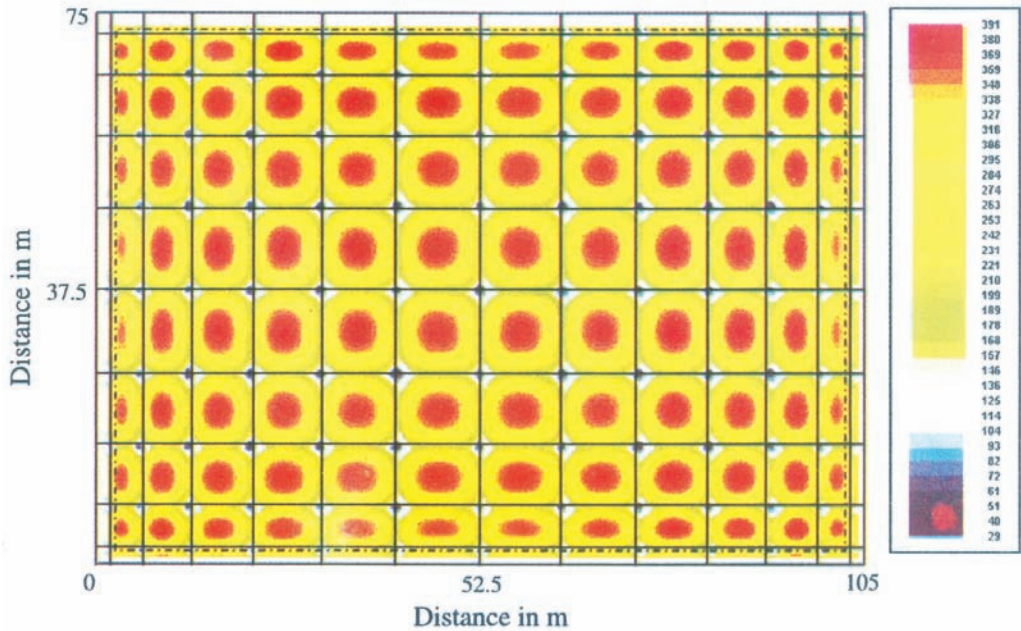


Fig. 11.18 : Touch voltage plot for grid with non-uniformly spaced conductors

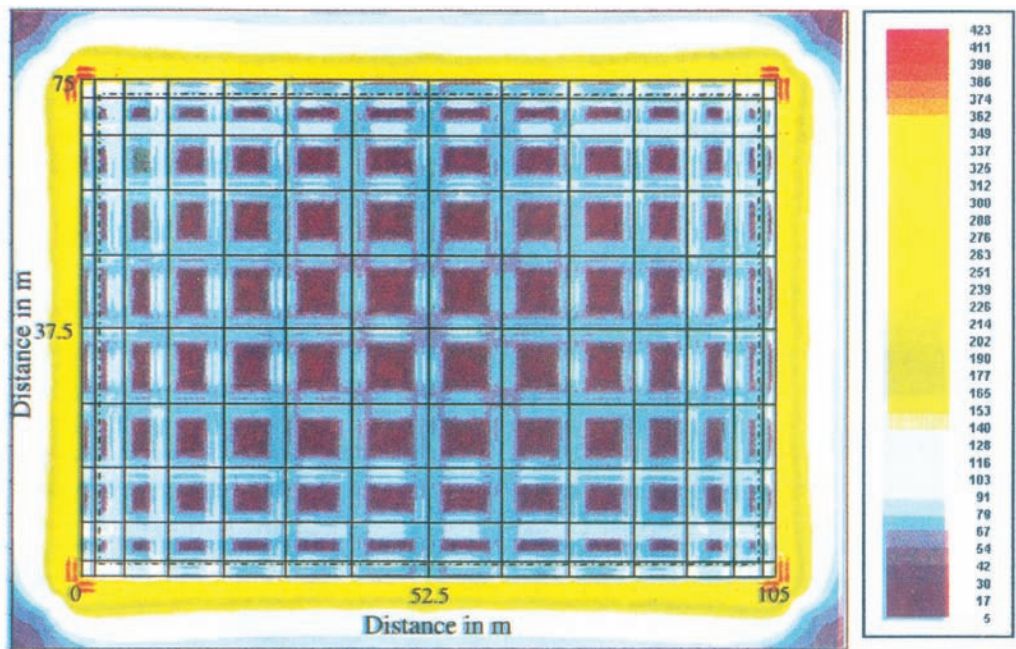


Fig. 11.19 : Overall step voltage plot for non-uniformly spaced grid

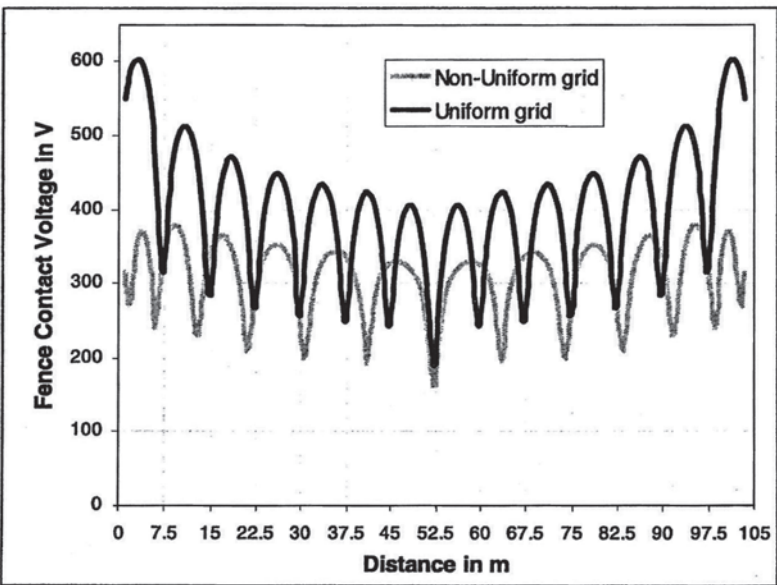


Fig. 11.20 : Fence contact voltage for uniformly and non-uniformly spaced grid of conductors

11.4 SINGLE LAYER VERSUS TWO-LAYER SOIL

In this section performance of earth grid electrode buried in two-layer soil is analyzed [1]. All other data, except for the soil model are the same as for grid buried in uniform soil given in Section 11.2.3. In the examples of this section, the top layer soil resistivity is fixed at $50 \Omega\text{-m}$; the bottom layer soil resistivity is varied as also the top layer height.

Figure 11.21 illustrates the effect of varying height of upper layer and value of K . It can be seen that for positive value of K (bottom layer soil resistivity is more than that of top layer), earth resistance decreases and for negative value of K (bottom layer soil resistivity is less than that of top layer), earth resistance increases with increase in top layer height. The increase or decreases in earth resistance with top layer height is fairly uniform. This suggests that, earth resistance is not very sensitive with respect to grid burial depth. However, maximum value of touch voltage is highly sensitive with respect to grid burial depth as seen in Figure 11.22. This can be seen by sudden step change in maximum value of touch voltage near top layer height of 0.6 m, e.g., for $K=0.9$, with 0.58 m top layer thickness, earth resistance is 3.76Ω and maximum touch voltage is 10280 V and with 0.62 m top layer thickness, earth resistance value is marginally reduced to 3.56Ω . but maximum touch voltage is reduced substantially to 4143 V. In former case, the grid is placed in soil of $950 \Omega\text{-m}$ resistivity, but in the latter case the grid is placed in soil of $50 \Omega\text{-m}$ resistivity.

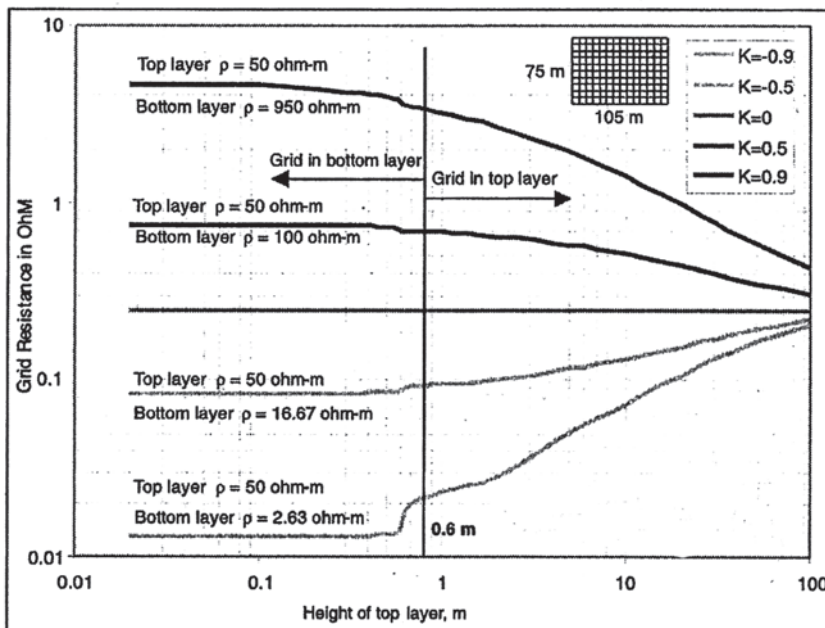


Fig. 11.21 : Earth resistance for two-layer soil

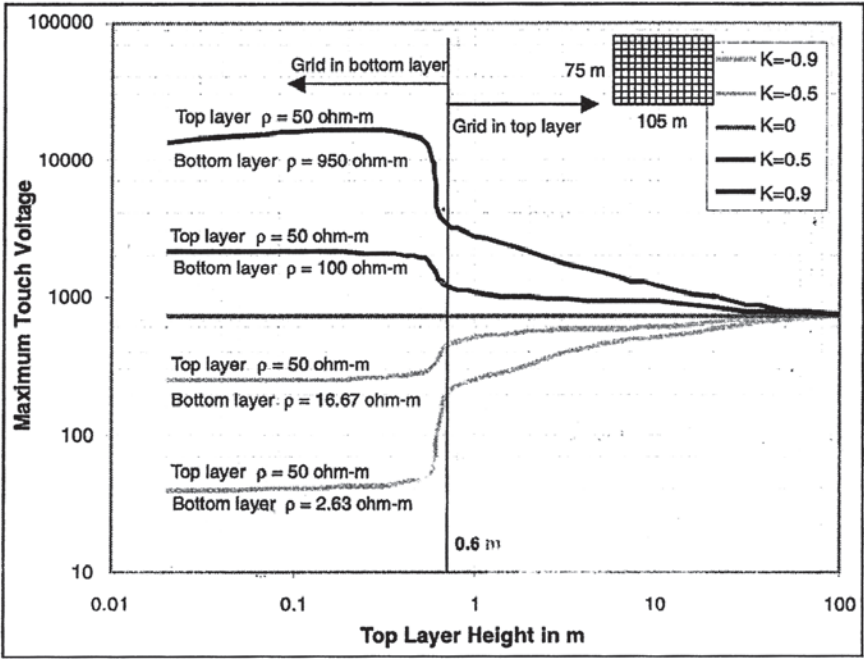


Fig. 11.22 : Maximum Touch Voltage for two-layer soil

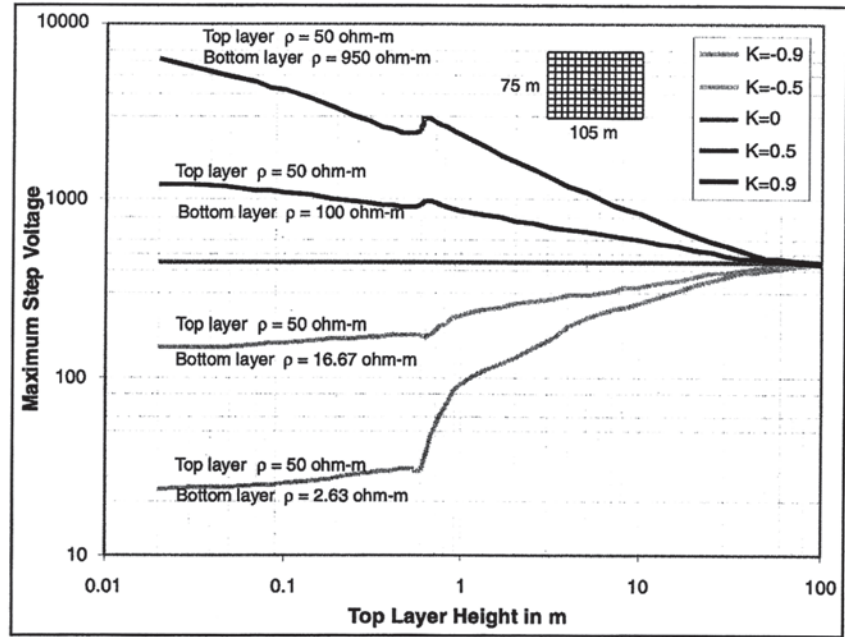


Fig. 11.23 : Maximum Step Voltage for two-layer soil

11.5 EARTH GRID IN HIGH RESISTIVITY SOIL

- (a) This section deals with the possible solution to the problem of design of grid electrode in the difficult condition of high resistivity soil. In this example too the other data, except for the soil model are the same as for the grid buried in uniform soil given in Section 11.2.3. Soil resistivity is taken as $300 \Omega\text{-m}$. Geometry of earth conductors of the grid electrode is varied. Two configurations, one with 11 conductors on the shorter side and 15 conductors along the longer side and the second with 16 and 22 conductors along the two sides, are considered. In both cases conductors are non-uniformly spaced. With soil resistivity of $300 \Omega\text{-m}$, values of permissible touch and step voltage are shown in Table 11.7.

Table 11.7 : Permissible values of touch and step voltages in soil of $300 \Omega\text{-m}$

Voltage	With 0.1 m top layer of gravel	On native soil without gravel
Touch Voltage (V)	696.9 V	237.8 V
Step Voltage (V)	2292.1 V	459.3 V

The maximum value of touch voltage and step voltage for 11×15 grid, and 16×22 grid is shown in Table 11.8. Conductor spacing for 11×15 grid can be seen in Figure 11.15 and 16×22 grid in figure 11.24. For 11×15 grid, the maximum touch voltage is 2344 V and maximum step voltage 2538 V. Corresponding values for 16×22 grid are 1448 V and 2602 V respectively. With further increase in number of conductor, touch and step voltage do not reduce significantly.

Table 11.8 : Comparison of results with software for 11×16 , and 16×22 grids

Parameter	Non-uniformly spaced 11×16 grid	Non-uniformly spaced 16×22 grid
Earth resistance	1.494 Ω	1.461 Ω
Maximum touch Voltage*	2344 V	1448 V
Maximum Step Voltage outside fence	2538 V	2602 V
Maximum Step Voltage inside switch yard fence	660 V	397 V
Applicable area for gravel spreading beyond perimeter conductor in order to protect humans from step voltage	10 m from perimeter conductor	11.5 m from perimeter conductor
* Maximum touch voltage computed in area up to a distance of 1 m beyond fence line		

- (b) Since both alternatives tried above result in unsafe design, other possible solutions to the problem could be any one or a combination of following options:
- Extension of grid area outside fence yard to control fence contact voltage,
 - Gradient control ring outside the fence yard buried at progressively increasing depths or inclined earth rods in order to control step voltage outside the fence yard,
 - Concrete /Bentonite encased electrode,
 - Deep driven vertical electrodes,
 - Counterpoise earth mat and
 - Satellite grid earth electrode

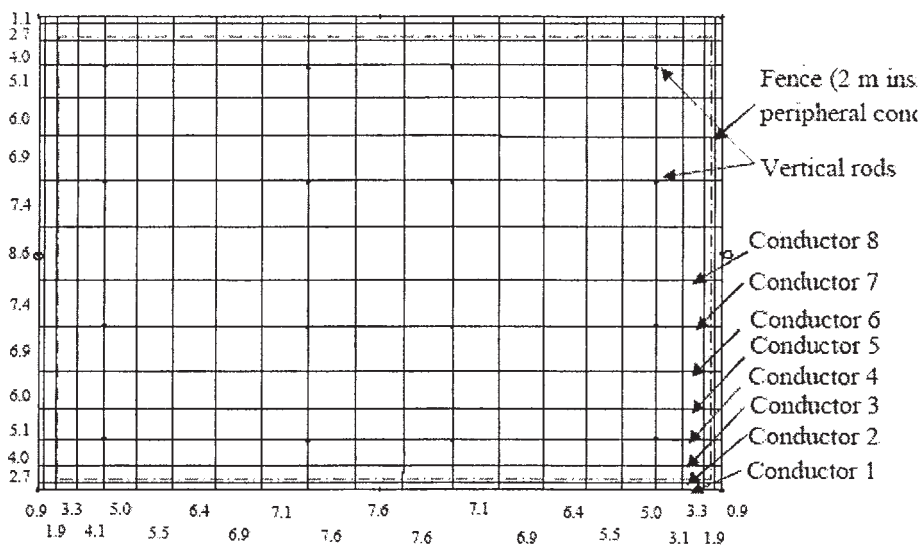


Fig. 11.24 Non uniformity spaced grid (16 × 22)

11.5.1 Extension of Grid Area Outside Fence Yard to Control Fence Contact Voltage

In this case grid is extended up to a distance of 5 m outside and away from fence. Hence grid area becomes 115 × 85 m. Now fence is located 7 m inside the perimeter conductor. The calculated result is shown in Table 11.9

Table 11.9 : Results of calculations for non uniformly spaced 16 × 22 grid

Parameter	Non-uniformly spaced grid (115 m × 85 m) with 16 × 22 conductors
Earth resistance	1.3182 Ω
Maximum touch voltage inside safety area *	1328 V
Maximum step voltage outside fence	2262 V
Maximum step voltage inside fence yard	357 V
Applicable area for gravel spreading beyond perimeter conductor in order to protect humans from step voltage	10 m from perimeter conductor (17 m from fence)
* Maximum touch voltage computed in area up to a distance of 1 m beyond fence line	

Here with a slight increase in area, grid resistance is decreased hence also the maximum values of touch and step voltage. Even then the calculated maximum touch voltage 1328 V is unacceptable. Also gravel would have to be extended to cover the area up to a total distance of 17 m from fence. This is also unacceptable.

11.5.2 Gradient Control Ring

A gradient control ring is used outside the outermost conductor of earth grid to control potentials outside the grid. Two gradient control rings, one, buried at 2 m depth, at a distance of 2.5 m

outside the last peripheral conductor and the other at 5 m from last peripheral conductor, buried at 4.5 m depth, are used in this example with the (16 × 22 m) grid as shown in Figure 11.25. The results calculated with software are shown in Table 11.10

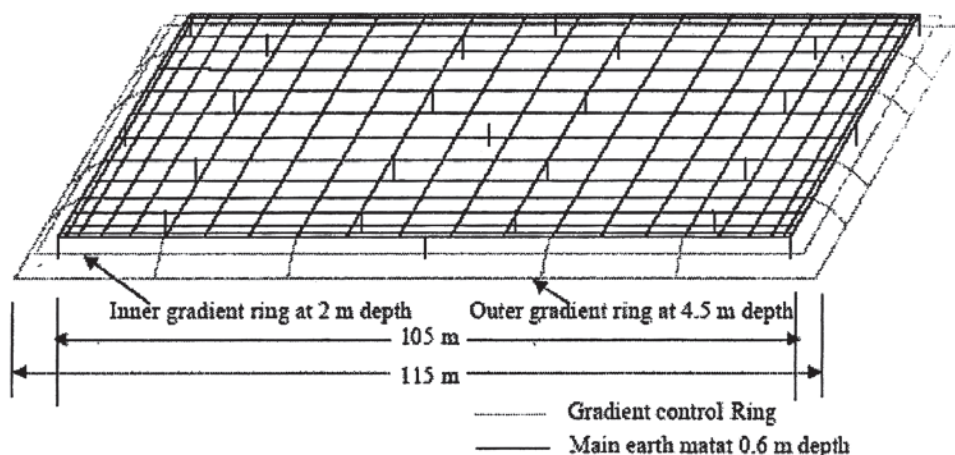


Fig. 11.25 : Configuration of earth grid conductors and gradient control conductors

Table 11.10 : Results of calculations for 16 x 22 grid with gradient control ring

Parameter	Non-uniformly spaced grid (115 m × 85 m) with 16 × 22 conductors
Earth resistance	1.2784 Ω
Maximum touch voltage inside safety area *	1076 V
Maximum step voltage outside fence	726.5 V
Maximum step voltage inside fence yard	265 V
Applicable area for gravel spreading beyond perimeter conductor in order to protect human from step voltage	9 m from perimeter conductor (16 m from fence)
* Maximum touch voltage computed in area up to a distance of 1 m beyond fence line	

Here, the maximum touch voltage is reduced to 1076 V and the maximum step voltage is drastically reduced to 726.5 V from 2602 V. Yet the maximum touch voltage is significantly higher than the permissible touch voltage.

In the case under discussion, the step voltage outside the fence yard, 726.5 V, where gravel may not be present exceeds the permissible value of 459.3 V, obtained with IEEE Std.80 formula. However, the standard refers to the test results indicating that 25 times as much current is required to produce the same current in the heart region, suggesting that step voltage must be several times higher than the IEEE standard 80 limit in order to produce ventricular fibrillation. Otherwise, with shock duration of 0.2 sec, the permissible step voltage without use of gravel is 727 V, which is a little larger than the maximum attainable calculated value. In view of the above reasons, gravel is not required outside the yard fence.

If shock duration of 0.2 sec for step voltage outside fence yard is not acceptable and also if strict compliance to the IEEE standard 80 is required then gravel is required to be spread to a distance of 15 m from fence line. However, gravel thickness may be reduced or gravel of lower resistivity can be used.

11.5.3 Concrete / Bentonite / Low Resistivity Backfill Encased Conductors along with Gradient Control Ring

In order to reduce touch voltage, soil around the conductor is modified as shown in Fig. 11.26.

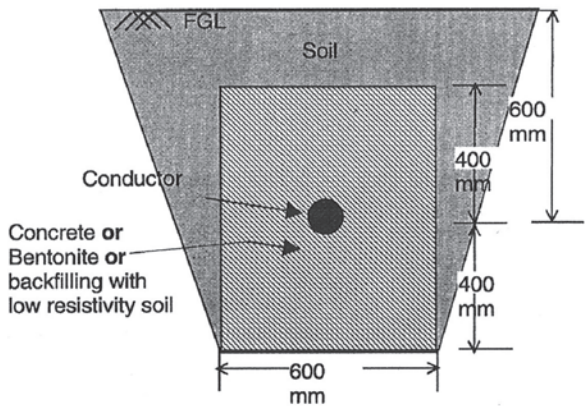


Fig. 11.26 : Use of resistivity enhancement material around earth conductors

The soil around all horizontal conductors is modified either with concrete or with bentonite or with low resistivity soil (backfilling). For calculation purposes, resistivity of enhancement material surrounding the earth conductors is considered as 100 Ω-m.

The earth conductors are modelled in software with cuboids of resistivity material of 100 Ω-m around all horizontal conductors. The grid configuration is shown in Fig. 11.27 and calculated results are given in Table 11.11.

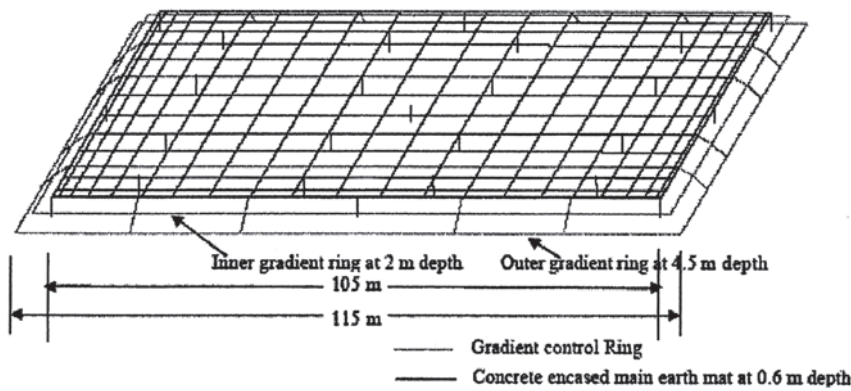


Fig. 11.27 : Configuration of non-uniform spaced grid with resistivity enhancement material around earth mat conductors

Table 11.11 : Results of calculations for 16 × 22 grid with lower resistivity material around horizontal conductors

Parameter	Non-uniformly spaced grid (115 m × 85 m) with 16 × 22 conductors
Earth resistance	1.2676 Ω
Maximum touch voltage inside safety area *	672 V
Maximum step voltage outside fence	833 V
Maximum step voltage inside fence	291 V
Applicable area for gravel spreading beyond perimeter conductor in order to protect human from step voltage	10 m from perimeter conductor (17 m from fence)
* Maximum touch voltage computed in area up to a distance of 1 m beyond fence line	

It can be seen that the earth resistance value remains unchanged even if the soil around conductor is modified. However, the maximum touch voltage is reduced significantly. The maximum step voltage is increased marginally.

11.5.4 Deep Driven Vertical Earth Electrodes along with Gradient Control Ring

Deep driven vertical rod electrodes or drilled ground wells can be used to reduce earth resistance. The effect of vertical rod electrodes has been analyzed by using 24 vertical ground rods, each 24 m long, and of 200 mm diameter, within the (16 x 22) grid as shown in Fig. 11.28. Calculated results are shown in Table 11.12.

It can be seen that the earth resistance value is reduced marginally. There cannot be much reduction in magnitude of earth resistance because, soil being homogeneous, resistivity is uniform throughout its depth. In fact, vertical ground rods are very effective for reducing earth resistance when they are used in two-layer soil and penetrate the bottom layer of low resistivity.

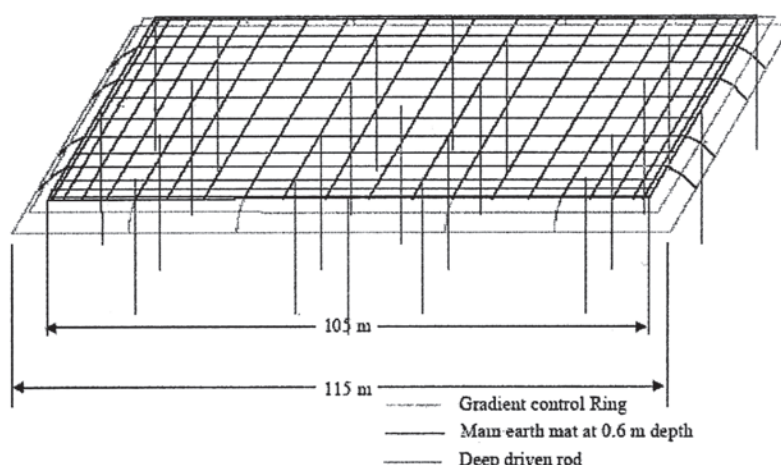


Fig. 11.28 : Non-uniform spaced grid with gradient control ring and 24 no deep driven vertical rods

Table 11.12 : Results of calculations for 16 x 22 grid with deep driven vertical ground rods

Parameter	Non-uniformly spaced grid(115 m × 85 m) with 16 × 22 conductors and 24vertical rod electrodes
Earth resistance	1.175 Ω
Maximum touch voltage inside safety area *	629 V
Maximum step voltage	599 V
Maximum step voltage inside fence yard	147 V
Applicable area for gravel spreading beyond perimeter conductor in order to protect humans from step voltage	6.5 m from perimeter conductor (13.5 m from fence)
* Maximum touch voltage computed in area up to a distance of 1 m beyond fence line	

11.5.5 Counterpoise Mat along with Gradient Control Ring

Concept of counterpoise mat is presented in Chapter 6. Counterpoise mat of size (95.9 m x 70.1 m) fabricated with 15 mm diameter MS conductor is installed at shallow depth of 0.3 m as shown in Fig. 11.29.

With the counterpoise mat connected to the main earth grid electrode that is buried at 0.6 m depth, the calculated results are shown in Table 11.13. It is seen that the touch voltage is drastically reduced to 447 V.

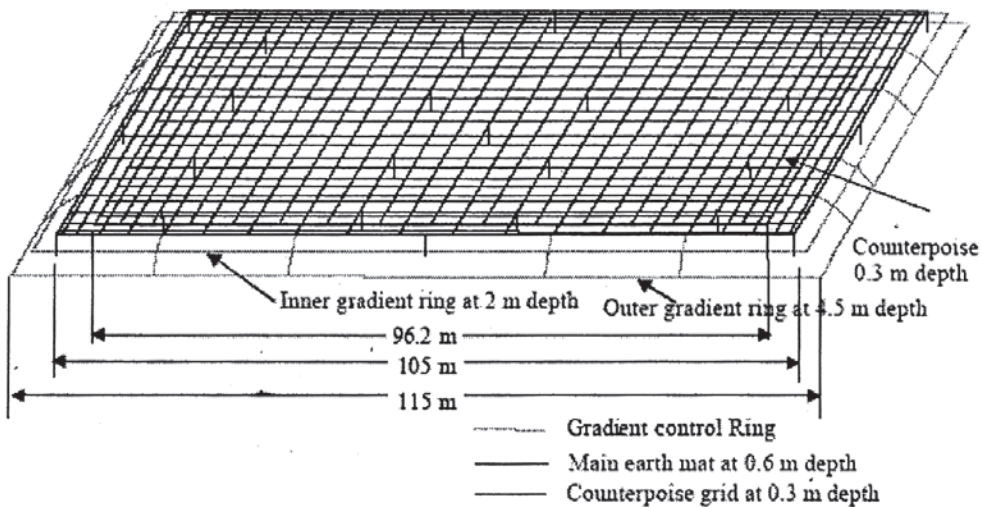


Fig. 11.29 : Configuration of conductors of counterpoise mat and main earth grid with potential control conductors outside the fence

Table 11.13 : Results of calculations for 16 x 22 grid together with counterpoise mat

Parameter	Non-uniformly spaced grid (115 m × 85 m) with 16 × 22 conductors and counterpoise mat
Earth resistance	1.271 Ω
Maximum touch voltage inside safety area *	447 V
Maximum step voltage outside fence	719V
Maximum step voltage inside fence yard	203 V
Applicable area for gravel spreading beyond perimeter conductor in order to protect humans against step voltage	8.5 m from perimeter conductor (15.5 m from fence)
* Maximum touch voltage computed in area up to a distance of 1 m beyond fence line	

11.5.6 Counterpoise Mat along with Concrete Encased Main Mat and Gradient Control Ring

Configuration of the grid together with the counterpoise mat is shown in Fig. 11.30.

With the counterpoise mat connected to the main earth grid and conductors of main earth grid encased in a concrete block, the calculated results are shown in Table 11.14. It is seen that the touch voltage is drastically reduced to 297 V.

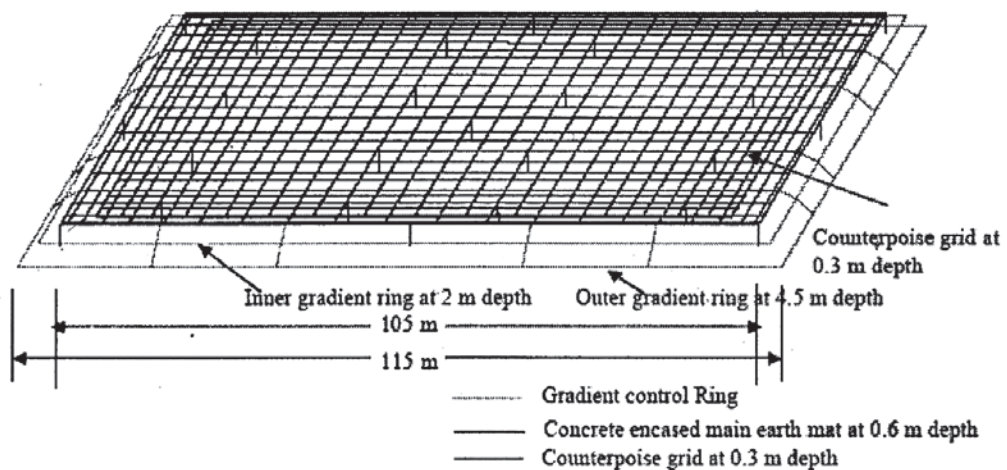


Fig. 11.30 : Configuration of conductors of counterpoise mat and concrete encased main earth grid with potential control conductors outside the fence

Table 11.14 : Results of calculations for 16 × 22 concrete encased grid together with counterpoise mat

Parameter	Non-uniformly spaced concrete encased grid (115 m × 85 m) with 16 × 22 conductors and counterpoise mat
Earth resistance	1.265 Ω
Maximum touch voltage inside safety area *	297 V
Maximum step voltage outside fence	830 V
Maximum step voltage inside fence yard	191.6V
Applicable area for gravel spreading beyond perimeter conductor in order to protect humans against step voltage	8.5 m from perimeter conductor (15.5 m from fence)
* Maximum touch voltage computed in area up to a distance of 1 m beyond fence line	

11.5.7 Satellite Grid Electrode

Satellite earth grid is installed to divert significant portion of grid current from main grid. A satellite grid together with the main grid is shown in Fig. 11.31.

The following data pertains to the satellite grid:

Satellite earth grid area	= 50 m × 50 m
Number of conductors	= 6 × 6
Soil resistivity	= 30 Ω-m
Diameter of conductor	= 15 mm
Depth of grid	= 1.2m
Distance from main grid	= 500 m
Impedance of connection from main grid to satellite grid	= 1 ohm

The main earth grid is the same as in Fig. 11.24 i.e.

Main earth grid area	= 105 m × 75 m
Number of conductors	= 16 × 22

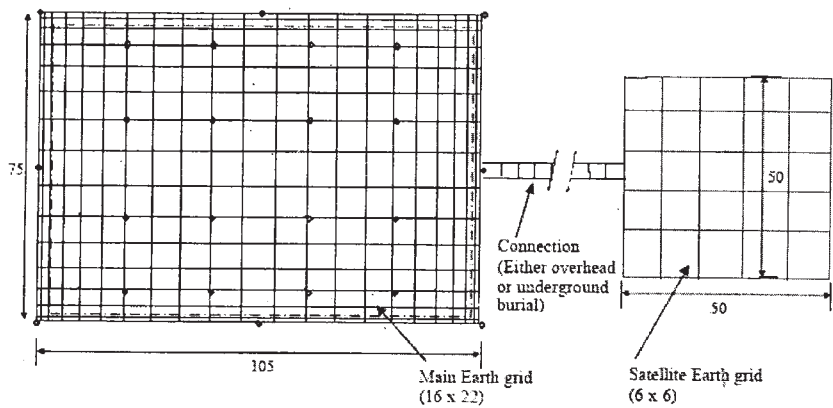


Fig. 11.31 Configuration of conductors of main earth grid with satellite earth grid

With the above data, earth resistance of satellite grid is 0.282 ohm. Earth resistance of the 105 m $\times$ 75 m main grid is 1.461 ohm as given in subsection 11.5, Table 11.8. Grid current division between the two grids depends on earth resistance of the two grids and impedance of the connection between them. Results obtained with software are shown in Table 11.15.

Table 11.15 : Results of calculations for 16 $\times$ 22 grid with satellite grid

Parameter	Non-uniformly spaced concrete encased grid (115 m $\times$ 85 m) with 16 $\times$ 22 conductors and counterpoise mat
Earth resistance	1.265 Ω
Maximum touch voltage inside safety area *	297 V
Maximum step voltage outside fence	830 V
Maximum step voltage inside fence yard	191.6V
Applicable area for gravel spreading beyond perimeter conductor in order to protect humans against step voltage	8.5 m from perimeter conductor (15.5 m from fence)
* Maximum touch voltage computed in area up to a distance of 1 m beyond fence line	

11.6 FENCE EARTHING

This section dealt with the fence earthing of substations. Several philosophies are in use with respect to the earthing of substation fence viz. (i) inclusion of fence within the earth grid area, and (ii) placement of fence outside the earth grid area with no electric bonding between fence and main station grid.

This section presents the five different cases of fence locations viz. -

- (i) Case A - Fence is placed 1.5 m inside the perimeter conductor of grid earth electrode (refer Fig. 11.32),
- (ii) Case B - Fence is placed on the top of perimeter conductor of grid earth electrode (Fig. 11.33),
- (iii) Case C - Fence is placed 5 m away from the perimeter conductor of grid earth electrode (Fig. 11.34),
- (iv) Case D - Fence is placed 3 m away from the perimeter conductor. Two separate conductors, one 2 m away and other at 0.5 m away from fence are placed outside the fence and connected to the fence at regular interval (Fig. 11.35),
- (v) Case E - Special case where main earthing system occupies only a small portion inside the fence area. Fence is placed 1.5 m inside the perimeter conductor (Fig. 11.36).

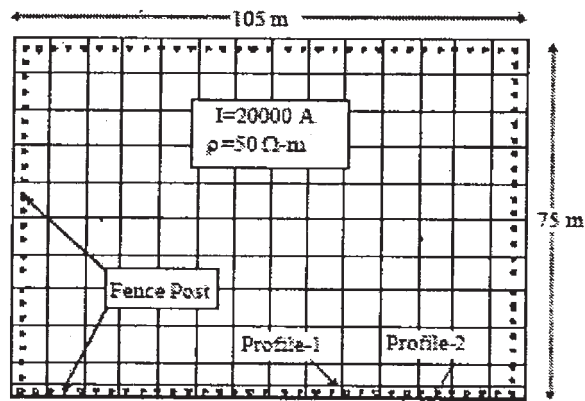


Fig. 11.32 : Fence is placed 1.5 m inside from the peripheral conductor. (Case A)

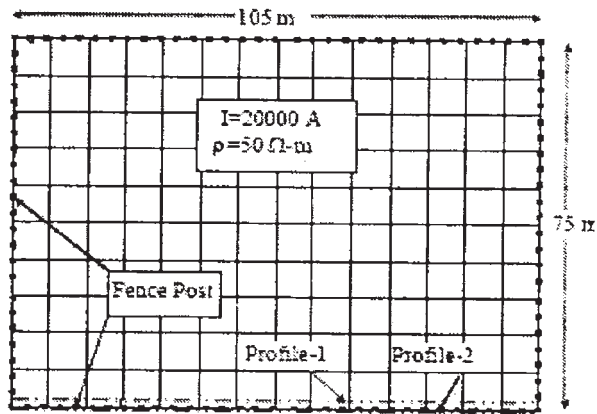


Fig. 11.33 : Fence is placed on the top peripheral conductor. (Case B)

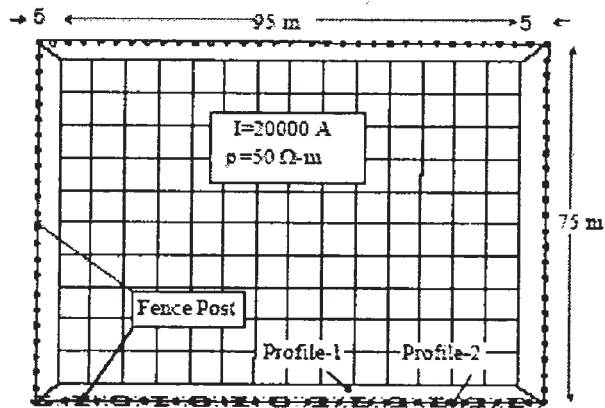


Fig. 11.34 : Fence is placed 5 m away from the peripheral conductor. (Case C)

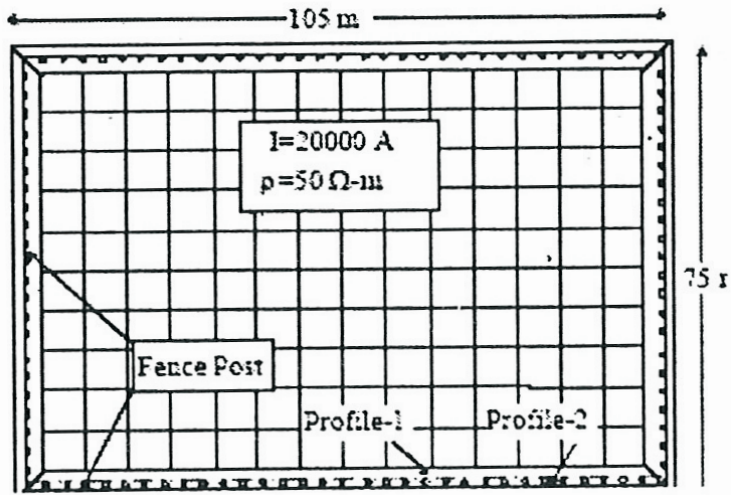


Fig. 11.35 : Fence is placed 3 m outside from the peripheral conductor. Two separate conductors, one at 2 m away and other at 0.5 m away from fence runs along the length of fence (Case D)

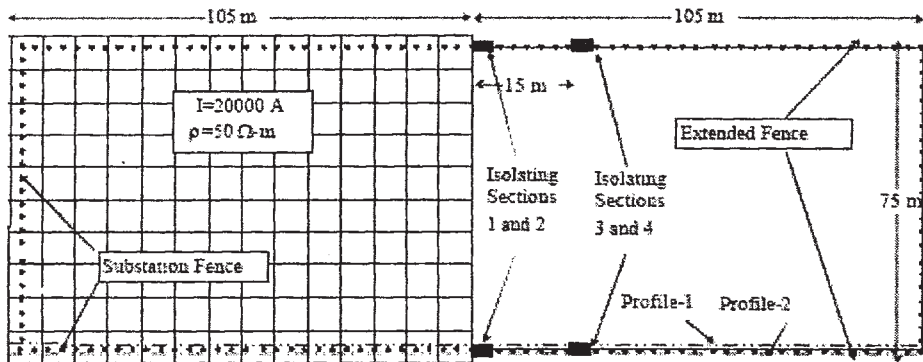


Fig. 11.36 : Fence is extended from the main mat and placed 1.5 m inside from the peripheral conductor (Case E)

All the above cases are studied with and without electric bonding between fence and substation earthing system. Design parameters for all cases are the same as in section 11.2.3. In all cases, each fence post is modeled as a 25 mm diameter vertical rod driven to a depth of 1 m. Distance between two fence posts is 3 m. If the fence is isolated from the main earthing system and earthed separately then one conductor of 25 mm diameter, not connected to the grid, but interconnecting a series of fence post at every 3 m distance is modelled.

Figures 11.32 to 11.36 display the earthing system arrangements for cases A to E respectively. Cases A to D have been analyzed for two scenarios

- (i) Fence connected to main earthing system,
- (ii) Fence isolated from main earthing system and earthed separately.

Case E has been analyzed for three scenarios

- (i) Fence connected to main earthing system
- (ii) Fence connected to main earthing system and part of fence is disconnected from the main earthing system by installing one pair of isolating sections (1-2) of 3 m each at the fence
- (iii) Fence connected to main earthing system and part of fence is disconnected from the main earthing system by installing two pairs of isolating sections (1-2 & 3-4) of 3 m each at the fence. Two pairs of isolating sections are at a distance of 15 m

To examine the fence contact potential in the substation area, the earth surface potentials are computed along the two profiles. These profiles consist of a number of observation points, which are spaced 0.125 m apart. Two profiles are chosen for all the cases. Profile 1 and 2 are located 1 m inside and outside the fence, respectively.

11.6.1 Case A: Fence 1.5 Inside Perimeter Conductor

Figure 11.37 shows the fence contact voltages along the profile-1 (inside the fence) and profile-2 (outside the fence). Although practically it is difficult to install the isolated fence in this case, the analysis of the same is done for academic purpose. Fence contact potential is the difference between the earth surface potential and fence EPR. Fence contact voltages, along profile-1 and profile-2 are higher in the case of connected fence. In the absence of crushed rock layer (gravel), fence contact potential outside the fence attains the maximum value of 578 V, which exceeds the safe touch threshold (166.6 V) by a significant margin. The maximum step potential of 403 V occurs outside the perimeter conductor, which exceeds safe step threshold (202 V). Complete gravelling inside the fence area and 3 m outside the fence line will ensure safe touch and step voltages. In the isolated fence case, fence contact voltage outside the fence attains the maximum value of 267 V, which also exceeds the safe touch threshold (166.6 V). In the isolated case, fence GPR/EPR (4486.3) is less than that of the main mat GPR/EPR (4985.5). This is simply because the fence tends to assume local soil potential when it is not connected to the grid. The reduction in fence contact potential in case of isolated fence is attributed to low value of fence GPR/EPR.

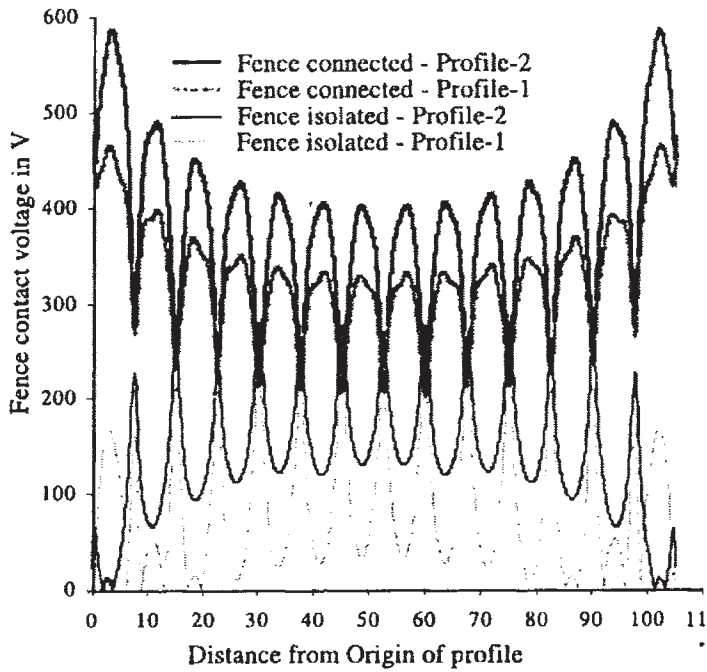


Fig. 11.37 Touch voltage along the fence: Fence is 1.5 m inside from the perimeter conductor (Case A)

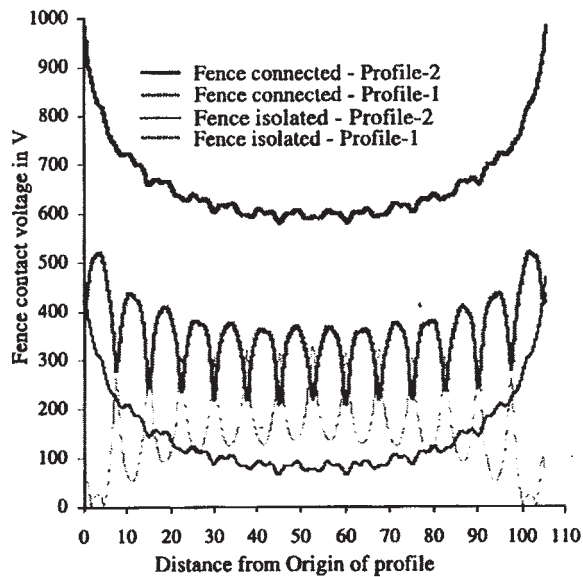


Fig. 11.38 Touch voltage along the fence: Fence is on the top of perimeter conductor (Case B)

11.6.2 Case B: Fence is on the Top of Perimeter Conductor

Figure 11.38 shows the fence contact voltages along the profile 1 and 2. Similar to case A, here the fence contact voltages are reduced significantly when fence is isolated. About 60 % length of fence is protected without use of crushed rock layer. However, the fence contact voltage along the profile-2 in case of connected fence increases to 938 V compared to 578 V of case A. This is because full GPR/EPR is transferred to the fence while earth surface potential near the fence along the profile-2 remains at a lower value in the absence of any conductor beyond the fence. Step potential will remain the same as case A.

In connected fence case, the laying of 0.1 m thick gravel of resistivity 3000 Ω -m will also not ensure safe fence contact voltage from outside the fence.

11.6.3 Case C: Fence 5 m Away from the Perimeter Conductor

The earth grid size in this case is considered as 95 m $\times$ 65 m. In case of disconnected fence, it is expected that fence contact voltages along profile 1 and 2 should be lower than case A and B. This is evident from Fig. 11.39. Large portion of fence (about 80 % of the length) is protected without use of crushed rock layer. However, the touch voltage of main mat inside the switchyard is increased because of reduction in the size of mat. The main mat EPR with isolated case is 5619.5 V, which is approximately 13 % higher than EPR of connected case (4987.2 V). However with the layer of crushed rock inside the fence area, touch and step voltages are less than the safety limit.

The maximum step voltage of 431 V occurs between the perimeter conductor and fence line. This requires the use of gravel only inside the fence area.

This arrangement suffers from the disadvantage that, if fence is inadvertently connected to the main earthing system, the fence-contact voltage outside the fence increases to 1002 V from 508 V

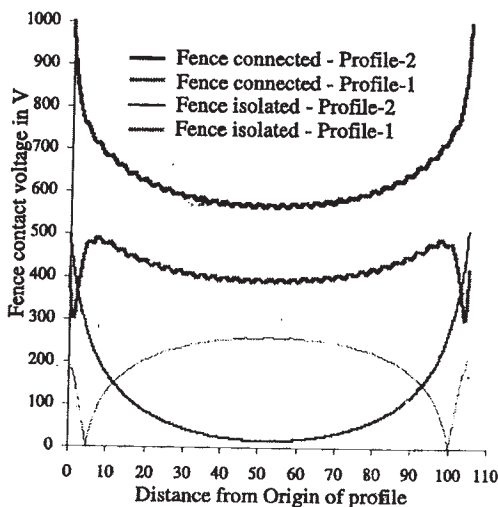


Fig. 11.39 Touch voltage along the fence: Fence is 5 m away from the perimeter

11.6.4 Case D: Fence 3 m Away from the Perimeter Conductor, Two Separate Conductors for Fence Earthing

This arrangement combines the advantages of case A and C and also accounts for the disadvantage of case C. In this case fence is kept 3 m away from the perimeter conductor. Two separate earth conductors, one 0.5 m and other 2 m outside the fence have been provided. The potential profiles are shown in Fig. 11.40.

For an isolated fence, the touch potential outside the fence is safe even without use of a crushed rock layer. However the touch potential inside the switchyard increases due to reduction in the size of earth grid.

The step voltage outside the fence is safe for this case and the touch voltages also fall within limits. This requires the use of gravel only inside the fence area. In any case if the fence is inadvertently connected to the main earthing system, the touch potential outside the fence is less than the touch voltage of case A but greater than the safe threshold value in the absence of gravel. For the inadvertent connection the step voltage is the same as case A and greater than the safe threshold value in the absence of gravel.

11.6.5 Case E: Fence Placed on the Top of Perimeter Conductor of Grid Earth Electrode and Fence Running Away from the Substation

Figures 11.41 and 11.42 show the fence contact voltages for three cases: (1) no isolating section connected (2) one isolating section pair (1-2) as shown in Fig. 11.36 is connected (3) both isolating section pairs (1-2 and 3-4) as shown in Fig. 11.36 are connected. Note that the portion of the fence to the left of isolating section pair (1-2) is always connected to the earth grid while the portion of the fence to the right of isolating section pair (1-2) is disconnected from the grid when isolating sections are installed.

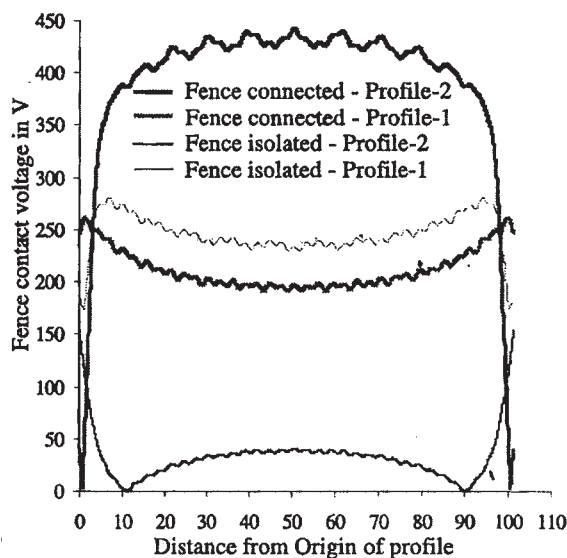


Fig. 11.40 Touch voltage along the fence : Fence is 5 m away from the perimeter

It can be seen from Fig. 11.41 that without any isolating section, the fence contact voltages are very high towards the right of the main substation area. The reason is high potential transfer to this portion of the fence resulting in increased values of fence contact voltages at these locations. Although connecting the fence to the earthing grid leads to a small reduction in the fence contact voltages in the region where the fence is closer to the earthing grid, the major concern is that it significantly increases the touch voltages to the remote portion of the fence (about 900 V) if no isolating section is provided. When the isolating section pair (1-2) is installed, the fence contact voltage at these locations decreases considerably, except near areas close to the isolating sections. To reduce the high touch voltages at these locations (i.e. near isolating section pair 1-2), isolating section pair (3-4) is installed. As shown in Fig. 11.42, the touch voltages are lower now at all locations. By using two pairs of isolating sections, touch voltages have been reduced below 600 V everywhere.

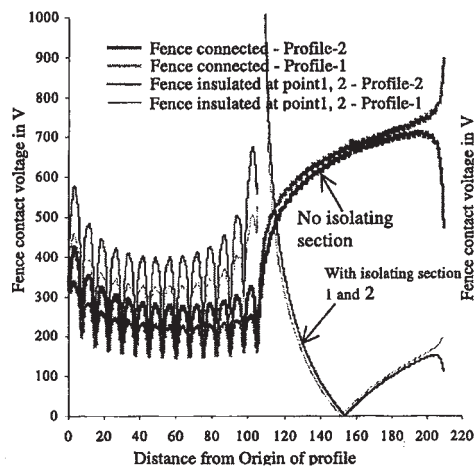


Fig. 11.41 Touch voltage along the fence: Fence is 1.5 m inside from the perimeter conductor. Fence extending far beyond grid area.(case E)

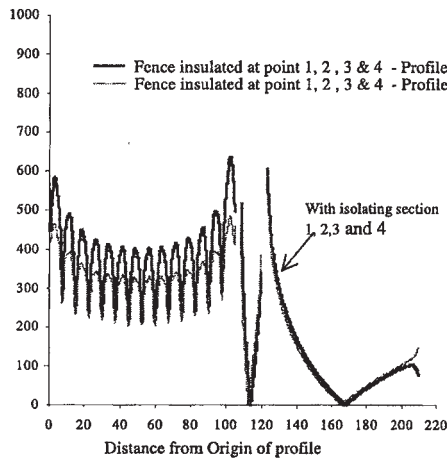


Fig. 11.42 Touch voltage along the fence: Fence is 1.5 m inside from the perimeter conductor. Fence extending far beyond grid area.(case E)

Disconnecting the remote portion of the fence from the earthing grid also improves the step potential outside the substation area.

11.7 EXAMPLE - INTERPRETATION OF SOIL RESISTIVITY MEASUREMENTS AND CHOICE OF SOIL MODEL & ITS IMPACT ON DESIGN

In this Section results of interpretation of the soil resistivity measurements at the site of the switchyard of a 400/220 kV substation are presented. A two-layer soil model is recommended. The magnitudes of dangerous voltages that shall be obtained if a uniform soil model was assumed are compared with those for two-layer soil model.

11.7.1 Soil Resistivity Data

Results of measurements made for determining soil resistivity at the site of a 400/220 kV substation are analyzed in this case study. The measurements for soil resistivity have been made at 4 locations namely, A-1, A-2, A-3, and A-4. At each location, measurements have been made in four radials directions. The radials at each location are denoted as N-S, E-W, NE-WS, and ES-NW.

Table 11.16 : Apparent measured soil resistivity at location A-1

Sl. No.	Elec-trode spacing (m)	Measured resistance along radials (Ohm)				Apparent soil resistivity (Ω -m)				
		N-S	E-W	NE-WS	ES-NW	N-S	E-W	NE-WS	ES-NW	Average
1	1.0	6.05	5.76	5.95	4.99	39.34	37.46	38.69	32.45	36.99
2	5.0	1.72	1.35	1.52	1.42	54.11	42.47	47.82	44.68	47.27
3	10.0	1.11	1.05	1.00	1.21	69.78	66.00	62.86	76.06	68.68
4	15.0	0.90	0.88	0.95	1.00	84.86	82.97	89.57	94.29	97.92
5	20.0	0.87	0.90	0.82	0.96	109.34	113.11	103.06	120.65	111.54
6	25.0	0.81	0.73	0.86	0.87	127.29	114.72	135.15	136.72	128.47

Table 11.17 : Apparent measured soil resistivity at location A-2

Sl. No.	Elec-trode spacing (m)	Measured resistance along radials (Ohm)				Apparent soil resistivity (Ω -m)				
		N-S	E-W	NE-WS	ES-NW	N-S	E-W	NE-WS	ES-NW	Average
1	1.0	6.08	7.42	6.95	6.47	39.54	48.25	45.19	42.07	43.76
2	5.0	1.32	1.28	1.22	1.29	41.53	40.27	38.38	40.59	40.19
3	10.0	1.12	1.08	1.14	1.05	70.40	67.89	71.66	66.00	68.99
4	15.0	0.98	0.97	0.93	0.95	92.40	91.46	87.69	89.57	90.28
5	20.0	0.89	0.85	0.92	0.88	111.86	106.83	115.63	110.60	111.23
6	25.0	0.78	0.79	0.82	0.85	122.58	124.15	128.86	133.58	127.29

Table 11.18 : Apparent measured soil resistivity at location A-3

Sl. No.	Electrode spacing (m)	Measured resistance along radials (Ohm)				Apparent soil resistivity (Ω -m)				
		N-S	E-W	NE-WS	ES-NW	N-S	E-W	NE-WS	ES-NW	Average
1	1.0	5.60	4.99	5.25	5.00	36.41	32.45	34.14	32.51	33.88
2	5.0	1.26	1.19	1.10	1.36	39.64	37.44	34.61	42.79	38.62
3	10.0	0.95	1.00	0.96	1.03	59.72	62.86	60.35	64.75	61.92
4	15.0	0.93	0.92	0.85	0.96	87.69	86.74	80.14	90.51	86.27
5	20.0	0.87	0.95	0.82	0.88	109.34	119.40	103.06	110.60	110.60
6	25.0	0.90	0.87	0.80	0.79	141.44	136.72	125.72	124.15	132.00

Table 11.19 : Apparent measured soil resistivity at location A-4

Sl. No.	Electrode spacing (m)	Measured resistance along radials (Ohm)				Apparent soil resistivity (Ω -m)				
		N-S	E-W	NE-WS	ES-NW	N-S	E-W	NE-WS	ES-NW	Average
1	1.0	4.83	4.31	4.77	3.92	31.41	28.03	31.02	25.49	28.99
2	5.0	1.15	1.29	1.09	1.17	36.18	40.59	34.29	36.81	36.97
3	10.0	0.99	1.05	0.96	0.99	62.23	66.00	60.35	62.23	62.70
4	15.0	0.92	0.90	0.90	0.98	86.74	84.86	84.86	92.40	87.22
5	20.0	0.86	0.81	0.84	0.91	108.09	101.80	105.57	114.37	107.46
6	25.0	0.82	0.78	0.82	0.90	128.86	122.58	128.86	141.44	130.44

Along each of the sixteen radials, six observations have been taken for electrode spacings of 1 m, 5 m, 10 m; 15 m, 20m, and 25 m. The depth of electrode is 250 mm. The observed values of measured resistance and the computed apparent soil resistivity values are given in Tables 11.16 to 11.19.

11.7.2 Average Apparent Measured Resistivity

In each of the Tables 11.16 to 11.19, the average of the values along the four radials at the site has also been given in the last column. The average values of apparent soil resistivity for the six values of electrode spacing for the whole station site are given in Table 11.20. The graph of the average values of apparent soil resistivity versus electrode spacing is given in Figure 11.43. The graphs of average soil resistivity from Tables 11.16 to 11.19 are shown by dotted lines; that of values from Table 11.20 is shown with a solid line.

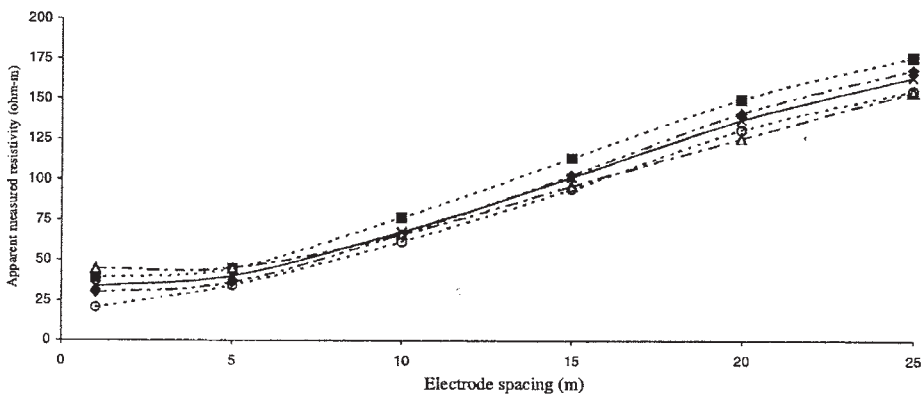
Table 11.20 : Average apparent measured resistivity for the station site

Sl. No.	Spacing (m)	Average apparent measured soil resistivity for the station site ($\Omega\text{-m}$)
1	1.0	35.90
2	5.0	40.76
3	10.0	65.57
4	15.0	87.92
5	20.0	110.21
6	25.0	129.55

11.7.3 Interpretation of the Measured Data

From perusal of the data in Tables 11.16 to 11.20 and Fig. 11.43, the following observations are made:

- Values of average apparent measured resistivity at all locations show a similar trend in all tables except in Table 11.17. The magnitude of soil resistivity increases as the electrode spacing is increased.
- In Table 11.17, there is a small decrease of resistivity for the electrode spacing of 5 m and then it increases for the rest of electrode spacings.
- The average of minimum measured resistivities at different locations for the electrode spacing of 1 m varies between 28.99 Ωm and 43.76 Ωm .
- The average of maximum measured resistivities at different locations for the largest electrode spacing of 25 m is approximately 130 Ωm .
- The average of all apparent measured resistivity values is 78.3187 Ωm . The percent difference between the maximum and the minimum measured resistivities in Table 11.20 and the average value is +65.4% and -54.2%, respectively. Since this spread is quite large, a two-layer soil model may be used to represent the resistivity variation at the site of substation as observed in the measurements [2].

**Fig. 11.43** Average apparent measured resistivity versus electrode spacing for substation

- (vi) The chosen model is to be applicable to the whole of station site. It is possible to obtain a soil model for the whole station site by using average values of measured apparent soil resistivity given in Table 11.20. For any given electrode spacing ‘a’ m, the apparent measured resistivity is average of soil resistivity up to a depth of ‘a’ m. The variation in apparent measured resistivity thus translates into variation of type of soil with depth below earth surface. The soil resistivity near the earth surface is comparatively low and increases as depth below earth surface increases.

11.7.4 Computer program SPEI [3] developed at Punjab Engineering College, Chandigarh, for determining such a model is used to obtain parameters of the best-fit two-layer soil. The two-layer soil model obtained from the average values of measured apparent soil resistivity given in Table 11.20 with SPEI is given in Table 11.21. A plot of the values of average measured apparent resistivity and that of the values of apparent resistivity generated from the above soil model as a function of electrode spacing are shown in Fig. 11.44.

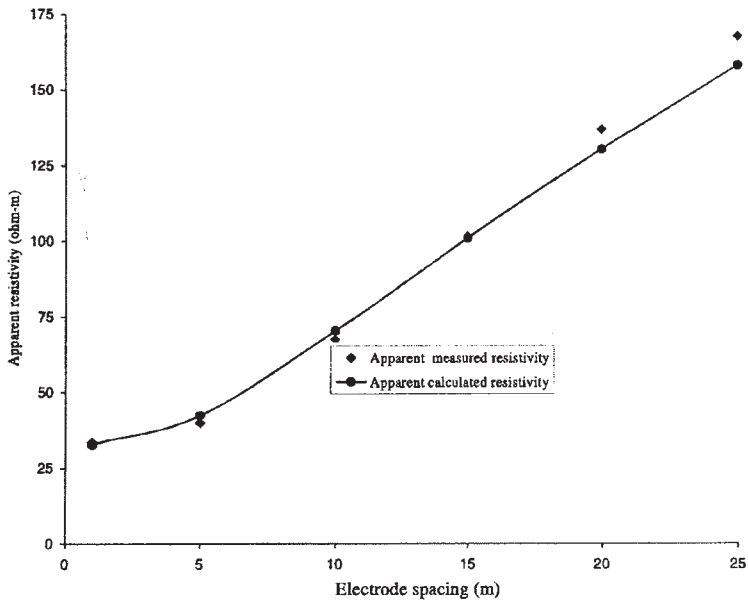


Fig. 11.44 Comparison of measured apparent resistivity and that calculated from two layer model

Table 11.21 : Two-layer soil model based on average measured resistivities

Resistivity of upper layer $\rho_1 = 35.18 \, \Omega\text{m}$
Resistivity of lower layer $\rho_2 = 418.86 \, \Omega\text{m}$
Depth of the upper layer $h = 6.82 \, \text{m}$

11.7.5 Recommendations

For designing the earthing system of the 400/220 kV substation, the soil can be represented by an equivalent two layer soil model. The parameters of the two-layer soil model are:

Resistivity of upper layer = 35.2 Ω -m

Resistivity of lower layer = 418.9 Ω -m

Depth of the upper layer = 6.82 metre

11.7.6 Comparison of Design with Different Soil Models

An earthing system was designed for the 400/220 kV substation with the two-layer soil model. For the earthing system configuration so obtained, the three parameters of earth resistance, step voltage and touch voltage were calculated corresponding to three different uniform-resistivity single layer soil models. The selected single layer soil models are (i) soil of resistivity 35.2 Ω -m, which is the top layer resistivity of two-layer soil model; (ii) soil of resistivity 418.9 Ω -m, which is the resistivity of bottom layer of two-layer soil model; and (iii) soil of resistivity 129.55 Ω -m, which is the largest average apparent measured soil resistivity in Table 11.20. The results for the four soil modes are given in Table 11.22.

Table 11.22 : Comparison of calculated values of R_G , E_S , and E_m for four soil models

Earthing system parameters	Two-layer soil model $\rho_1 = 35.2 \Omega\text{m}$, $\rho_2 = 418.9 \Omega\text{m}$, $h = 6.82 \text{ m}$	Single-layer soil model $\rho = 35.2 \Omega\text{m}$	Single-layer soil model $\rho = 418.9 \Omega\text{m}$	Single-layer soil model $\rho = 129.55 \Omega\text{m}$
Earth resistance	0.3992 Ω	0.0521 Ω	0.6201 Ω	0.1918 Ω
Step voltage	269.65 V	90.1 V	1072.7V	331.8 V
Touch voltage	455.96 V	157.27 V	1872.27 V	579.08 V

It is seen from the table that the values obtained for the two-layer model are not matched by any of the single layer soil models. If the largest average apparent measured resistivity is used the step and touch voltages are 23% and 27%, respectively, more than the values obtained with two layer model; however the difference in magnitude of earth resistance value is much larger.

11.8 SUMMARY

In this Chapter examples illustrating different aspects of design of earth grid electrode for a station are given. The examples include the following:

- Calculation of earth fault current and grid current
- Design of grid electrode with empirical formulas
- Design of grid electrode with software
- Effect of non-equispaced grid conductors

- (v) Analysis of grid in two-layer soil
- (vi) Effect of measures to improve performance of grid in high resistivity soil
- (vii) Analysis of various options in fence earthing
- (viii) Interpretation of soil resistivity measurements and choice of soil model

REFERENCES

- [1] Dawalibi, F., and Mukhedkar, D., "Optimum design of substation grounding in two-layer earth structure; Part I—Analytical study, Part II—Comparison between theoretical and experimental results, and Part HI—Study of grounding grids performance and new electrodes configuration," IEEE Transactions on Power Apparatus and Systems, vol. PAS-94, no. 2, pp. 252-261, 262-266, 267-272, Mar./Apr. 1975.
- [2] Meliopoulos, A.P. and Papalexopoulos, A.D. 'Interpretation of Soil Resistivity Measurements: Experience with Model SOMIP,' IEEE Transactions on Power Delivery, Oct. 1986, pp. 142-151.
- [3] Hans R. Seedher and Arora, J.K. 'Estimation of Two Layer Soil Parameters Using Finite Wenner Resistivity Expression', IEEE Trans, on Power Delivery, Oct. 1992, pp. 1213-1217.

CHAPTER - 12

Earthing of GIS Substations

***Synopsis** Gas insulated substation is subject to the earth fault current that is similar in magnitude as at other substations. There are certain conditions that are typically obtained at a GIS. In this chapter such conditions and their effect on earthing installation at a GIS are described. A major source of material is IEEE-Standard 80 -2000. [1]*

12.1 INTRODUCTION

GIS is acronym for Gas Insulated Substation and is also used for Gas Insulated Switchgear. The earthing system at a GIS is required to fulfill the conditions that are described in Section 1.1 of this manual. Besides these another condition that can arise is that of very high frequency transients. These transients are caused by electrical breakdown in the insulating gas across the contacts of a switching device or in course of a fault. The transients can couple onto the earthing system and may have to be considered in its design. These transients may cause high magnitude, short duration earth potential rises and electromagnetic interference. EMI mitigation techniques can require special considerations in earthing design.

12.1.1 Definitions

(i) ***Gas Insulated Substation (GIS)***

A gas insulated substation is a compact, multicomponent assembly, enclosed in an earthed metallic housing in which the primary insulating medium is a compressed gas, and which normally consists of switchgear, and associated equipment.

(ii) ***Continuous Enclosure***

A bus enclosure in which the consecutive sections of the housing along same phase conductor are bonded together to provide an electrically continuous current path throughout the entire enclosure length. Cross-bondings, connecting the other phase enclosures, are made only at the extremities of the installation and at a few selected intermediate points.

(iii) ***Enclosure Currents***

Currents that result from the voltages induced in the metallic enclosure by the current(s) flowing in the enclosed conductor(s).

(iv) ***Main Ground Bus***

A conductor or system of conductors provided for connecting all designated metallic components of GIS to a substation earthing system.

(v) ***Transient Enclosure Voltage (TEV)***

These are very fast transient phenomena, which are found on the earthed enclosure of GIS systems. Typically, earthing leads are too long at the frequencies of interest to effectively

prevent the occurrence of TEV. The phenomenon is also known as transient ground rise (TGR) or transient ground potential rise (TGPR).

(vi) ***Very Fast Transients (VFT)***

It is a class of transients generated internally within GIS characterized by short duration and very high frequency. VFT is generated by the rapid collapse of voltage during breakdown of the insulating gas, either across the contacts of a switching device or line-to-earth during a fault. These transients can have rise times of nanoseconds implying a frequency content extending to about 100 MHz. However, dominant oscillation frequencies, which are related to physical length of GIS bus, are usually in the 20 – 40 MHz range.

(vii) ***Very Fast Transient Overvoltage (VFTO)***

These are system overvoltages that result from generation of VFT. While VFT is one of the main constituents of VFTO, some lower frequency (≈ 1 MHz) component may be present as a result of the discharge of lumped capacitance (voltage transformers). Typically, VFTO will not exceed 2.0 per unit, though higher magnitudes are possible in specific instances.

12.2 STANDARD AND CBIP PUBLICATIONS

Information about GIS earthing may be obtained from the following publications:

- ANSI/IEEE Standard 80-2000, IEEE Guide for Safety in AC Substation Grounding, IEEE, New York, 2000.
- CIGRE 44, Earthing of GIS – An Application Guide prepared by CIGRE Working Group 23.10.
- IEC 517 – Gas Insulated Metal Enclosed Switchgear for Rated Voltages 72.5 kV and above.

12.3 EARTHING REQUIREMENTS OF GIS

While the physical characteristics of the GIS will have a profound effect on a number of aspects of its earthing design, the basic requirements of an earthing system for a GIS installation are not different from those for an air-insulated substation (AIS), i.e., safety of the operating staff against any hazard and protection of equipment against electromagnetic interference and damage.

The area occupied by a GIS is typically 10-25% of that of an equivalent air-insulated station (AIS). Therefore, achieving the required EPR or the earth resistance of grid earth electrode is a more challenging task. Also the items of equipment are closer together; this may necessitate more closely spaced earth conductors. A view of GIS equipment is shown in Figure 12.1.

12.3.1 Earthing Design Principles

Design principles of earth electrode for GIS are same as those for an AIS described in this manual. The principal parameters of design namely, (i) complete layout of station and equipment, (ii) soil



Fig. 12.1: A view of equipment of a GIS

resistivity in and around the area of the station, (iii) line to earth short circuit fault current, (iv) shape and material of earth conductor, (v) grid current, (vi) fault duration and shock duration must be determined / specified.

The earthing system of the substation buildings, especially of buildings with gas insulated switchgear must be capable of carrying power frequency short circuit currents (earth fault currents) and high frequency currents from switching and lightning. The requirements from the high frequency currents determine the layout of the earthing system, which can be characterized as a meshed network (or a cage shaped network) in order to give low impedance across it. Some special conductors of this cage are rated to fulfill the power frequency requirements.

Size of earth conductors is calculated as described in Section 3.8. When preparing a layout of earth conductors, the outermost conductor should enclose the maximum possible area of the station. In case of indoor station, the earth conductors are welded together and embedded in the concrete of the lowest floor. The earth conductors are wrapped to the reinforcement mats and have risers to the indoor earthing system. If a continuous reinforced concrete floor slab is being used, then connecting the reinforcement steel mesh and structural steel to earth grid is a good option; both the GIS enclosures and the structural steel will be approximately at the same potential. Closer spacing of reinforcement steel will result in an even potential on floor of the GIS hall. In case use of reinforcing steel is considered desirable as earth conductors, they should preferably be welded.

When sufficient area in transverse directions is not available, deep driven earth rod electrode may be suitable placed in the grid earth electrode area. The rods may be placed in mixture of bentonite and coke breeze and sulphate salts as illustrated in Section 8.3 to obtain suitable value of earth resistance.

In GIS, concrete foundations may cause irregularities in current discharge path. In this respect, a simple monolithic concrete steel reinforced slab is advantageous, both as auxiliary grounding device and for seismic reasons.

Touch & Step voltages have to be considered mainly in outdoor substations. GIS buildings have an elaborate meshed earthing system, which comprises all metal parts like foundation reinforcement steel, earth mats, earth conductors and the GIS housing. In case of a power frequency earth fault the total of this earthing system assumes an earth potential rise with respect to the distant references earth. However the voltage differences between the metal parts of the building are very small. Dangerous touch or step voltages do not exist.

An earth bus may be provided on each side of the GIS equipment for direct and short earthing connection. A main earthing conductor that is connected to grid earth electrode at several places may be run along the walls of the GIS hall for earthing of various components that can carry the fault current. Typical earthing arrangement of a GIS is shown in Figure 12.2.

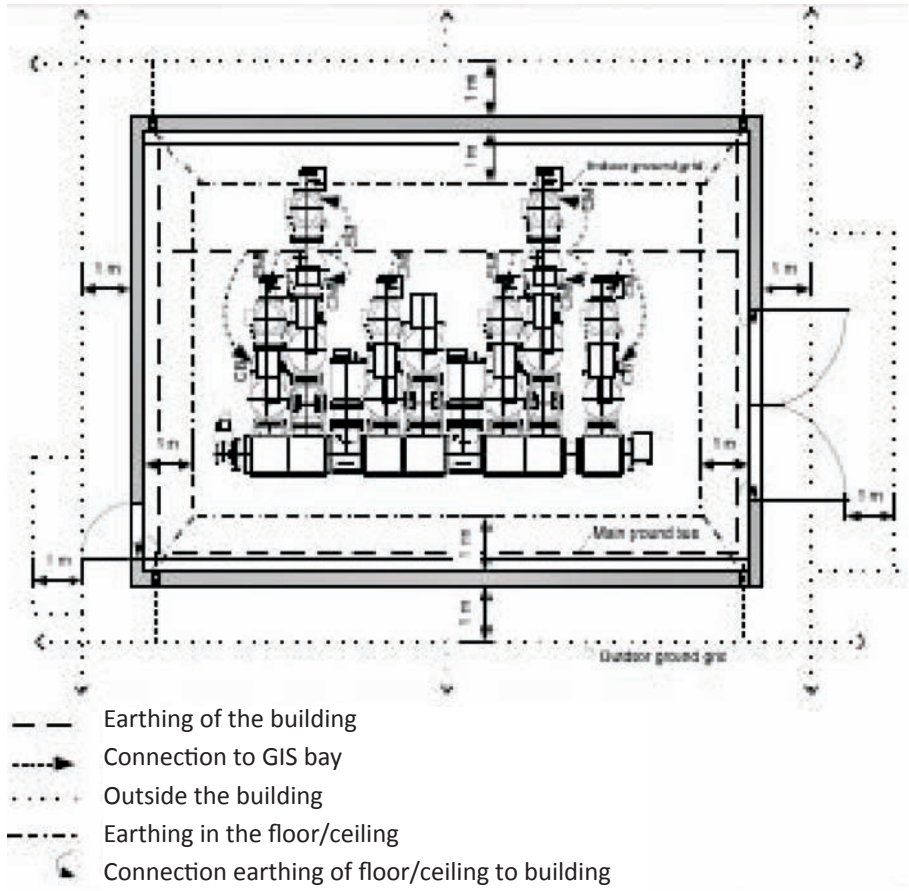


Fig. 12.2: Typical Earthing Arrangement of GIS

12.3.2 Transient Enclosure Voltage

Transient enclosure voltage is caused not by power frequency currents but by high frequency current. TEV can occur due to lightning strokes, operation of lightning arrestors, Phase to earth faults and discharges between contacts during switching due to breakdown of insulating gas, mainly disconnect operations. TEV is set up by the currents fed into the earthing system and the capacitance of GIS installation and can have rise times as low as 3 – 20 nanoseconds, but are only sustained for 20 – 30 milliseconds at the most. The high frequency currents cause local transient potential rise because of the relatively high reactance of the earth connections, e.g. 1 metre length of straight conductor can have reactance of 60 ohms at 10 MHz whereas it would be approximately 0.0003 ohms at 50 Hz. Thus the earth connections must be as short and direct as possible; bends in earthing conductors can cause high reactance at high frequencies.

12.3.3 Earthing of Enclosures and Circulating Currents

In GIS each phase has a separate enclosure; current flowing in phase conductor produces a magnetic flux around it. A voltage is induced in the enclosure by this flux. When the enclosure is continuous, a longitudinal current flows in the enclosure. The magnitude of current depends on the size of the enclosure and the phase spacing between the buses. In case continuity of all phase enclosures is maintained with short connections at both ends, the enclosure current is only slightly less than that flowing in the enclosed bus conductor but opposite in direction. Return path of the current is through the enclosures of adjacent phases when the load is equalized between phases; also the flux is mainly constrained in the enclosures. If there is strong external magnetic field, it can create problems like local overheating of structures around GIS, electromagnetic vibrations, increased induction in control cables etc. Excessive currents should not be induced in adjacent frames, structures or reinforcing steel, and current loops via other station equipments should be avoided.

In continuous type enclosures that are normally used, induced current and phase conductor current form a concentric pair. When currents in phases are symmetric, there is effective shielding of flux which is confined inside the enclosures. Under unsymmetrical faults, the dc component is not shielded and causes an external voltage drop due to enclosure resistance. Local overheating of structures around GI equipment, electromagnetic vibration induced voltages in control cables are other possible effects. Frequent bonding and earthing of GIS enclosure is advised to minimize the hazardous touch and step voltages within the GIS area. Provision of earth mats that are connected to GIS enclosures and earthed are an additional safety measure. All metallic enclosures of switchgear assembly should be earthed properly through the base frame of the switchgear so as to ensure the minimum flow of circulating currents.

When earthed at designated points, bus enclosure design should ensure that there is proper bonding between them so that significant voltage difference does not exist between individual enclosure sections and that neither the supporting structures nor any part of earthing system is adversely affected by flow of induced currents. Further power cable earth shields should be joined to the earthing system separately from GIS enclosures. Wherever there are discontinuities in enclosures / changes in the medium e.g. at cable terminations or transformer connections, special care should be taken to limit very fast transient over voltages and to prevent circulating currents in circuit

breakers and transformer tanks. Design of cable terminations should be such that an isolating air gap or proper insulation is provided. Enclosure current return currents cannot be permitted to flow through any mounted current transformers.

The owner should give details of earthing system envisaged by him for integration with special earthing requirements of the manufacturer, if any.

12.4 IMPLEMENTATION

12.4.1 It is the GIS equipment manufacturer who usually designs and gives specifications of the main earth bus of the GIS and also how the user is to connect the GIS assembly to the station earth. The manufacturer is also responsible for the following:

- (a) The subassembly to subassembly bonding to assure safe voltage gradients between all intentionally earthed parts of GIS assembly and the main earth bus.
- (b) Provision of readily accessible pads or connectors, capable of carrying the anticipated maximum fault current, and of sufficient mechanical strength to withstand electromagnetic forces and normal abuse
- (c) Provide connectors allowing at least for two paths to earth from the main earth bus, or from each metallic enclosure and auxiliary piece of GIS equipment designated for a connection to the substation earth if the main earth bus of the GIS assembly does not actually exist

12.4.2 Some further considerations are:

- (a) All cables should be shielded and earthed.
- (b) Cables with separate function should be routed in separate cable trenches.
- (c) An earthing conductor to be laid parallel to the control cable trenches.
- (d) Star point of CT & PT is to be formed at only one point only. This will avoid galvanic coupling of current from earthing network to the control cable core.
- (e) Metallic trays are to be used over enclosures.
- (f) Cable should form a radial network. Mesh network should be avoided.
- (g) Owing to the distance between ends of control cables which have comparatively large impedance to high frequencies, high potential difference can occur between cable ends. To alleviate this problem the control cables should be led away from the enclosures from the entry point. Further cables should be placed in conduits or totally enclosed metal trays.
- (h) If there is ultra-sensitive equipment, it should be enclosed within Faraday's cage like arrangement
- (i) All enclosures of GIS should be earthed at several points to the earth bus through the base frames of the GIS. All conduits and cable sheaths should be earthed to earth bus available in control cubicles and marshalling boxes.

- (j) Recommendations of the manufacturer and multipoint earthing normally ensures touch and step voltages within the respective permissible values.
- (k) Spacing of earth mat in the GIS hall may be adjusted as per manufacturer's recommendation. It should be bonded with floor reinforcement for better performance of transient high frequency signals. Similarly all earthing risers should be bonded to floor reinforcement.
- (l) When connecting IS risers with earthing risers, the requirement of bi-metallic strip for dissimilar metal, if any, should be taken care of. The contact surface should be properly leaned and contact paste applied to have better joint and less contact resistance.
- (m) Shielded cables should be earthed at one end only
- (n) To avoid circulation of enclosure current beyond regular path, power cable sheath should be earthed directly without involving the enclosure in the earth path. To facilitate this isolation, design of cable termination should be such that an isolating air gap or proper insulating elements are provided.
- (o) Proper care should be taken to ensure that current transformers mounted on GIS do not carry the enclosure return current
- (p) Wherever there are discontinuities in enclosure/changes in the medium e.g. at cable terminations or transformer connections, special care should be taken to limit very fast transient over voltages and to prevent circulating currents in circuit breakers and transformer tanks.
- (q) GIS cable terminations and other discontinuities in the enclosure are significant sources of Transient Earth Potential Rise phenomenon. The isolation between the directly earthed power cable sheath and the enclosure may give rise to Transient Potential Rise phenomenon. Particular attention should be given to limit it.
- (r) In GIS, concrete foundations may cause irregularities in current discharge path. A simple monolithic concrete steel reinforced slab is advantageous, both as auxiliary earthing device and for seismic purposes.

12.5 SUMMARY

Earthing of all GIS equipments at a station is planned by the manufacturer of the equipments. The Customer has to provide earth conductors so that the equipments can be earthed properly. Various factors that come into operation are described in this chapter. The principles advice is to earth the equipments (i) close to circuit breakers, (ii) close to cable sealing ends, (iii) close to SF6/air bushings, and (iv) close to instrument transformers. Main problem about design of the earth grid electrode for a GIS is reduced area of land required for such a station. This makes it all the more important to calculate grid current correctly; software for this purpose is being provided with this manual. The earth resistance cannot be less than a certain value. The deciding factor is the maximum permissible magnitude of EPR. Various possibilities of limited area stations are discussed in Chapter 6.

REFERENCES

- [1] ANSI/IEEE Standard 80-2000, *IEEE Guide for Safety in AC Substation Grounding*, IEEE, New York 2000
- [2] CIGRE 44, *Earthing of GIS – An Application Guide* prepared by CIGRE Working Group 23.10.
- [3] Earthing of GIS, Communicated by NHPC

EARTH ELECTRODE FOR GENERATING STATIONS

A.1 INTRODUCTION

A. 1.1 A thermal generating station usually has a large physical area; the area, over which earth electrode is laid, is usually quite extensive. On the other hand at a hydel surface generating station, without storage dam nearby, or if the generating station is underground, the physical area is comparatively smaller; the area available for laying earth electrode is limited. The underground station usually has several adits branching off the main caverns. The three factors that affect the earth potential rise of earth electrode at any station are (i) area of earth electrode, (ii) soil resistivity and (iii) earth fault current.

A. 1.2 Principal Features of Earthing at a Generating Station

Earth electrode at each station has different features. Some characteristic features of earthing at a generating station are:

- (i) At a generating station, there are large buried metallic structures, which are not considered when designing the earth electrode.
- (ii) Large spaces in a generating station are indoors. The areas where the personnel generally work at such stations have concrete floors.
- (iii) The personnel moving about on concrete floor do not face the step and touch voltage situation as happens at an outdoor substation where the personnel are in contact with earth or gravel/crushed rock spread on earth.
- (iv) There are usually closely spaced rebar conductors within concrete floor. The rebar conductors usually get connected to earthed structures or earthing conductors. These conductors may not be used in earth electrode calculations, but they do present a nominally equipotential surface. Also, concrete has very large resistivity when dry, and resistance to flow of current is high.
- (v) The earth conductors that are required for making equipment connections to earth electrode are buried in concrete.

A. 1.3 Recommendations for Earthing at Generating Station

- (i) At a generating station where area outside the station buildings is available for burying earth electrode, resistivity measurements are carried out in such areas, and an average soil model, uniform soil or layered soil, is used for designing the earth electrode. At the station where area for laying earth electrode outside the station building is scarce, earth electrode conductors are to be buried under the station building itself.
- (ii) When preparing layout of earth electrode conductors, an earth conductor should be laid at the periphery of the station. Earth conductors should also be laid around each building, as a ring, at a distance of 1 m from the building. Earth conductors are laid in between at chosen intervals.
- (iii) An adequate number of risers, minimum of two, should be taken from the earth electrode conductors laid under the floor as at (i) above or from the ring conductor around the building as at (ii) above.

- (iv) Inside a building, a ring earth conductor should be installed along the outer wall of the building at each floor. Within the main building housing main generators / transformers, cross earthing conductors that divide the floor into a grid, should be laid where required for providing earth connection points for the equipments. The spacing of cross conductors shall depend on layout of equipment.
- (v) In an underground hydel station, the rock walls may have only a small thickness of concrete cover. At such a station, the earth conductors are to be laid in grid form in the floor as well as on the walls of caverns and the ceiling, wherever any devices/fixtures requiring electric power supply are installed. The dangerous voltage situation can be touch voltage. The spacing of earth conductors has to be such that touch voltage is less than the permissible value. This may need spacing of about 4 m.

APPENDIX - B

PREPARATION OF DATA FOR PROGRAM 'gridi' FOR COMPUTATION OF GRID CURRENT AND OPERATION OF PROGRAM

B.1 INTRODUCTION

- B.1.1 This file covers the preparation of data file for the program gridi and execution of the program.

The program is used to determine grid current with the algorithm that is used in program PAG [1]. The input data about each of the lines consists of either the conductor spacing data together with the characteristics of earth/shield wires, or the self and mutual impedance of earth/shield wire of each line. Each line is assumed to have more than 25 spans.

In the current version of the software, it is set up as Grid_Current. It can then be launched from the list of programmes that is displayed when one clicks on 'All Programme' on the 'Start' screen.

B.2 USE OF PROGRAM GRIDI

- B.2.1 This write-up gives the format of Input file for executing program **gridi**.
- B.2.2 The program **gridi** is WINDOWS based and is used for determining the current diverted by Earth Wires and the Grid Current from Earth Fault Current.
- B.2.3 The program uses self-impedance of earth wire and mutual impedance between earth wire and phase conductors to determine these currents.
- B.2.4 There are two options for inputting data about earth wire: - Option 1) the self impedance and mutual impedances are given directly for the line having more than 20 spans that is considered infinite; Option 2) the geometrical configuration of the line in an average span of the line is given, and impedances are calculated in the program.
- B.2.5 The input file is a Text file and may be generated in Word pad.
- B.2.6 The First two lines of data are for Identification of the problem. Each is of 72 or less characters. There should be no commas in these lines.
- B.2.7 The Third line contains three values: - 1) 'Opt' is option and is either 1 or 2; 2) 'nl' is Number of Lines and is an Integer from 1 to 10; 3) 'rg' is Earth Resistance at the station under reference.

B.3 OPTION 1

When option is 1

- B.3.1 The Third line is followed by 'nl' pairs of lines corresponding to 'nl' transmission lines. In each pair the first line is for Identification of the line and has up to 72 characters. There should be no commas in this line. The second line has six data.

These are (i) Resistance part of Self Impedance of earth wire, (ii) Reactance part of Self Impedance of earth wire, (iii) Resistance part of Mutual Impedance of earth wire, (iv) Reactance part of Mutual Impedance of earth wire, and Fault Current magnitudes for the line in the rectangular form a_0 (v) Real component, and (vi) Imaginary component.

B.4 OPTION 2

When option is 2

B.4.1 The Fourth line has Two data: - (i) 'f', the Frequency in Hz, and (ii) 'rho', the Average Soil Resistivity in Ω -m along the right of way of transmission line and is often the same as average soil resistivity in the station area for a uniform soil model or average resistivity otherwise.

B.4.2 Next there are 'nl' Sets of data, one for each transmission line. In each set the first line has two integer numbers: (i) 'nc', Number of conductors of all phases on the tower, 3 for a single circuit line, 6 for a double circuit line, 6 for a single circuit line with each phase conductor a bundle of two conductors etc. and (ii) 'nsw', Number of earth/shield wires in the transmission line (either 1 or 2).

On next line/s are 'nc' sets of data, each data set giving x, and z co-ordinates of the phase conductors (in m) one by one; (origin for x-axis is through center line of cross section of tower and that of z-axis is at earth surface). All data are separated by commas; there should not be a comma at the end of any line.

On the next line follow 'nsw' sets of data, each set giving x, and z co-ordinates of one earth wire

The next line of each set has Two data - (i) 'rkm', resistance in Ω . per km of the earth wire, and (ii) 'gmrew', geometric mean radius of the earth/shield wire in m.

Next line of each set has Two data: - (i) 'spanl', Length of average span in m and (ii) 'tfr', Tower footing resistance in Ω .

The last line in each set is fault current contribution of the line in rectangular form i.e. real part and imaginary part separated by a comma.

B.5 INPUT AND OUTPUT FILES OF ILLUSTRATIVE EXAMPLES**B.5.1 INPUT Data for Option 1**

This is test data for the gridi program in Visual Basic using impedances

Grid Current with data of Earth Wire for S/stn with 400 kV and 200 kV Lines
1,4,0.0203643

First 400 kV double circuit line from Substation

2.85441,0.51427,0.14043,0.37096,10000,0

Second 400 kV double circuit line from Substation

2.85441,0.51427,0.14043,0.37096,10000,0

First 220 kV double circuit line from Substation

3.663543,0.49908,0.08564,0.27123,10000,0

Second 220 kV double circuit line from Substation

3.663543,0.49908,0.08564,0.27123,10000,0

B.5.1.1 Part of OUTPUT for Option 1

“Name of the project under analysis is given below:”

This is test data for the gridi program in Visual Basic

Grid Current with data of Earth Wire for S/stn with 400 kV and 200 kV Lines

Number of transmission lines are: 4

Earth resistance of the station is: 0.0203643

The earth wire currents are printed below :

Trans, line #	Real component	Imag. component”
1	954.8388	1102.581
2	954.8388	1102.581
3	528.0276	648.9442
4	528.0276	648.9442

“ The grid current is printed below”

“ Real omponent	Imag. component”
37034.2670898438	-3503.05023193359

“ The grid current phasor is printed below”

“ Magnitude	Phase angle”
37199.5739197284	-5.403498

B .5.2 INPUT Data for Option 2

This is test data for the gridi program in Visual Basic using spacings

Grid Current with data of Earth Wire for S/stn with 400 kV and 200 kV Lines

2,4,0.02036432

50,50

400 kV double circuit line. Phase Cond. quad MOOSE & EW 2/3.66 mm

24,2

-6.625,27.065,-6.175,27.065,6.175,27.065,6.625,27.065

-6.625,26.615,-6.175,26.615,6.175,26.615,6.625,26.615

-9.675,17.315,-9.225,17.315,9.225,17.315,9.675,17.315

-9.675,16.865,-9.225,16.865,9.225,16.865,9.675,16.865

-8.145,9.085,-7.695,9.085,7.695,9.085,8.145,9.085

-8.145,8.635,-7.695,8.635,8.635,8.635,8.145,8.635

-3.2,36.59,3.2,36.59

3.0434,.004276

400,10

10000,0

400 kV double circuit line. Phase Cond. quad MOOSE & EW 2/3.66 mm

24,2

-6.625,27.065,-6.175,27.065,6.175,27.065,6.625,27.065

-6.625,26.615,-6.175,26.615,6.175,26.615,6.625,26.615

-9.675,17.315,-9.225,17.315,9.225,17.315,9.675,17.315
 -9.675,16.865,-9.225,16.865,9.225,16.865,9.675,16.865
 -8.145,9.085,-7.695,9.085,7.695,9.085,8.145,9.085
 -8.145,8.635,-7.695,8.635,8.635,8.635,8.145,8.635
 -3.2,36.59,3.2,36.59
 3.0434,004276
 400,10 -
 10000,0
 220 kV double circuit line. Phase Cond. twin MOOSE & EW 1/3.66 mm
 12,1
 -4.555,17.9,-4.105,17.9,4.105,17.9,4.555,17.9
 -4.725,12.45,-4.555,12.45,4.555,12.45,4.725,12.45
 -4.575,7.3,-4.575,7.3,4.575,7.3,4.575,7.3
 0,25.885
 3.0434,004276
 320,10
 10000,0
 220 kV double circuit line. Phase Cond. twin MOOSE & EW 1/3.66 mm
 12,1
 -4.555,17.9,-4.105,17.9,4.105,17.9,4.555,17.9
 -4.725,12.45,-4.555,12.45,4.555,12.45,4.725,12.45
 -4.575,7.3,-4.575,7.3,4.575,7.3,4.575,7.3
 0,25.885
 3.0434,004276
 320,10
 10000,0

B.5.2.1 OUTPUT for Option 2

“Name of the project under analysis is given below:”
 This is test data for the gridi program in Visual Basic
 Grid Current with data of Earth Wire for S/stn with 400 kV and 200 kV Lines
 Number of transmission lines are: 4
 Earth resistnce of the station is: 0.02036432
 “400 kV double circuit line. Phase Cond. quad MOOSE & EW 2/3.66 mm”
 24,2
 -6.625,27.065,-6.175,27.065,6.175,27.065,6.625,27.065,-6.625,26.615,
 -6.175,26.615,6.175,26.615,6.625,26.615,-9.675,17.315,
 -9.225,17.315,9.225,17.315,9.075,17.315,-9.675,16.865,
 -9.225,16.865,9.225,16.865,9.675,16.865,-8.145,9.085,
 -7.695,9.085,7.695,9.085,8.145,9.085,-8.145,8.635,
 -7.695,8.635,8.635,8.635,8.145,8.635,-3.2,36.59,3.2,36.59,1
 3.0434,004276
 400,10
 10000,0
 “400 kV double circuit line. Phase Cond. quad MOOSE & EW 2/3.66 mm
 24,2

-6.625,27.065,-6.175,27.065,6.175,27.065,6.625,27.065,-6.625,26.615,
 -6.175,26.615,6.175,26.615,6.625,26.615,-9.675,17.315,
 -9.225,17.315,9.225,17.315,9.675,17.315,-9.675,16.865,
 -9.225,16.865,9.225,16.865,9.675,16.865,-8.145,9.085,
 -7.695,9.085,7.695,9.085,8.145,9.085,-8.145,8.635,
 -7.695,8.635,8.635,8.635,8.145,8.635,-3.2,36.59,3.2,36.59,2
 3,0434,.004276

400,10

10000,0

“220 kV double circuit line. Phase Cond. twin MOOSE & EW 1/3.66 mm

12,1

-4.555,17.9,-4.105,17.9,4.105,17.9,4.555,17.9,-4.725,12.45,

-4.555,12.45,4.555,12.45,4.725,12.45,-4.575,7.3,

-4.575,7.3,4.575,7.3,4.575,7.3,0,25.885,3

3.0434,.004276

320,10

10000,0

“220 kV double circuit line. Phase Cond. twin MOOSE & EW 1/3.66 mm

12,1

-4.555,17.9,-4.105,17.9,4.105,17.9,4.555,17.9,-4.725,12.45,

-4.555,12.45,4.555,12.45,4.725,12.45,-4.575,7.3,-4.575,7.3,

4.575,7.3,4.575,7.3,0,25.885,4

3.0434,.004276

320,10

10000,0

10000,0

20000,0

30000,0

40000,0

“The earth wire currents are printed below”

“Trans, line #	Real component	Image component”
1	954.4989	1102.518
2	954.4988	1102.518
3	531.0755	662.1812
4	531.0755	662.1812

“The grid current is printed below”

“ Real component	Image component”
37028.8512573242	-3529.39916992188

“The grid current phaser is printed below”

Magnitude	Phase angle”
37196.6730224315	-5.444689

B.6 OPERATION OF PROGRAM gridi

- (a) Double click on symbol of executable file gridi launch from 'all programme'
- (b) On the resulting initial screen, single click on indicated box on left side.
- (c) On the next screen, first select the hard disk partition on which data file resides from the drop down list (suggest same partition on which gridi resides)
- (d) Also from drop down list of directories in the chosen partition reach the folder in which data file resides and double click on it. If there are sub folders double click each as it appears in the same drop down list till name of data file and other files of the last folder appear in the box" on the right side of the screen. The list is scrolled to view name of the data file.
- (e) Single click the name of data file to select it. The name will appear in the box by side of text box 'selected file'.
- (f) Single click on OK button.
- (g) On the resulting screen single click on button 'click here to start input'
- (h) Some or all of the rest of boxes are filled with appropriate data. Check for correctness of data. If there is error, click on button 'End', otherwise click on button 'Next' to continue reading data from data file.
- (i) On next screen, click on box at the top. Data for line 1 will be displayed. Check data for line 1. Keep clicking at the same box for data of the rest of lines to appear and checking data of these lines till 'End of data' appears in box by the side of 'End' box.
- (j) If any data is erroneous at any stage, click on 'End' button. When 'end of data' appears after a click, click at the button 'Click here to go to analysis screen'.
- (k) Next screen appears. Click at the button 'Click here to start calculations'.
- (l) If 'Calculations complete' appears in box below, click at box 'If calculations complete click here to start display'.
- (m) The result display screen appears. Click repeatedly to see current diverted by earth wires of different lines and also grid current.

REFERENCE

- [1] Scedher, H.R. Arora, J.K. and Soni, S.K. 'A Practical Approach for Computation of Grid Current,' *IEEE Transactions on Power Delivery*, vol. 14, pp. 897-902, July 1999.

APPENDIX – C

PREPARATION OF DATA FOR PROGRAM ‘SOIL_MODEL’ FOR COMPUTATION OF SOIL MODEL AND OPERATION OF PROGRAM

C.1 INTRODUCTION

- C.1.1 This file covers the preparation of data file for the program **Soil_Model** and execution of program.

The program is used to determine “Uniform” soil model or “Two_layer” soil model from measured data. The input data consists of the number of radials, the number of spacings for each radial, all measured values of resistance by the four probe Wenner method and also the electrode spacing for each observation.

In the current version of the software, it is set up as Soil-model. It can then be launched from the list of programs that is displayed when one clicks on ‘All Programs’ on the ‘Start’ screen

C.2 USE OF PROGRAM SOIL_MODEL

- C.2.1 This write-up gives the format of Input file for executing program **Soil_Model**
- C.2.2 The program **Soil_Model** is windows based and is used to determine the soil model, Uniform or Two-layer, from the Wenner method of soil resistivity measurements
- C.2.3 The program uses probe spacing and measured resistance to determine apparent measured soil resistivity for each probe spacing. These values are used to determine Uniform soil model or Two-layer soil model as desired. In case of uniform soil model it is average of apparent measured resistivities. In case of two-layer soil model iterative search process outlined in Section 9.3.4.4 is used
- C.2.4 The input file is a Text file and may be generated in Wordpad.
- C.2.5 The first two text lines are for identification of the problem. No comma should be used on these two lines or at the end of any other subsequent line.
- C.2.6 The third line gives the number of locations at which measurements are made. It is an integer number (NLOC). NLOC equals total number of radials.
- C.2.7 Fourth line is the number of electrode spacings at the i th location starting with the first location. (NS(I))
- C.2.8 From line No. 5 to line No. 5+NS(1), there is measurement data of location 1. Each line has three values separated by commas, namely, (i) electrode spacing in meters, (ii) depth of burial of electrode (m), this value is zero if depth of burial is about (1/20) of electrode spacing, and (iii) measured resistance value in ohms.
- C.2.9 After this there are NS(2) lines of data for location No. 2 if any, and so on till data of all (NLOC) locations is given.

C.2.30 Next line is text data. If expected soil model is two-layer then the data line is 'Two_layer', otherwise it is 'Uniform'. (Note capital letters.)

C.2.10 In case of uniform soil model, data is now complete.

C.2.11 In case of two-layer model there are two more lines of data. The first of these two lines has 7 data separated by commas. These are (i) Initial estimate of top layer resistivity in ohm-m, (ii) Initial estimate of resistivity of bottom layer, (iii) Initial estimate of depth of upper layer of soil model, (iv) Upper limit on number of iterations (suggested 50), (v) The minimum change in value of parameters in an iteration (suggested 0.001), (vi) next is 0 or 1, if 1, log function of performance index is used; if 0, then performance index is not log function. (suggested 0), (vii) seventh is a fraction multiplier of root mean square error for deleting data points outside the fractional spread to fit a model by neglecting values with error more than the fraction x root mean squared error (suggested 1.5 - 2), if more than 20% data points are neglected with this criterion, program terminates; if this feature is not required, a large number like 100 may be given.

C.2.12 The last line has three values separated by commas, i) the minimum value of iterative element (suggested 0.0001), ii) the upper limit on the terms of infinite series of images in simulation (suggested 100 for $0.1 < \text{RHO1}/\text{RHO2} < 10$). It is to be increased to 200 or even larger number if the ratio is outside the suggested limits. iii) Next is either 0, if intermediate results are not to be written to output file and 1, if intermediate results are to be written to output file.

C.3 INPUT AND OUTPUT FILES OF ILLUSTRATIVE EXAMPLES

Four samples of input data file are given below:

C.3.1 INPUT data for example 1

Name of Data File is data.dat

This is trial data for determining uniform soil model

2
3
2,0,12
5,0,4
10,0,1
3
2,0,15
4,0,6
10,0,2.8
Uniform

C.3.1.1 OUTPUT for example 1

"Name of the project under analysis is given below:"

Name of Data File is data.dat

This is trial data for determining uniform soil model

Number of measurement locations in the station area are: 2

1,2,0,12,150.7964

2,5,0,4,125.6637

3,10,0,1,62.83186

1,2,0,15,188.4956

2,4,0,6,150.7964

3,10,0,2.8,175.929196166992

Average of all apparent measured resistivity values is = 142.418863423665

Spread of app. meas. resistivity values is = + 32.3529448003311 % and -55.8823499475525 %

C.3.2 INPUT data for example 2

Name of Data File is data1.dat

This is trial data for determining two-layer soil model

2

3

2,0,12

5,0,4

10,0,1

3

2,0,15

4,0,6

10,0,2.8

Two_layer

200,100,1,10,.01,0,20

.001,100,1

C.3.2.1 Part of OUTPUT for example 2

“Name of the project under analysis is given below:”

Name of Data File is data1.dat

This is trial data for determining uniform soil model

Number of measurement locations in the station area are: 2

1,2,0,12,150.7964

2,5,0,4,125.6637

3,10,0,1,62.83186

1,2,0,15,188.4956

2,4,0,6,150.7964

3,10,0,2.8,175.929196166992

200,100,1,10,.01,0,20

.001,100,1

Average app meas resistivity = 169.646 for elec spacing of 2

Average app meas resistivity = 150.7964 for elec spacing of 4

Average app meas resistivity = 125.6637 for elec spacing of 5

Average app meas resistivity = 119.380525970459 for elec spacing of 10

RO2 and RO1 are = 100 200

“* FXGR,”1,200,100,1

Resistivity of upper layer = 200

Resistivity of bottom layer = 100

Height of upper layer = 1

Value of performance index F = 0.154348

After 1 iterations values of F, RO1, RO2 and H are 0.2558919 100 112.0531 1.5

After 2 iterations values of F, RO1, RO2 and H are 6.661699E-02 150 109.627
1.789298

After 3 iterations values of F, RO1, RO2 and H are 7.463662E-03 189.6296 112.1725
1.9875

After 4 iterations values of F, RO1, RO2 and H are 7.295804E-03 189.9398 112.6506
1.907411

After 5 iterations values of F, RO1, RO2 and H are 7.29477E-03 189.5961 112.4914
1.922078

Convergence criterion satisfied after 5 iterations

Final values of RO1, RO2, H are given below 189.5961 112.4914 1.922078

“* FXGR,”5,189.5961,112.4914,1.922078

****Final Soil Model Generated****Resistivity of upper layer = 189.5961

Resistivity of bottom layer = 112.4914

Height of upper layer = 1.922078

Value of performance index(F) = 7.29476667282186E-03

Comparison of Meas. and Computed App. Resistivities

Electrode spacing	Meas. App. Resistivity	App. Resistivity Gen.from Model	%DIFF
2	169.646	170.995872420595	-0.795701891183853
4	150.7964	141.778489959605	5.98021894693375
5	125.6637	133.047452074023	-5.87579384446144
10	119.380525970459	117.681059874496	1.42357060685754

Percentage RMS Difference = 4.27047031157631

C.3.3 INPUT data for example 3

data for sample substation

average measured resistance for all locations

1

6

.5,0,256.65

1,0,104.92

5,0,.44344

10,0,.06802

20,0,.04223

30,0,.03142

Uniform

C.3.3.1 OUTPUT for example 3

“Name of the project under analysis is given below:”

data for samle substation

average measured resistance for all locations

Number of measurement locations in the station area are: 1

1,.5,0,256.65,806.289776980877

2,1,0,104.92,659.231820774078

3,5,0,.44344,13.9310799992

4,10,0,.06802,4.2738231172

5,20,0,.04223,5.306778051

6,30,0,.03142,5.922531752

Average of all apparent measured resistivity values is = 249.15930177906

Spread of app. meas. resistivity values is = + 223.60412443917022714082844069 % and
-98.28470256310568001307279687 %

C.3.4 INPUT data for example 4

data for sample substation

average measured resistance for all locations

1

6

.5,0,256.65

1,0,104.92

5,0,.44344

10,0,.06802

20,0,.04223

30,0,.03142

Two_layer

800,5,1,500,.001,0,1.69

.001,500,0

C.3.4.1 OUTPUT for example 4

“Name of the project under analysis is given below:”

data for sample substation

average measured resistance for all locations

Number of measurement locations in the station area are: 1

1,.5,0,256.65,806.289776980877

2,1,0,104.92,659.231820774078

3,5,0,.44344,13.9310799992

4,10,0,.06802,4.2738231172

5,20,0,.04223,5.306778051

6,30,0,.03142,5.922531752

800,5,1,500,.001,0,1.69

.001,500,0

Average app meas resistivity = 806.289776980877 for elec spacing of 0.5

Average app meas resistivity = 659.231820774078 for elec spacing of 1

Average app meas resistivity = 13.9310799992 for elec spacing of 5

Average app meas resistivity = 4.2738231172 for elec spacing of 10

Average app meas resistivity = 5.306778051 for elec spacing of 20

Average app meas resistivity = 5.922531752 for elec spacing of 30

RO2 and RO1 are = 5 800

“* FXGR,”1,800,5,1

Resistivity of upper layer = 800

Resistivity of bottom layer = 5

Height of upper layer = 1

Value of performance index F = 0.2649249

“* FXGR,”1,808.5339,4.897346,1.263856

After 1 iterations values of F, RO1, RO2 and H are 0.1691312 808.5339 4.897346 1.263856

“* FXGR,”2,847.6996,4.89616,1.17676

After 2 iterations values of F, RO1, RO2 and H are 0.0675325 847.6996 4.89616 1.17676

“* FXGR,”3,851.771,4.894108,1.168169

After 3 iterations values of F, RO1, RO2 and H are 6.685258E-02 851.771 4.894108 1.168169

“* FXGR,”4,851.7452,4.894138,1.168129

After 4 iterations values of F, RO1, RO2 and H are 6.685259E-02 851.7452 4.894138 1.168129

“* FXGR,”5,851.7449,4.894112,1.168129

After 5 iterations values of F, RO1, RO2 and H are 6.685259E-02 851.7449 4.894112 1.168129

“* FXGR,”6,851.7449,4.894165,1.168129

After 6 iterations values of F, RO1, RO2 and H are 6.685252E-02 851.7449 4.894165 1.168129

Convergence criterion stisfied after 6 iterations

Final values of RO1, RO2, H are given below 851.7449 4.894165 1.168129

“* FXGR,”6,851.7449,4.894165,1.168129

****Final Soil Model Generated****Resistivity of upper layer = 851.7449

Resistivity of bottom layer = 4.894165

Height of upper layer = 1.168129

Value of performance index(F) = 6.68525417724842E-02

Comparison of Meas. and Computed App. Resistivities

Electrode spacing---Meas. App. Resistivity---App. Resistivity Gen.from Model %DIFF

0.5	806.289776980877	814.159406717138	-0.976029969751835
1	659.231820774078	653.800224186243	0.823928136378527
5	13.9310799992	13.8767287610713	0.390143762342632
10	4.2738231172	5.03930313556816	-17.9108962416649
20	5.306778051	4.9240460274105	7.21213519573212
30	5.922531752	4.90715583230062	17.144288122654

Percentage RMS Difference = 10.5556100228334

“* The following points have error which is larger than spread times the root mean square error
*”,1,10,4.2738231172,-17.9108962416649,

“* FXGR,”1,849.0115,4.579991,1.177219

After 1 iterations values of F, RO1, RO2 and H are 6.787196E-02 849.0115 4.579991 1.177219

“* FXGR,”2,854.309,5.553694,1.153144

After 2 iterations values of F, RO1, RO2 and H are 6.668897E-03 854.309 5.553694 1.153144

“* FXGR,”3,854.6556,5.553676,1.152387

After 3 iterations values of F, RO1, RO2 and H are 6.664288E-03 854.6556 5.553676 1.152387

Convergence criterion stified after 3 iterations

Final values of RO1, RO2, H are given below 854.6556 5.553676 1.152387

“* FXGR,”3,854.6556,5.553676,1.152387

*****Final Soil Model Generated*****Resistivity of upper layer = 854.6556

Resistivity of bottom layer = 5.553676

Height of upper layer = 1.152387

Value of performance index(F) = 6.66429178733178E-03

Comparison of Meas. and Computed App. Resistivities

Electrode spacing---Meas. App. Resistivity---App. Resistivity Gen.from Model %DIFF

0.5	806.289776980877	815.602811337205	-1.15504804998636
1	659.231820774078	650.772233162578	1.28324925899506
5	13.9310799992	13.9548747381019	-0.170803256332874
20	5.306778051	5.58664937799939	-5.27384653687477
30	5.922531752	5.56807219468557	5.98493292927742

Percentage RMS Difference = 3.65083327127706

*****COMPARISON WITH GIVEN DATA*****VALUE OF PERFORMANCE INDEX (F)
= 0.126476579530902

* COMPARISON MEAS. AND COMPUTED APPARENT RESISTIVITIES *

ELECTRODE SPACING APP MEAS RESISTIVITY GENERATED FROM MODEL %DIFF

0.5	806.2898	815.602811337205	-1.15504581481218
1	659.2318	650.772233162578	1.28324786201119
5	13.93108	13.9548747381019	-0.170804234221578
10	4.273823	5.58664937799939	-30.7178378105164
20	5.306778	5.56807219468557	-4.92378324270248

* PERCENTAGE RMS DIFF. = 14.5187568069091

C.4 OPERATION OF PROGRAM SOIL_MODEL

- Double click on symbol of executable file **Soil_model** / Initiate from ‘**All Programs**’.
- On the resulting initial screen, single click on indicated box on left side.
- On the next screen, first select the hard disk partition on which data file resides from the drop down list (suggest same partition on which **Soil_model** resides).
- Also from drop down list reach the folder in which data file resides and double

click on it. If there are subfolders double click each as it appears in the same drop down list till name of data file and other files of the last folder appear in the box on the right side of the screen.

- (e) Single click the name of data file to select it. The name will appear in the box by the side of txt box 'selected file'.
- (f) Single click on OK button.
- (g) On the resulting screen single click on button 'click to start input'.
- (h) The rest of boxes are filled with appropriate data. Check for correctness of data. If there is error, click on button 'End', otherwise click on button 'Next'.
- (i) On next screen, click on button 'Next keep clicking here till end of data appears in box below'.
- (j) Check data that appears in boxes on the screen for any errors, If erroneous, click on 'End' button, otherwise click repeatedly on the same button at top,
- (k) Check data each time, till after a click 'End of data' appears in box by the side of text box 'End of data'.
- (l) Now click on 'Click here to go to analysis screen' button. Next screen appears.
- (m) Click on 'Start Analysis, click for uniform model' button if uniform soil model is to be obtained.
- (n) If selected soil model is Uniform, 'All done' will appear in text box above 'End' button. Click on 'End' button and look for results in the output.txt file. This file resides in the same folder as the data file.
- (o) If it was Two-layer model, click repeatedly on 'In case of two-layer soil click to continue till all done appears' button till 'All done' appears in text box above 'End' button. During this process average measured resistivity and corresponding electrode spacing will appear in text boxes on the left. After all done appears, click on 'Next' button.
- (p) The next screen appears with 'Commence modelling' button on left top. Click on this button. When analysis is complete, data appears in three boxes. 'All done' appears above 'End' button. Click on 'End' button and look for results in the output.txt file. This file resides in the same folder as the data file.

At any time, analysis can be terminated by a click on 'End' button of the screen.

A Truly Maintenance Free and Environment Friendly solutions in Electrical Grounding for Industrial / Commercial establishments, Offices and Residences.



PowerFill™

A carbon based non corrosive, highly conductive powdered material which improves the grounding effectiveness.

14.2 / 17.2 / 25 / 32 mm diameter
copper bonded steel electrodes
in lengths of 1220 / 2000 / 3000



PowerSet™

When the applications call for a hard setting backfill material, PowerSet is recommended. When mixed with water or exposed to moisture, PowerSet attains the hardening characteristics of cement while retaining its highly conductive properties. PowerSet will remain highly conductive even during drought condition.

SPECIAL CHARACTERISTICS OF OUR BACKFILL COMPOUND :

- Does not contain any hazardous chemicals
- Electronically conductive (Like in metals) and is not dependent on moisture
- Environment friendly and conforms to ANSI / NSF standard 60 for use near potable ground water systems.
- Will not leech / diffuse into the ground
- Not affected by drought
- Ease of installation in rocky terrain.

Complies with IS 3043 / BS 7430 & IEEE 80



Jef Techno Solutions Private Limited.

www.jeftechno.net

Info@jeftechno.net