Optimal Design Software for Substation Grounding

Major Project Report

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Certificate

This is to certify that the Major Project Report entitled **" Optimal design software for substation grounding "** submitted by **Mr.Patel Shaileshbhai Haribhai (Roll No: 12MEEE23)** towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Electrical Power Systems of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

Different types of substations in an electric power system play different but crucial role in functioning of power system. In a substation design, the attention is paid for the design of grounding system as gaffe in it proves dangerous to the system and working personnel. Design of an effective grounding system is key to the substation performance because it deals with personnel safety and also operation and protection of equipment.

Responsibility of keeping the substation safe is upon the grounding system installed within it. The absence of reliable and effective grounding system in any substation, can result in malfunctioning or non-operation of control and protective devices and may prove hazardous for persons working therein. Therefore, the grounding system design is a task that must be performed critically.

This report is aimed at describing the development of and functioning of software for optimal design of substation grounding systems for square and rectangular areas. IEEE standard 80 - 2000 is widely accepted document pertinent to safe practices to be followed while designing grounding systems for electrical substations. Using equations there in (i.e. IEEE Std. 80 2000) blended with finite element (FE) methodology is implemented for the design of grounding system.

A software named **" Ground Grid Designer (GGD) "** has been developed using MATLAB as mathematical computing tool as well as GUI programming platform. GGD can be deployed as a standalone application using MATLAB runtime compiler add-on, so that it can be used on the computer even where MATLAB is not installed. Designing substation grounding employing FE technique results into a 3D graphical representation indicating potential at any point within and (slightly) outside the grid area. It is also feasible to find the area of high potential on the ground during abnormal / fault condition. The information availed thus helps in modifying the ground design as per the standard requirements.

The GGD is designed to cater to design of grounding grid of any rating of substation, however limited to two basic shapes and single soil layer. The software offers three possibility, of which optimal design can be justified. Two methods out of three has a Variation as opposed to the designs of a literature.
In addition to grounding system analysis and optimization, GGD allows derivation of soil model from available Earth Resistance Testing (ERT) data. It can extract uniform soil models from available test data, to be used in further calculations. Performance of the software is evaluated by comparison with Ground Grid Systems (GGS) module of ETAP and IEEE 80-2000 design. Sample design problems solved with the help of both the software produce quite comparable results in majority of the cases. Thus by such software testing, technical soundness of the software is proved. In certain cases GGD is found to be superior than ETAP and IEEE 80-2000 design. Some standard designs available in the literature has been tested and optimal design is thus proposed. Typically, a new approach is suggested for a grounding grid design.

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Nomenclature

A .... Area occupied by the grounding grid conductors (m^2)

A_{mm^2} .... Cross section area of conductor (mm^2)

D_f .... Decrement factor to take into account current asymmetry

$E_{step-50}$ .... Tolerable Step voltage for person weighing 50 Kg (Volts)

$E_{step-70}$ .... Tolerable Step voltage for person weighing 70 Kg (Volts)

$E_{touch-50}$ .... Tolerable touch voltage for person weighing 50 Kg (Volts)

$E_{touch-70}$ .... Tolerable touch voltage for person weighing 50 Kg (Volts)

h .... Depth of burial of grid in the ground (m)

h_s .... depth of surface layer (m)

I .... Maximum rms fault current (kA)

I_B .... Current flowing through human body (kA)

I_f .... Maximum symmetrical rms fault current (kA)

I_G .... Maximum current flowing through ground grid (kA)

K_0 .... $(1/\alpha_0)$ or $(1/\alpha_r)$ -T_r ($^\circ C$)

L_c .... Total length of conductors lying in horizontal plane (m)

L_r .... Length of each Ground rod (m)

L_R .... Total length of vertical ground rods (m)

L_x .... Maximum length of grid in X direction (m)

L_y .... Maximum length of grid in Y direction (m)

N_r .... No. of vertical ground rods

N_x .... No. of ground grid conductor in X direction

N_y .... No. of ground grid conductor in Y direction

r .... Radius of ground grid conductor(m)

R_g .... Resistance of ground Grid (Ω)

S_f .... Current division factor

T_a .... DC offset time constant (sec)

T_{amb} .... Ambient temperature ($^\circ C$)

T_m .... Maximum allowable temperature ($°C$)

T_r .... Reference temperature for material ($°C$)

t_f .... Fault duration (sec)

t_s .... Shock duration (sec)

$V_{touch(max)}$ .... Maximum actual touch voltage in grid area (Volts)

$V_{touch(min)}$ .... Minimum actual touch voltage in grid area (Volts)

VDF .... Voltage Distribution Factor

α_0 .... Thermal co-efficient of resistivity at 0 $°C$ ($°C^{-1}$)

α_r .... Thermal co-efficient of resistivity at reference temperature ($°C^{-1}$)

ρ .... Uniform Soil resistivity ($\Omega \cdot m$)

ρ_a .... Apparent resistivity in Earth Resistivity Test ($\Omega \cdot m$)

ρ_r .... Resistivity of conductor at reference temperature ($\mu\Omega \cdot cm$)

ρ_s .... Surface layer resistivity ($\Omega \cdot m$)

Abbreviations

GPR .... Ground Potential Rise

IEEE .... Institute of Electrical and Electronics Engineers, NY, USA

GGS .... Ground Grid Systems

ERT .... Earth Resistivity Testing

TCAP .... Thermal capacity of material per unit volume (J/($cm^3 \cdot ^\circ C$))

Contents

Chapter 1

Introduction

The importance of well designed grounding system to the performance of power system and safety of personnel has been well recognized since the early days of power systems. Unfortunately, design procedures are hindered by a number of factors that are difficult to quantify. Based primarily on experience and simple analytical models, the first guide for the design of substation grounding systems was introduced in 1961: the ANSI/IEEE Standered 80-2000.[2] This document, together with two major revisions in 1976 and 1986, has been the primary tool available to substation engineers for analysis and design of substation grounding systems.[1]

Standard 80 provides design criteria and guidance above to what should be considered in the process of designing a grounding system. In addition, it provides design equation applicable to simple grounding systems. The increased complexity and higher short-circuit capacities of present-day interconnected power systems requires improved analysis methods and design procedures for grounding systems. Improved analysis method, which are computer based, have been developed.

1.1 Background

On its way from generating station to the end consumer, electrical power passes through different kinds of substations. Continuity of electrical power supply depends to a considerable extent upon the successful operation of substation. It is, therefore, essential to exercise atmost care while designing and building a substation. Grounding system plays crucial role in the performance of a substation as it provides a place for connecting system neutral points, equipment body and support structures to the earth. It also ensures safety of working personnel within the substation and enables earth fault detection and protection. It provides path for discharging the earth currents from neutrals of equipments, faults, surge arrestors, overhead shielding wires etc. It keeps step and touch potential within tolerable limits. Hence, properly designed and installed grounding system ensures reliable performance of electrical substation, safety of persons working within or near substation and limits the ground potential rise within acceptable levels. Substation grounding system being an essential part of the overall electrical system, its design is also of very much importance.

A well designed grounding system ensures following :

1) It provides means of dissipating electrical current into earth without exceeding operating limits of equipment.

2) It provides safe environment to protect personnel in the vicinity of the grounded facilities from the dangers of electric shock under normal and fault conditions.[2]

1.2 Literature Review

Gary Gilbert - High Voltage Grounding Systems.[1]

The goal of the thesis is to improve upon the current restrictions for the grounding grid design as laid by IEEE - 80 - 2000 i.e. applicability to uniform soil models only and use of relatively simpler grid geometries, while minimizing the material and installation costs of a grid. The first part of the research examines previous work through a combination of literature review, mathematical computations, and field measurements to validate the theoretical aspects of grid design. The thesis introduces method for extraction of optimized uniform and two-layer soil model with fast accurate calculations directly from soil measurements. Next, the thesis develops enhanced grounding parameter equations using Simpsons rule of integration. The final part of the thesis demonstrates how it is possible to optimize the configuration of the grounding grid itself, minimizing costs, and yet achieving a safe installation. The techniques are applied to existing real-world grid designs, and the results obtained show the effectiveness of the method in reducing construction costs. This thesis shows how these construction and material savings are realized by utilizing a process whereby the grounding system design minimizes the overall cost. The overall contribution of this thesis is the optimization of the grounding grid design by eliminating the current restrictions found in the IEEE standards 80 and 81, respectively, and offering an optimized grounding system design, starting from the soil model to the actual grounding design itself.

IEEE guide for safety in ac substation grounding - IEEE standard 80.[2]

This guide serves as a mentor in the field of grounding system design. It guides how safe practices can be followed in AC substation grounding system design. This guide is primarily concerned with safe grounding practices for power frequencies in the range of 50-60 Hz. The intent of this guide is to provide guidance and information pertinent to safe grounding practices in ac substation design. Specific purposes of this guide are to

- Establish, as a basis for design, the safe limits of potential differences that can exist in a substation under fault conditions between points that can be contacted by the human body.
- Review substation grounding practices with special reference to safety, and develop criteria for a safe design.
- Based on these criteria, provide a procedure for the design of practical grounding systems.
- Develop analytical methods as an aid in the understanding and solution of typical gradient problems.

Safety criteria established by this guide are accepted world wide. It establishes the safe limits of the potential differences that can exist in a substation during the worst case fault conditions. Simplified procedure for design of any practical grounding system, subjected to constrains of the safety criteria established therein is elaborated. It provides guide lines for designing any safe grounding system. This is basically meant for substations located in sites having uniform resistivity soils. However, some light is also thrown on modeling of soil as two layered soil.

IEEE guide for measuring earth resistivity, ground impedance and earth surface potentials of a grounding system - IEEE standard 81.[3]

Measuring earth resistivity and deriving appropriate soil model to be used in the grounding system calculations is of prime importance before starting actual design of substation grounding system. Measuring actual grounding system impedance and earth surface potentials is of great importance after the actual grounding system has been installed. This standard gives guidelines for measurement and interpretation of earth resistivity and for measurement of grounding system impedance and earth surface potentials for any practical substation. It describes various methods for measurement of earth resistivity at substation site. From the measured resistivity data an earth model has to be extracted which represents the substation soil structure best suited for grounding system calculations. This guide gives idea about interpretation techniques which can be used to derive soil model as uniform resistivity soil or two layered soil. After soil resistivity model is known, grounding system resistance, touch voltages, step voltages and earth surface potentials can be calculated. This guide also describes how to measure earth impedance of grounding system and earth surface potentials in order to verify the theoretically calculated values.

John D Mc Donald. - Electrical power substation engineering.[4]

This book emphasizes on importance and objectives of the substation grounding system. It states that for safety there has to be appropriate interaction between two grounding systems namely Intentional ground and Accidental ground. It explains concept of accidental ground circuit and criteria for the safe grounding design is derived. Also method for design of practical grounding system is explained in detail based on the standard IEEE 80 - 2000. Finally various factor affecting the performance of the grid are discussed with relevant graphs.

A.P.Sakis-Power System Grounding and Transients[5].

This book have two chapter for grounding system design.In first chapter discussed analysis procedures of power system grounding systems.These techniques are applicable to the analysis of substation grounding systems as well as transmission tower grounding.The methodologies are based on dc analysis, which is accurate for spatially small systems energized with low-frequency currents and voltages. Under these conditions,the resistance of the grounding system is the dominant component of the impedance. The reactance is typically neglected.This approach is accurate for most practical grounding systems. For spatially large systems, however, especially grounding systems in low soil resistivity, it is possible that the reactance may be the dominant component of the impedance even at low frequencies(i.e.,60Hz). The reactance of a grounding system can be computed with fungistatic analysis, which is not presented in this book.

In second chapter discussed design procedures of substation grounding systems.The objective of these procedures is to define a grounding system that meets safety requirements. IEEE Standard 80 delineates safety requirements for ac substation grounding systems.The design procedure is iterative, based on analysis and subsequent modification of the grounding system until the safety requirements are met.The single most important item of the process is accurate determination of the maximum ground potential rise. Other important items are investigation of special points of danger. A qualitative discussion and examples were presented, as were two comprehensive examples of the iterative design procedure. By necessity, computer-based models of grounding system are required in the design process.

N.C. Chang and C.H Lee. - Computation of ground resistances and assessment of ground grid safety at 161/23.9-kV indoor type substation.[6]

This paper presents accurate formulas to calculate apparent soil resistivity in order to simplify two layered soil structure into equivalent one layer soil model. Also an empirical formula is suggested which adds a correction factor to widely used Sveraks resistance formula to calculate the resistance of ground grid and vertical ground rods as a whole while utilizing a simplified one layer soil model for the two layered earth structure. Here authors have computed resistance of grounding grid for three indoor substations of Taiwan Power Company by four various methods namely

1) Schwartzs equation considering only single layered soil structure

2) Salama and Chows equation considering two layer soil model with grid buried in the lower layer

3) Most widely used Sveraks formula using simplified one layer soil model of two layered earth and

4) An empirical formula adding a corrective factor to the Sveraks formula.

Authors have compared the results obtained by all the four equations with the practically measured values and found that the first method gives the most erroneous result because it neglects the second layer at all and the last method gives the most accurate result comparable to the practically measured values. Sveraks formula is widely accepted now a days and is also used by IEEE - 80. Use of this formula here also gives quite good results with minor error. GPR values calculated by all the four methods are compared with safety criteria of IEEE standard 80 which shows superiority of the empirical equation and poor performance of the Schwartzs one layer model. Thus as suggested by the authors, when two layered soil is encountered, empirical formulas given here for apparent resistivity and grounding system resistance should be used.

Salama M M A Chow Y.L. and Elsherbiny M.M. - Resistance formulas for grounding system in two layer earth.[7]

Preliminary grounding system designs need simple and reasonably accurate formulas to calculate grounding system resistance. This paper gives resistance formulas of grounding system components namely: Ground grid, Vertically driven rod bed and combination of grid and rod bed installed in two layered soil. Authors have verified the validity of formulas by checking against the results obtained with various numerical methods. Here authors have applied novel synthetic asymptotic approach for deriving resistance formulas. Equations derived here are easy to use and yet accurate. They can be easily implemented in computer software form or even used with hand calculator as well. Moreover these formulas do not require use of empirical tables or graphs for calculating grounding system resistance values. Formula given for driven rod bed is found quite efficient and when used with other equations available for the grounding grid resistance such as in [8], the overall results obtained are quite realistic. Hence this paper serves very much useful for calculating grounding system resistance in two layered soils.

Victor Gerez, Arun Balakrishnan, Baldev Thapar and Donald A. Blank - Evaluation of ground resistance of a grounding grid of any shape.[8]

One of the basic steps in determination of preliminary layout and size of a grounding grid of AC substations is calculation of grid resistance. Simplified calculations when applied to grids of different shapes produce considerable errors. This paper presents a formula which can be applied to determine the ground resistance of grid of any of the basic shapes. Results obtained with this formula have been verified by comparison with accurate results obtained with computer software. While using this formula with ground rods and also in two layered soil, some modification has to be applied to this formula. This paper serves very much useful for mathematical modeling of ground grids of various shapes.

Dawalibi F. P. and Blattner C. J. - Earth Resistivity Measurement Interpretation Techniques.[9]

This paper describes earth resistivity measurement interpretation techniques. It explains two approaches viz. graphical curve matching technique and analytical soil model derivation technique along with use of computer programming. Initially it discusses soil structure modeling problem as inverse problem where from known electrical properties of earth, its physical properties in terms of soil resistivity and soil layer depth are to be derived. It gives formulas for apparent resistivity in terms of resistivities of two layers for soils having horizontal stratification and also for vertical stratified soils formulas are provided. Next, authors discuss how equivalent two layered soil model can be interpreted from Earth Resistivity Testing (ERT) data using Sunde's graphical method. Finally guidance for implementation of theoretical concepts in terms of computer program is given where by using the computer programming two layered soil model can be derived from ERT data.

Ahdab Elmorshedy, Rabah Amer, Sherif Ghoneim and Holger Hirsch. - Surface Potential Calculation for Grounding Grids.[10]

In this paper a study of grounding grid performance with variation of soil layer depth is carried out for grounding system of a practical 22 kV substation having grid made up of copper. CDEGS software is used as a grounding system analyzer tool. Soil resistivity test is carried out at the substation site and the equivalent soil model is generated with the help of CDEGS. The soil is modeled as two layered soil with lower layer having higher resistivity than upper layer. Grounding system performance is analyzed considering two factors

1) By varying the depth of burial of ground grid with fixed ground rod length

2) By varying ground rod length keeping depth of burial fixed

As observed from the analysis, GPR reduces as the depth of burial increases until the boundary of two layers is reached. When the grid is buried in the lower layer soil with higher resistivity, GPR goes on increasing rather than reducing. Hence thickness of upper layer has significant influence on the surface potential distribution, especially when the second layer has higher resistivity than the first layer. In case of variation in ground rod length, GPR goes on decreasing as length of rods is increased irrespective of whether they are only in upper layer or approach the boundary of two layers or even penetrate the high resistivity lower layer. Thus increased length of ground rods plays an important role in the GPR reduction, thereby improving performance of the grounding system. In actual practise deep driven rods are considered to be effective solution in the situations when soil has very high resistivity or when upper layer is likely to freeze due to snow fall because rods dissipate current in the deep earth having resistivity nearly constant throughout the year .

O.P. Rahi, Abhas Kumar Singh, Shashi Kant Gupta, Shilpa Goyal-Design of Earthing System for a Substation : A Case Study.[11]

This paper presents the design of earthing system for 132 KV substation and simulation for calculation of required parameters. This paper is to provide information pertinent to safe earthing practices in ac substation design and to establish the safe limits of potential difference under normal and fault conditions. The grounding grid system of a practical 220 kV substation is calculated by MATLAB program. The supporting data has been obtained from actual field tested at the substation. Standard equations are used in the design of earthing system to get desired parameters such as touch and step voltage criteria for safety, earth resistance, grid resistance, maximum grid current, minimum conductor size and electrode size, maximum fault current level and resistivity of soil. By selection the proper horizontal conductor size, vertical electrode size and soil resistivity, the best choice of the project for safety is performed. This paper mentions the calculation of the desired parameters which are simulated by MATLAB program. Some simulated results are evaluated.

Fikri Baris Uzunlar, zcan Kalenderli-Three Dimensional Grounding Grid Design.[12]

This study presents an advanced methodology and a computer model for analysis of grounding systems conforming to standards IEEE Std 80-2000, IEEE Std 81- 1983 and IEEE Std 837-2002. The methodology and computer program is validated with actual system measurements. The accuracy of computer algorithm is dependent on how well the soil model and physical layout reflect actual field conditions. The tolerable voltage limits and the maximum predicted voltage values are calculated using empirical formula in given standard. The step, touch and mesh voltages and hot zones are calculated according to the recommendations in given standard and the differences between them are investigated and clarified. The simulations are carried out with the aim to verify the possibility of introducing some practical design criteria helpful for engineering applications. Substation grounding grid design and analysis module is specially designed to help engineers optimize the design of new grids and reinforce existing grids, of any shape, by virtue of easy to use, built-in danger point evaluation facilities.

L. M. Coa-Comparative Study between IEEE Std. 80-2000 and Finite Elements Method application for Grounding Systems Analysis.[13]

This paper presents a brief compilation of typical and particular cases of grounding systems calculation using procedures proposed by IEEEstd 80-2000 simulated by means of a software developed under the mathematical tool MATLAB, based on the Finite Elements Method. This study consists, basically, of tables and graphics that show a series of interesting results and offer are liable and practical instrument for the grounding systems design.

Kaustubh A. Vyas-Optimal Design of Substation Grounding Systems.[14]

This report is aimed at describing the development of and utilization of software for optimal design of substation grounding systems. Here, IEEE methodology for design of grounding system is implemented in computer programming environment. Software named ‘ Economical Substation Grounding System Designer (ESGSD) ’ has been developed using MATLAB as mathematical computing tool as well as programming platform and MATLAB runtime compiler for windows standalone application.

Working of ESGSD is divided in main two parts

- It allows simple performance analysis for grounding system having ground grid of any of the five basic shapes. It follows IEEE criteria for this purpose and additionally allows modeling of soil as two layered structure.

- By selecting appropriate optimization options, ESGSD is able to give optimal design of substation grounding system for grounding grids having any of the basic shapes and located in uniform or two layered soil.

In addition to grounding system analysis and optimization, ESGSD allows derivation of soil model from available Earth Resistance Testing (ERT) data. It can extract both type of soil models i.e. uniform and two layered soil models from available test data, to be used in further calculations.

1.3 Problem Identification and Proposed Solution

In order to ensure correct operation of control and protective devices and for safety of working personnel and equipments in the substation designing safe and effective grounding system for any substation is of prime importance. Keeping in view the exercises to be carried out in designing the grounding system, problem undertaken here is of designing optimal grounding systems for HV / EHV substations. Grounding system of the substations is designed using basic philosophy of IEEE standard 80-2000 ‘ IEEE Guide for safety in AC substation grounding ’ [2]. However, certain modifications are made to basic equations given in IEEE guide, so that design of grounding system can be obtained in uniform soil layered . IEEE standard 80-2000 design equation gives single point of Touch, Step,and Mesh potential. [2]

In order to design safe and economical grounding system for any substation, software is developed using MATLAB as mathematical computing tool as well as programming platform. This is attempted to reduce the calculations, re-calculations and established standardized approach. It implements theoretical concepts of FE method in to programming environment to give grounding system analysis tool. Additionally, soil model derivation algorithm and different design applied for optimization to simple grounding system analysis procedure in order to extract appropriate soil model from ERT data and obtain optimal design of the grounding system.

1.4 Objectives of the Project

This project is intended for designing optimal grounding system for high voltage substation. In order to ensure the accomplishment of the project, following objectives are defined.

- Thoroughly study and understand the safe grounding practices as explained in IEEE 80 - 2000 and FE method.
- Develop coding to implement the theoretical concepts of FE method for grounding system design into the computer software.
- Verify the software outcome with known test systems to a good accuracy level.
- Suggest modification(s) to the design, to improve grounding performance.

1.5 Project Planning

Figure1.1 shows block diagram describing overall planning of the project. As seen from the flow chart, the main task of the project has been divided in various four phases namely

- Implementation of concepts given in FE method in the software form using MATLAB coding.
- Extending simple FE method design procedure for uniform soil layered so that it can handle more realistic cases rather than using IEEE 80-2000 design methodology.
- Implementation of FE method using MATLAB.

Also technical performance of the software developed here is tested by comparing the results given by it with those obtained from GGS module of ETAP professional software and IEEE 80-2000.

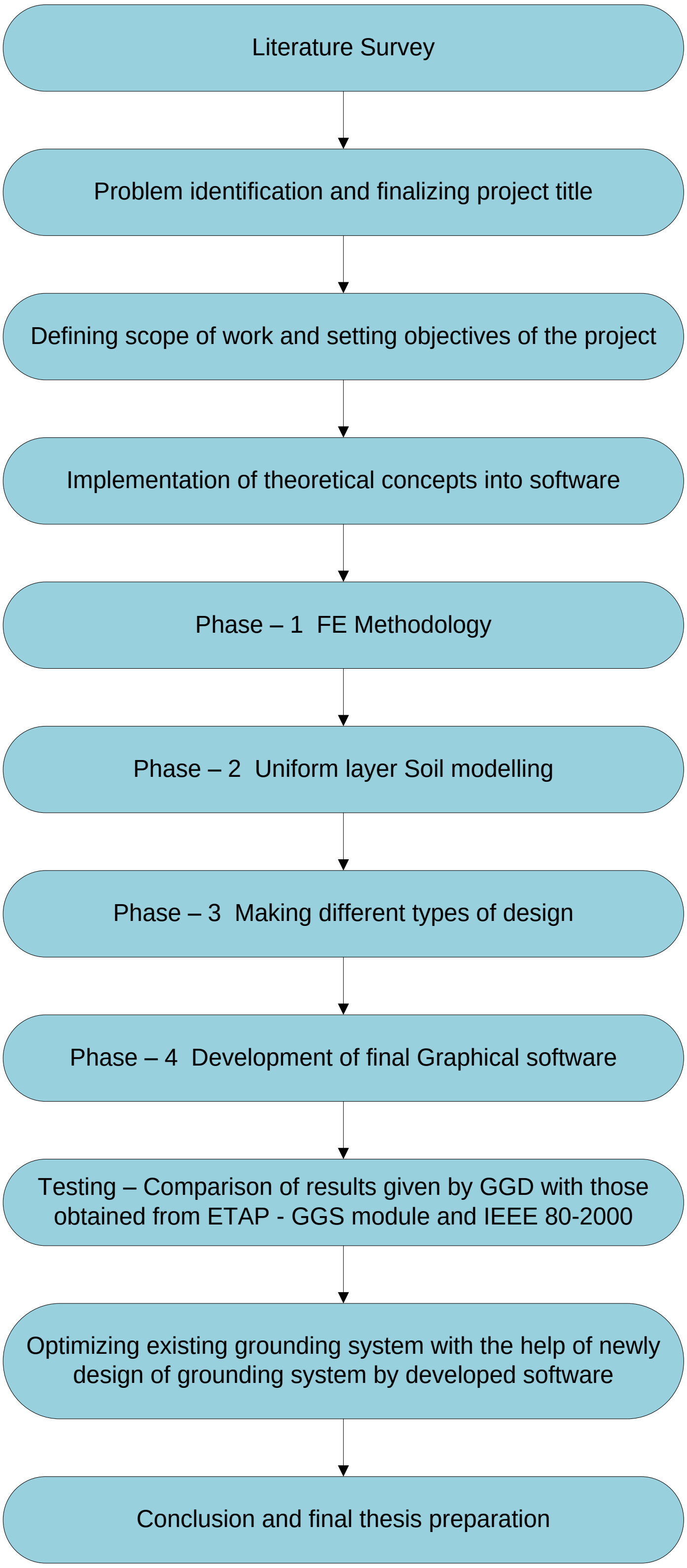

Figure 1.1: Block Diagram of Project Planning

1.6 Thesis Organization

Thesis of the major project entitled **" Optimal Design Software for Substation Grounding "** is organized in eight chapters and two appendices to describe the theoretical basis of substation grounding system design and its implementation carried out during during the due course of the major project

Ch.1 : Introduction and Literature Review :- It gives theoretical background and explains significance of the topic of the project. Then literature review highlights important findings from some of the papers surveyed during the period of the project work. Based on this, problem definition is decided and solution for the problem found is proposed. Next, objectives for the entire duration of the project work are fixed, scope of the work is defined and modular planning of the entire project is prepared. Finally thesis organization describes how the report is arranged for presenting the work in simple and illustrative way.

Ch.2 : Importance of Grounding System :- It starts with explaining importance of grounding system for successful operation of entire power system. It describes reasons for providing grounding system. Concept of accidental ground circuit is explained with relevant figures and equations. Next, safety criteria for touch and step potentials are derived as per IEEE guidelines which is most important step in the grounding system design process.

Ch.3 : Importance and Derivation of Soil Model :- This chapter introduces role of soil characteristics in grounding system design and importance of selection of appropriate soil model for grounding system design calculations is introduced. The significance of soil model to be used for grounding system design and describes soil resistivity measurement techniques used in actual practice. Then it describes how mathematical model of soil can be derived from ERT data available form field testing. Then it shows implementation of this theoretical concept in the software GGD.

Ch.4 : Numerical Analysis Using FE Method :- This chapter explain the FE method for grounding design.In FE method first calculate the VDF(voltage distribution factor) by self and mutual resistance with different direction (x,y,z) and transfer resistance for the ground potential by Combined Integration/Matrix Method. For calculation of Ground Resistance, GPR, Touch potential, Step potential.

Ch.5 : FE Methodology for Grounding Design :- This begins with specifying the objectives of grounding system design and role of FE method in that design procedure. Then step by step methodology for design of grounding system as per FE methodology is elaborated with necessary equations. As the design procedure of Fe method is pertinent to uniform soils only.

Ch.6 : Software deployment :- It describes implementation of the concepts given in FE metod in the software form by converting relevant equations in MATLAB code. Working of the software GGD is explained along with the flowchart depicting the algorithm used for development of the software. Analysis options provided by the software are enlisted and details of various input output modules of the software are discussed briefly.

Ch.7 : Validation Performance of GGD Software :- Performance of the software is validated by means of software testing i.e. sample problems of IEEE 80-2000 Annex-B (Example-1,2,3)have been solved by using GGD and standard software ETAP -GGS. Results given by GGD are compared with the results obtained from ETAP and IEEE 80-2000 Annex-B (Example-1,2,3)..

Ch.8 : Conclusion :- This provides essence of the whole project work in brief and states important findings as obtained during this work.Grounding system design as per FE methodology in optimized way is almost complete by the end of this project work. However still concept of method of images can be implemented in the same software to get more rigorous analysis. This chapter throws light on what novel things can be attempted in this project work in future.

Chapter 2

Importance of Grounding System

2.1 Important Definitions

(1) Ground : 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.

(2) Grounding : Connection of any equipment body or neutral point with the general mass of the earth, by means of a low resistance conducting path having sufficient current carrying carrying capacity, such that equipment remains at reference or earth potential is known as earthing or grounding.

(3) Grounding grid : A system of horizontal ground electrodes that consists of a number of interconnected, bare conductors buried in the earth, providing a common ground for electrical devices or metallic structures, usually in one specific location.

(4) Grounding system : It comprises of all interconnected grounding facilities in a specific area.

(5) Ground potential rise (GPR) : The maximum electrical potential that a substation grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. This voltage, GPR, is equal to the maximum grid current times the grid resistance.

(6) Mesh voltage : The maximum touch voltage within a mesh of a ground grid.

(7) Metal-to-metal touch voltage: The difference in potential between metallic objects or structures within the substation site that may be bridged by direct hand to-hand or hand-to-feet contact.

(8) Step voltage : The difference in surface potential experienced by a person bridging a distance of 1 m with the feet without contacting any grounded object.

(9) Touch voltage : The potential difference between the ground potential rise (GPR)and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure.

(10) Transferred voltage : A special case of the touch voltage where a voltage is transferred into or out of the substation from or to a remote point external to the substation site.

2.2 Importance of Grounding System

In every electrical installation, one of the most important aspects is adequate grounding; more specifically, the grounding of high-voltage substations to protect people and equipment in the event of an electrical fault. Well-designed grounding systems ensure the performance of power systems and safety of personnel. Design procedures, however, are often hindered by a number of factors that are difficult to quantify. Based primarily on experience and simple analytical models, the first guide for the design of substation grounding systems was introduced in 1961: the ANSI/IEEE Std 80-2000[2]. This document, together with three major revisions in 1976, 1986, and 2000, has been the primary tool available to substation engineers for analysis and design of substation grounding systems. The IEEE Std 80-2000 is limited to the uniform soil model, which is not found in many substation locations; however the IEEE Std 81-1983 [3] offers empirical solutions for the two layer soil model. The empirical solutions offered within this standard still rely on complex image theory which drastically slows the computational speed of the solution whereby researchers are limited with its usage.

When there is a ground fault at a substation, the flow of ground current depends on the impedances of the various possible paths. Currents may flow between portions of the substation ground grid, between the ground grid and the surrounding earth (i.e. out of the substation area), along overhead sky wires, or along a combination of all these paths. The potential rise of a substation when a current is flowing through its ground must be limited to a safe value so that there is no danger to anyone touching conductive material, such as the substation fence. Figure 2.1 demonstrates the step, touch and the ground potential rise voltages that a worker could be subjected in the event of a ground fault. The ground potential rise (GPR) at the station is equal

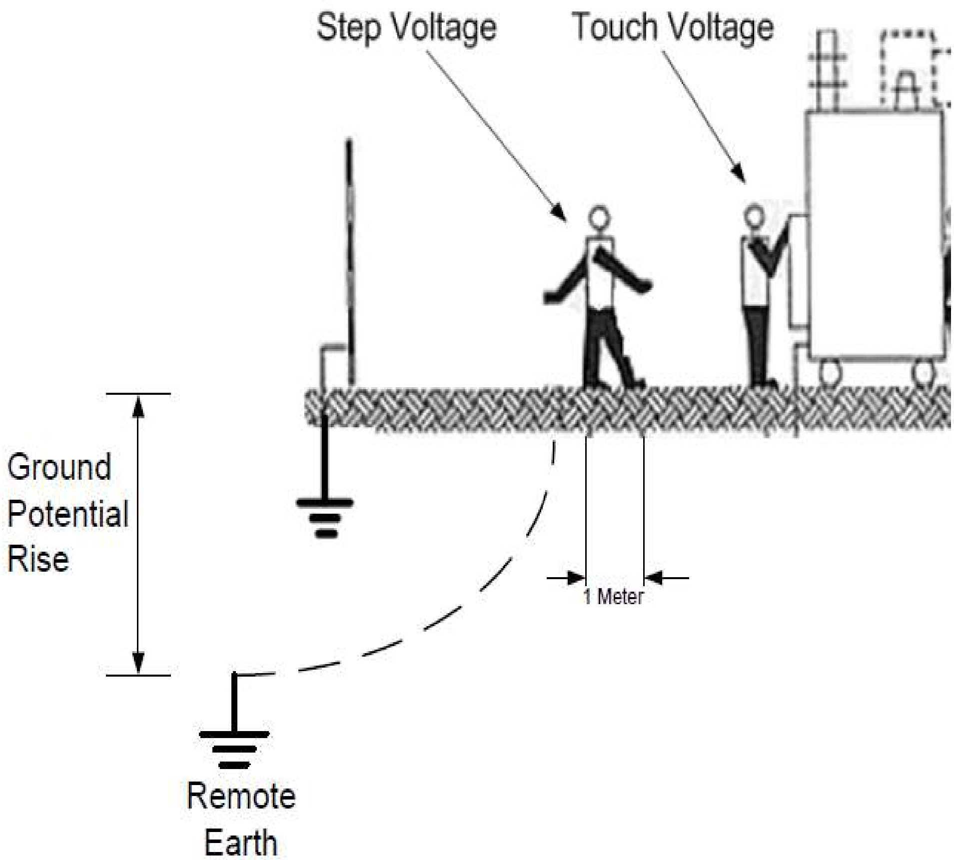

Figure 2.1: step, touch and the ground potential rise (GPR)

to the current flowing between the ground and the surrounding earth multiplied by the station grounding resistance in relation to remote earth. It is desirable that the substation grounding system provide a low impedance path to allow for the fast safe dissipation of any and all fault currents. The prevailing practice of most utilities is to install a grid of horizontal ground electrodes (buried bare copper conductors) supplemented by a number of vertical ground rods connected to the grid, and by a number of equipment grounding mats and interconnecting cables. The grounding grid provides a common ground for the electrical equipment and for all metallic structures at the station. It also limits the surface potential gradient. The vertical ground rods decrease the overall resistance of the substation. There are three variables that affect the resistance of the ground rods[1].

- The ground itself can affect the resistance of the ground rods. The soil around the rods is seldom homogeneous and resistance values can vary greatly.
- The depth of the ground electrode can affect the resistance of the ground rods. This is a very effective way of decreasing substation resistance. The earth is in layers and the resistivity of each layer considerably changes from layer to layer. Generally, doubling the length of the rod can decrease resistance by about 40%. Most of the rod is below frost level so freezing will not considerably increase the substation resistance.
- The diameter of the ground electrode can affect the resistance of the ground rods. The diameter of the rod affects the resistance but the effect is not very large. Doubling the diameter of the rod will decrease the rod resistance by only 10 %. Each grounding rod has its sphere of influence and, to be effective, the rods cannot be crowded. In general, the spacing between the rods should not be less than the depth to which they are driven.

2.3 Concept of Accidental Grounding Circuits

For DC and power frequency currents human body can be approximated by a resistance. Generally accepted value of the body resistance is 1000 ohms which represents resistance of human body form hand to feet, hand to hand or from one foot to the other foot.

Accidental ground circuits considered for establishment of safety criteria are.
1. Touch voltage accidental ground circuit
2. Step voltage accidental ground circuit
Safety criterion for substation grounding system design is based upon tolerable body current limits. The magnitude and duration of the current flowing through a human body at power frequency should be less than that value which can cause ventricular fibrillation of the heart. The duration for which a power frequency current can be tolerated by most people is related to the magnitude by following equations as suggested by Dalziel[2].

$$I_B = \frac{K}{\sqrt{t_s}} \tag{2.1}$$

Formulas for allowable body current are as follows

where

I_B=Body current

k= Constant as per body weight.

For people weighing 50 Kg

$$I_B = \frac{0.116}{\sqrt{t_s}} \tag{2.2}$$

For people weighing 70 Kg

$$I_B = \frac{0.157}{\sqrt{t_s}} \tag{2.3}$$

Figure 2.2 and 2.3 show two most commonly encountered shock conditions viz. Step voltage and Touch voltage and their equivalent circuits. A person exposed to shock condition due to contact with grounded metallic object which is at different potential than the earth surface potential is said to have experienced a touch voltage and current I_b passes through its body from hand through both feet to ground. A person exposed to shock because of passage of fault current through human body from one foot to another foot through lower part of body into the grounding system is said to have experienced a step potential on the substation earth surface. It is because of flow of high magnitude of fault current through the ground grid. Values of Z_{th} for the two equivalent circuits are as follows.

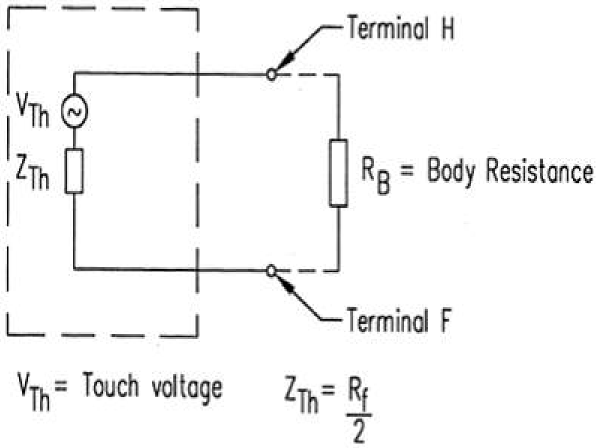

Figure 2.2: Touch voltage equivalent circuit

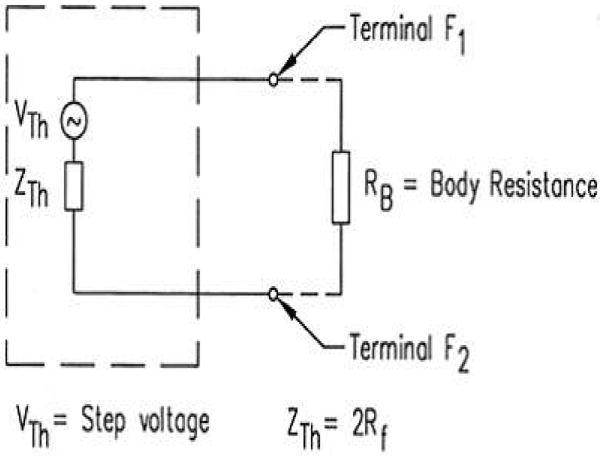

Figure 2.3: Step voltage equivalent circuit

For touch voltage accidental circuit

$$Z_{th} = \frac{R_f}{2} \tag{2.4}$$

For step voltage accidental circuit

$$Z_{th} = 2R_f \tag{2.5}$$

where R_f =ground resistance of one foot.

Z_{th} =Thevenin's equivalent impedance.

For the purpose of circuit analysis value of Rf as suggested by Laureate is given by

$$R_f = \frac{\rho}{4b} \tag{2.6}$$

where ρ=earth surface resistivity

b= radius of metallic disc representing human foot on the ground surface.

2.4 Safety Criteria as per IEEE Guideline

In above equations value of b is taken as 0.08 meter traditionally and hence Thevenins equivalent impedance for the aforesaid two cases become

For touch voltage accidental circuit

$$Z_{th} = \frac{R_f}{2} = 1.5\rho \tag{2.7}$$

For step voltage accidental circuit

$$Z_{th} = 2R_f = 6\rho \tag{2.8}$$

Generally in substations a thin layer (6 - 15 cm) of crushed rock or other high resistivity material is used to enhance safety of persons working therein. This layer of high resistivity material adds to foot resistance. This is taken into account in resistance formula as follows.

Considering effect of surface layer resistivity ρ_s , value of R_f gets modified by a factor C_s known as surface layer derating factor as follows

$$R_f = \left(\frac{\rho_s}{4b}\right) C_s \tag{2.9}$$

Here Cs can be calculated by an empirical formula

$$C_s = 1 - \frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09} \tag{2.10}$$

where

C_s= surface layer derating factor

ρ_s= surface layer resistivity

h_s=thickness of surface layer

Thus permissibal total equivalent voltage are

$$E_{touch} = I_B \cdot (R_B + 1.5\rho_s C_s) \tag{2.11}$$

$$E_{step} = I_B \cdot (R_B + 6\rho_s C_s) \tag{2.12}$$

Safety of a person depends on preventing critical amount of shock energy from being absorbed by human body before the fault is cleared and the system is de - energized. Maximum driving voltage of any circuit should not exceed the limits defined herein For step voltage the limit is

$$E_{step} = I_B \cdot (R_B + 2R_f) \tag{2.13}$$

Thus step voltage safety limit equations become
For person weighing 50 Kg

$$E_{step50} = (1000 + 6\rho_s C_s) \cdot \frac{0.116}{\sqrt{t_s}} \tag{2.14}$$

For person weighing 70 Kg

$$E_{step70} = (1000 + 6\rho_s C_s) \cdot \frac{0.157}{\sqrt{t_s}} \tag{2.15}$$

For touch voltage the limit is

$$E_{touch} = I_B \cdot \left(R_B + \frac{R_f}{2} \right) \tag{2.16}$$

Thus touch voltage safety limit equations become

For person weighing 50 Kg

$$E_{touch50} = (1000 + 1.5\rho_s C_s) \cdot \frac{0.116}{\sqrt{t_s}} \tag{2.17}$$

For person weighing 70 Kg

$$E_{touch70} = (1000 + 1.5\rho_s C_s) \cdot \frac{0.157}{\sqrt{t_s}} \tag{2.18}$$

where

E_{step}=Step voltage in Volts

E_touch=Touch voltage in Volts

C_s= surface layer derating factor

ρ_s= surface layer resistivity in $(\Omega \cdot m)$

t_s=Shock duration in sec

These safety criteria as established by IEEE are accepted world wide as safety constraints while designing any grounding system

Chapter 3

Importance and Derivation of Soil Model

3.1 Selection of Appropriate Soil Model

Design of grounding system requires development of a suitable mathematical model of soil to represent the electrical properties of the earth in which the grid will be installed. The most commonly used soil models are uniform resistivity soil and two layered soil models. Substation sites where the soil may possess uniform resistivity through out the area and up to considerable depth are seldom found. Typically there are several layers each having different resistivities. Hence uniform soil model should be used only when there is a moderate variation in apparent resistivity. In homogeneous soil, uniform resistivity soil model is reasonably accurate. However if there is large variation in measured apparent resistivity, uniform soil model is unlikely to yield accurate results. In such situations, more accurate representation of actual soil condition can be obtained by use of two layered soil model. Hence derivation of appropriate soil model is essential while designing grounding system for substations, otherwise erroneous results are likely to be obtained.

3.2 Representation of Soil Models

3.2.1 Uniform Soil Model

A uniform soil model can be used instead of the multilayered soil model whenever the two-layer or multilayered computation tools are not available. Unfortunately, an upper bound of the error on all relevant grounding parameters is difficult to estimate in general, but when the contrast between the various layer resistivities is moderate, an average soil resistivity value may be used as a first approximation or to establish order of magnitudes [2]. This soil model is represented as only single layer of uniform resistivity with resistivity at various locations in the soil being nearer to the average resistivity of the soil which has been assigned as uniform resistivity of the soil. Figure3.1 shows uniform resistivity soil

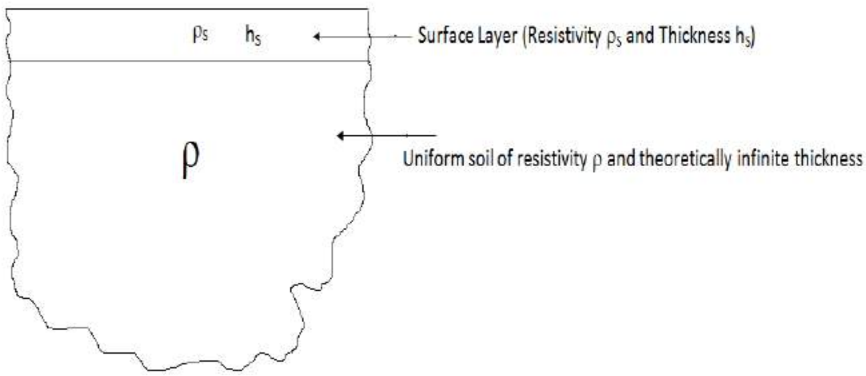

Figure 3.1: Uniform resistivity model

3.2.2 Two-Layer Soil Model

Typically, the observed resistivities vary when plotted as a function of the probe spacing. Large variations in probe spacing (a variance of greater than 30 percent) indicate that the earth is non-uniform, and a two-layer soil model must be used. Using a single-layer model in such a situation has been shown to cause significant errors in resistivities .

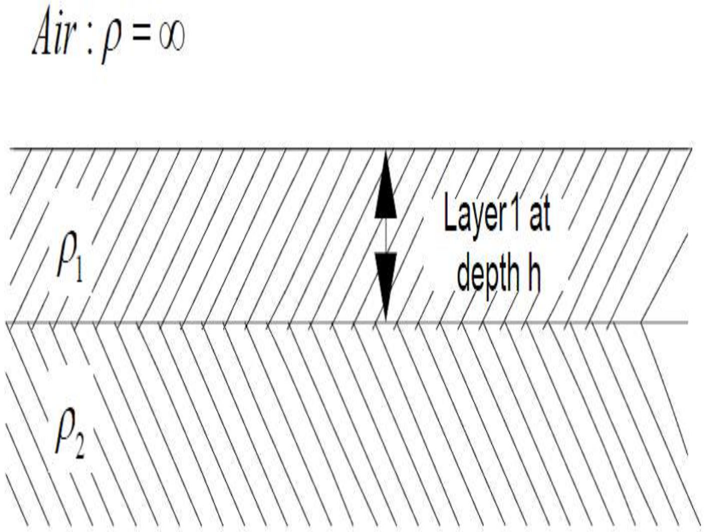

Figure 3.2: Two-layer resistivity model

Figure 3.2 represents the two layered soil model, which has an upper layer of a finite depth, h, and resistivity, ρ_1, over a lower layer of infinite depth and resistivity , ρ_2. The difficulty in using this model is the mathematical determination of the depth of layer one, due to the numerous variations in the structure and properties of the earth. The research presented by authors introduces a new technique that can be used for both the uniform and two layered models.

The methods used for interpolating the soil model from field measurements can be grouped into two categories: empirical or analytical. Empirical methods are typically developed through a combination of interpolation and field measurements. Sunde [1, 16] first proposed a graphical method to approximate a two-layer soil model, based on the interpretation of a series of curves which are commonly called the Sunde curves, and Figure 3.3 shows those curves.

Parameters ρ_1 and ρ_2 are obtained by inspection of resistivity measurements. The third parameter, h, is obtained by Sundes graphical method, which is explained in detail in the IEEE Standard 80, along with an example [2]. In Sundes method, the graph shown in Figure 3.3 is used to approximate a two-layer soil model, which is based on the Wenner four-pin test data or another method discussed earlier within the chapter. The parameters ρ_1 and ρ_2 are obtained by inspection of resistivity

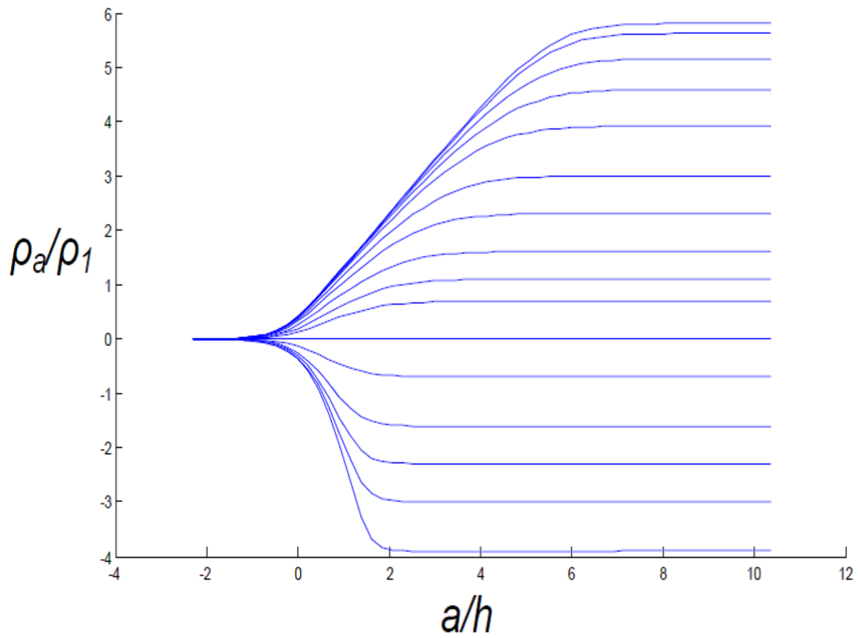

Figure 3.3: Sunde curves for two-layer soil structure from image thory

measurements and this is one of the limitations of the graphical methods as the designer begins the soil model determination by guessing. The parameter h is then obtained by Sundes graphical method, as follows:

(a) Plot a graph of apparent resistivity ρ_a on y-axis verses pin spacing on x-axis.

(b) Estimate ρ_1 and ρ_2 from the graph plotted in (a). ρ_a corresponding to a smaller spacing is ρ_1 and for a larger spacing is ρ_2. Extend the apparent resistivity graph at both ends to obtain these extreme resistivity values if the field data are insufficient.

(c) Determine ρ_1/ρ_1 and select a curve on the Sunde graph in Figure 3.4, which matches closely, or interpolate and draw a new curve on the graph.

(d) Select the value on the y-axis of ρ_a/ρ_1 within the sloped region of the appropriate ρ_2/ρ_1 curve of from Figure 3.4.

(e) Read the corresponding value of a/h on the x-axis.

(f) Compute a by multiplying the selected value, ρ_a/ρ_1, in (d) by ρ_1.

(g) Read the corresponding probe spacing from the apparent resistivity graph plotted in (a).

(h) Compute h, the depth of the upper level, using the appropriate probe separation, a.

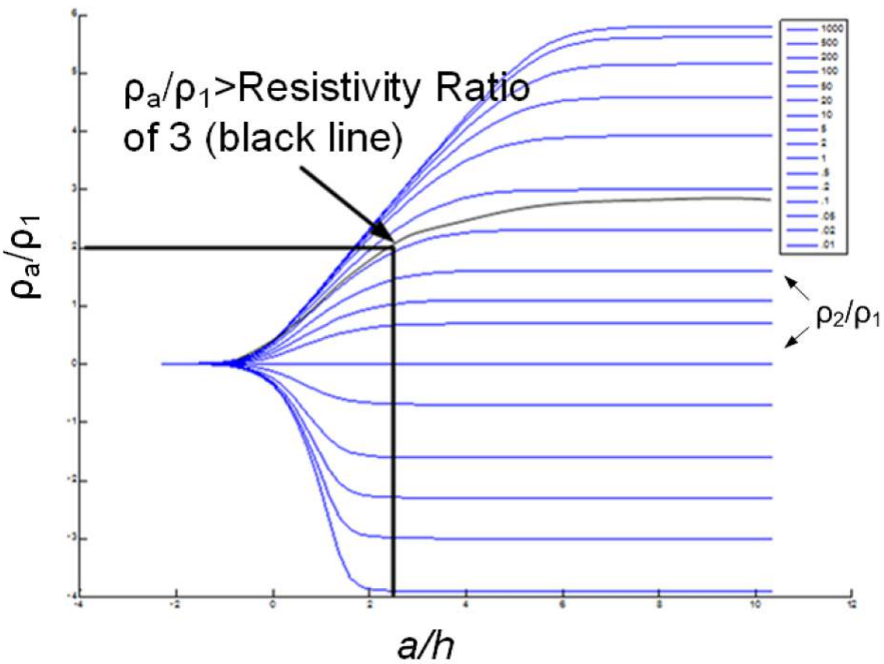

Figure 3.4: Sunde curves for two-layer soil structure from image thory

3.3 Significance of Soil Modeling in Substation Grounding System Design

The most commonly used soil model for grounding system design purpose are uniform and two layered soil models as described before. For simplicity of calculations and design of grounding system strictly according to IEEE guidelines, uniform soil model is preferred by many designers. In many cases if soil is not uniform, it is forcefully made uniform by soil treatment and addition of appropriate chemical backfills like bentonite. However if actual soil conditions are to be taken into account, two layered or even multi layered soil model has to be considered. For many of the cases where soil is multilayered, two layered equivalent of that soil will serve the purpose with sufficient accuracy. Hence here discussion is confined upto two layered soils only. Resistivity investigations of a substation site are essential for determining both the general soil composition and degree of homogeneity. Estimates based on soil classification yield only a rough approximation of the resistivity. Actual resistivity tests therefore are imperative.

3.4 Soil Resistivity Measurements

Factors such as maximum probe depth, lengths of cables required, efficiency of the measuring technique, cost (determined by time and the size of the survey crew), and ease of interpretation of the data must be considered when selecting the test type. Three common test types are the Wenner 4-Probe Method, Schlumberger Array, and the Driven Rod (3-Probe) Method. These methods will be discussed below. In homogenous isotropic earth, the resistivity will be constant; however, if the earth is non-homogenous and the electrode spacing is varied, a different value of resistivity will be found for each surface measurement. This measured value of soil resistivity is referred to as the apparent resistivity, a as measurement is used in the calculation of the soil model and is not the actual value of resistivity. This reinforces the requirement for an accurate soil model. For the three common test types, the measurement techniques and the test methods equations will be presented.

3.4.1 Wenner Array method

In the Wenner method (See Figure 3.5), all four probes are moved for each test, with the spacing between each adjacent pair remaining the same . In the Wenner 4-probe method, it is possible to measure the average resistivity of the soil between the two center probes to a depth equal to the probe spacing between adjacent probes. If the probe spacing is increased, then the average soil resistivity is measured to a greater depth[3]. If the average resistivity increases as the probe spacing increases, there is a region of soil having resistivity at the greater depth.

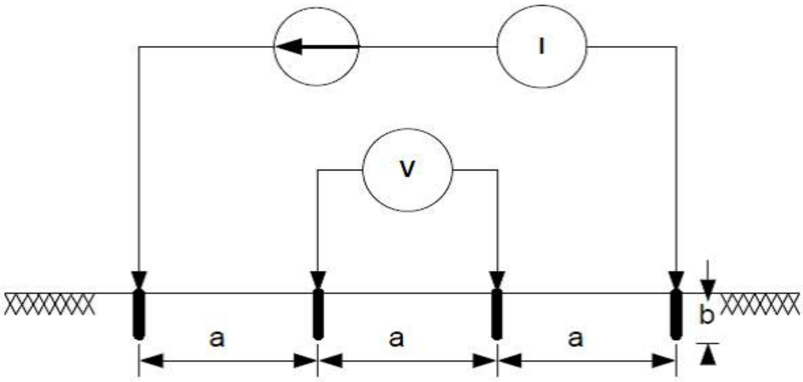

Figure 3.5: Wenner four-probe method

Equation 3.1, determines the apparent resistivity based on the surface measurements as shown in Figure 3.5 if the penetration of the probe, b, is small compared to the spacing of the four probes.

$$\rho_a = 2\pi a R \tag{3.1}$$

where

ρ_a is the apparent resistivity in $(\Omega \cdot m)$

a is the probe spacing (m)

R is the measured resistance (Ω)

If the ratio between the penetrations of the probe b is similar to the spacing of the four probes, then (3.2) must be used as the apparent resistivity is matched closer to the probe depth. It is suggested that when there is more the one layer of soil this equation allows for greater accuracy in the determination of soil depths. This is a curve fitted equation, developed by Wenner.

$$\rho_a = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2+4b^2}} - \frac{a}{\sqrt{a^2+b^2}}} \tag{3.2}$$

where

ρ_a is the calculated apparent resistivity $(\Omega \cdot m)$

R is measured resistance (Ω)

a is distance between adjacent electrodes (m)

b is depth of electrodes (m)

3.4.2 Schlumberger Array method

The Schlumberger array (Figure 3.6) requires that the outer probes be moved four or five times for each position of the inner probes [3]. The reduction in the number of probe moves also reduces the effect of lateral variation in the test results. Considerable time savings can be achieved by using this method, since there will be fewer probe placements than those required by the Wenner method, with similar results. The minimum spacing accessible is in the order of 10m (for a 0.5 m inner spacing), thereby necessitating the use of the Wenner configuration for smaller spacing. Lower voltage readings are obtained when using the Schlumberger arrays. This may be a critical problem where the depth required to be tested is beyond the capability of the test equipment or the voltage readings are too small to be useful. The Schlumberger array

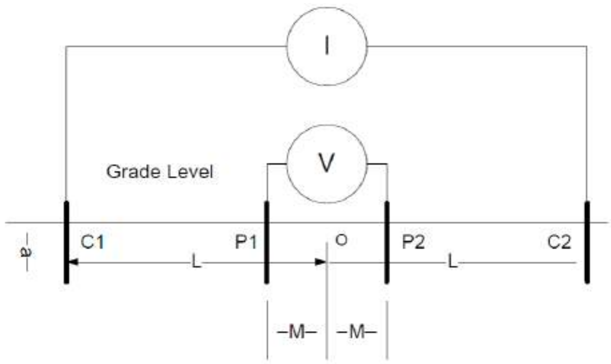

Figure 3.6: Schlumberger array

is more complex, with the spacing between the current probes not equal to the spacing between the potential probes. Equation 3.3 determines the apparent resistivity based on the surface measurements as shown in Figure 3.6.

$$\rho_a = \frac{2\pi L^2 R}{2M} \tag{3.3}$$

where ρ_a is the apparent resistivity $(\Omega \cdot m)$

R is measured resistance (Ω)

L is the distance from the center line to the outer probes (m)

M is the distance from the center line to the inner probes (m)

3.4.3 Driven Rod method

The driven rod method (Figure 3.7) is generally employed where transmission line structures are located[3]. This method is preferred because the measurements can be obtained without varying the spacing as required by the previous methods Equation

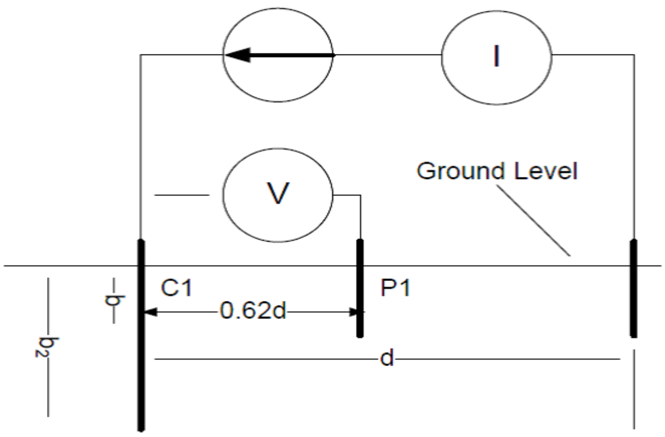

Figure 3.7: Driven Rod (3-Probe) method.

3.4 determines the apparent resistivity based on the surface measurements as shown in Figure 3.7.

$$\rho_a = \frac{2\pi b_2 R}{ln(\frac{2b_2}{d})} \tag{3.4}$$

where

ρ_a is the apparent resistivity $(\Omega \cdot m)$

R is measured resistance (Ω)

b_2 is the length of the driven rod in contact with the earth (m)

d is the spacing between the current probes (m)

Significant tests from Ohio State University have demonstrated that all of the measurement techniques above yield. In the research, however, it was determined that there must be significant changes in the measurement spacings. For example, an increase of 1m to 2m in spacing would yield results significantly different than smaller incremental spacing changes, like from 1.1m to 1.2m.

3.5 Derivation of Mathematical Model of Substation Soil

After getting basic knowledge about importance of selection of appropriate soil model in grounding system design and basic types of soil models that can be used, now it is praiseworthy to discuss about how mathematical model of the soil can be obtained from measured Earth Resistivity Testing (ERT) data. Interpretation of apparent resistivity obtained in the field is perhaps the most difficult part of the measurement program. The basic objective is to derive a soil model that is a good approximation of the actual soil. Soil resistivity varies laterally and with respect to depth, depending on the soil stratification.The most commonly used soil resistivity models are the uniform soil model and the two-layer soil model as described before. Two-layer soil models are often a good approximation of many soil structures while multilayered soil models may be used for more complex soil conditions. Interpretation of the soil resistivity measurements may be accomplished either manually or by use of computer analysis techniques

3.5.1 Derivation of Uniform Soil Model

The approximate uniform soil resistivity may be obtained by taking an arithmetic average of the measured apparent resistivity data as shown in Equation 3.5

$$\rho_{a(av)} = \frac{\rho_{a(1)} + \rho_{a(2)} + \rho_{a(3)} + ... + \rho_{a(n)}}{n} \tag{3.5}$$

where

$\rho_{a(1)}$, $\rho_{a(2)}$, $\rho_{a(3)}$, ... , $\rho_{a(n)}$ are the measured apparent resistivity data obtained at different spacings in the four-pin method or at different depths in the driven ground rod method in $\Omega \cdot m$

n = total number of measurements

A majority of the soils will not meet the criteria of Eq. 3.5. It is difficult to develop a uniform soil model when the resistivity of a soil varies significantly and soils are actually considered to be not uniform. Yet another approximation of uniform soil model is given by following Eq. 3.6

$$\rho_{a(av)} = \frac{\rho_{a(max)} + \rho_{a(min)}}{2} \tag{3.6}$$

where

$\rho_{a(max)}$ is the maximum apparent resistivity value (from measured data) in $\Omega \cdot m$

$\rho_{a(min)}$ is the minimum apparent resistivity value (from measured data) in $\Omega \cdot m$

There are number of assumptions made in the above study. As a result, the Equation 3.6 should be used with caution.

In software GGD this approach has been implemented in terms of MATLAB code that facilitates soil model extraction from measured resistivity data. Soil model module of GGD is shown in following figure 3.8. It facilitates soil model extraction from available ERT data if mathematical model of soil is not known. However if mathematical model of soil is already known it also allows direct manual entry of soil parameters for uniform soil.

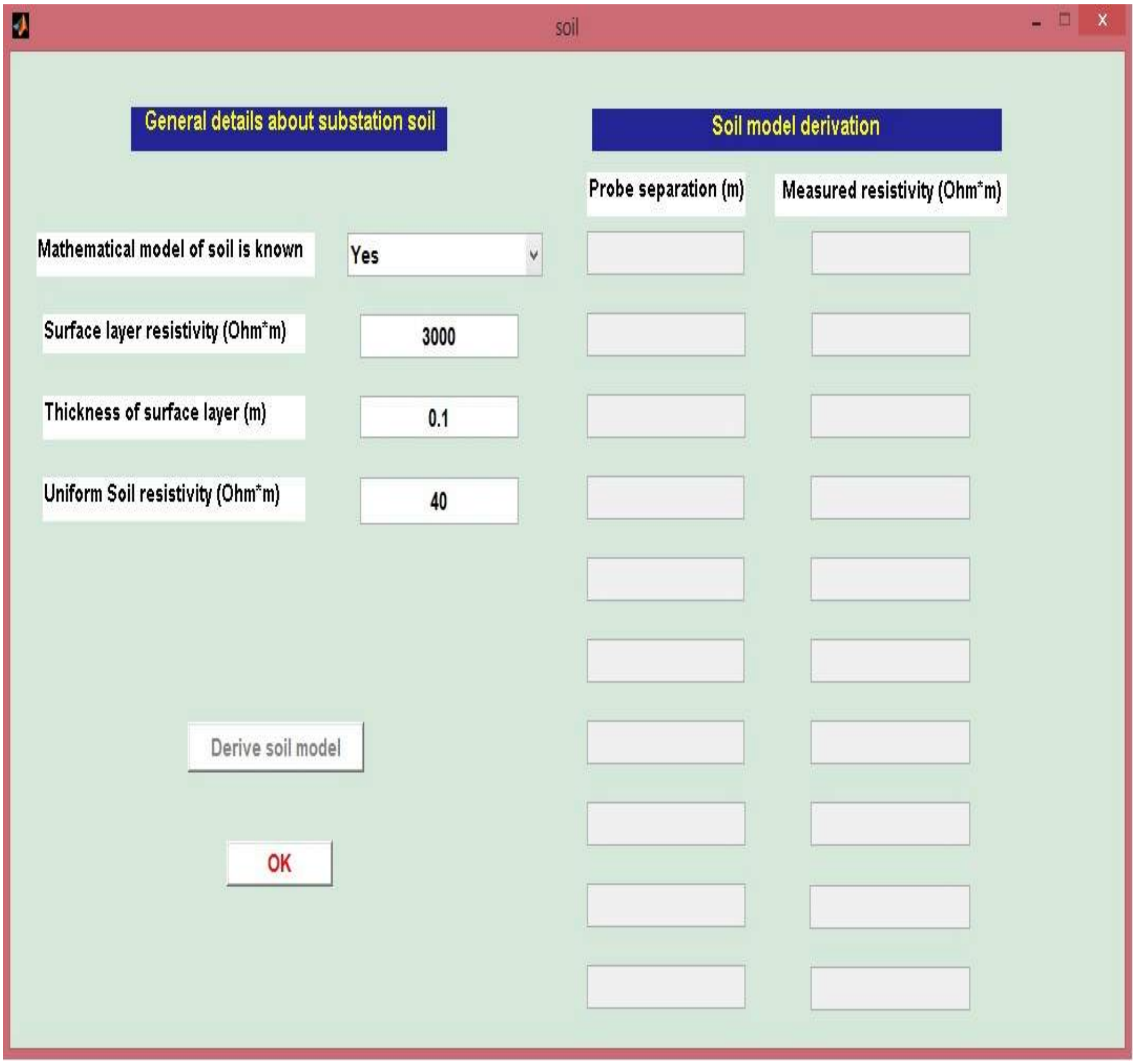

Figure 3.8: Soil model page of GGD

Chapter 4

Numerical Analysis Using FE Method

4.1 Matrix Method for Numerical Analysis of Grounding Systems

The basic equation (4.1) can be utilized in a number of ways for the purpose of analysis of a practical grounding system[5]. The basic idea in all methods is to divide a grounding system into small segments. Then utilization of the basic equations results in a relationship between the voltage of these segments and the electric current emanating from the surface of the segments.

$$V_1(r,z) = \frac{I_S}{4\pi\sigma_1}\{[(x-x_s)^2+(y-y_s)^2+(z-z_s)^2]^{-0.5}+[(x-x_s)^2+(y-y_s)^2+(z+z_s)^2]^{-0.5}\} \tag{4.1}$$

where

r,z =the coordinates of the point A relative to a system of cylindrical coordinates

Consider, for example, the simple system of Fig.4.1(a). The ground electrodes are divided into n very small segments. Let total electric current Ii emanate from the surface of segment i and flow into earth as is illustrated in Fig. 4.1(b).

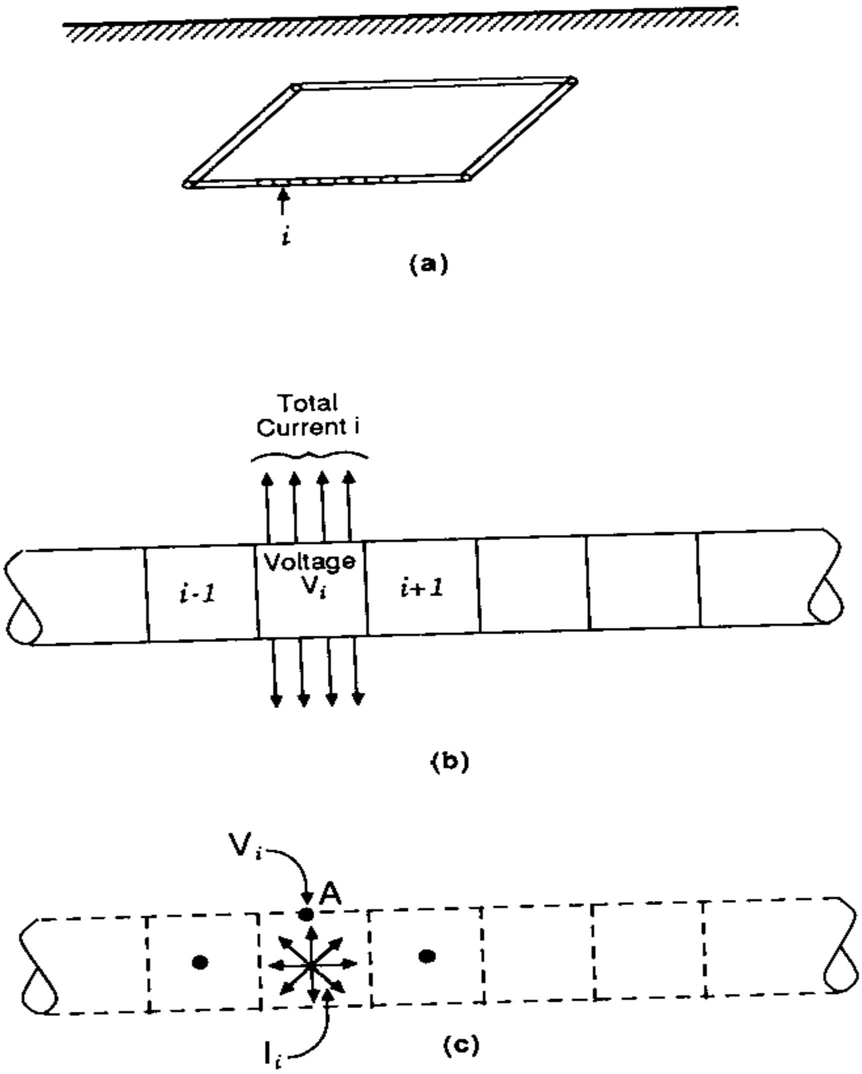

Figure 4.1: Illustration of the matrix method, (a) Simple grounding system, (b) small segments i-1, i,i+1 and (c) mathematical model of segment i.

The figure also illustrates the neighbors of segment i. If segment i is very small, it can be represented with a point source of electric current I_i located at the center of the segment; the voltage at the surface of the segment is V_i' This is illustrated in Fig.4.1(c). The same model can be assumed for segments i-1, i + 1, and all other segments. Then the basic equations are utilized to develop relationships among the electric currents I_j, i = 1, 2, ... , n , and the voltages V_i, i = 1, 2, ... , n . Specifically, the voltage V_i (i. e., voltage of segment i) at point A will be

$$V_i = \sum_{j=1}^{n} f(x_{Ai}, y_{Ai}, z_{Ai}, x_j, y_j, z_j, \sigma) I_j \tag{4.2}$$

where

$$\begin{aligned} f(x_{Ai}, y_{Ai}, z_{Ai}, x_j, y_j, z_j, \sigma) = \frac{1}{4\pi\sigma}\{ & [(x_{Ai} - x_j)^2 + (y_{Ai} - y_j)^2 + (z_{Ai} - z_j)^2]^{-0.5} \\ & +[(x_{Ai} - x_j)^2 + (y_{Ai} - y_j)^2 + (z_{Ai} + z_j)^2]^{-0.5}\} \end{aligned} \tag{4.3}$$

and

(x_{Ai}, y_{Ai}, z_{Ai})=coordinates of point A located on the surface of segment i

(X_j, Y_j, Z_j)=coordinates of the center of segment j

I_j=total electric current emanating from the surface of segment j

In general, n such equations can be written, one for each segment:

$$V_1 = \sum_{j=1}^{n} f(x_{A1}, y_{A1}, z_{A1}, x_j, y_j, z_j, \sigma) I_j \tag{4.4}$$

$$V_2 = \sum_{j=1}^{n} f(x_{A2}, y_{A2}, z_{A2}, x_j, y_j, z_j, \sigma) I_j \tag{4.5}$$

$$V_n = \sum_{j=1}^{n} f(x_{An}, y_{An}, z_{An}, x_j, y_j, z_j, \sigma) I_j \tag{4.6}$$

If the voltages V_i, i = 1, 2, ... , n , are known, then the equations above can be solved to yield the electric currents I_j, j = 1, 2, ... , n. Once the electric currents are specified, the voltage V(x, y , z) at any point (x,y,z) in the earth can be computed from the equation

$$V(x, y, z) = \sum_{j=1}^{n} f(x, y, z, X_j, Y_j, Z_j, \sigma) I_j \tag{4.7}$$

In general, grounding systems are constructed with copper conductors. In this case, because of the high conductivity of copper, the entire grounding system is at essentially the same potential, the ground potential rise (GPR). Thus the voltage of all segments is the same and equal to V (i.e., $V_1 = V_2 = V_3 = ... = V_n = V$).

Equations (4.5) can be written in compact matrix notation:

$$V_1 = [VDF][I] \tag{4.8}$$

where

$1^T = [1\ 1\ 1\ ...\ 1]$

$[I]^T = [I_1\ I_2\ ...\ I_n]$

$$[VDF]_{i,j} = f(x_{Ai}, y_{Ai}, z_{Ai}, X_j, Y_j, Z_j, \sigma) \tag{4.9}$$

and V is the ground potential rise of the grounding system. The electric currents [I] are computed from

$$[I] = [VDF]^{-1} * 1 * V \tag{4.10}$$

Note that the electric currents are proportional to the ground potential rise. Thus a resistance can be computed for the grounding sys tern as the ratio of the ground potential rise over the total electric current. Specifically, the total electric current is

$$I_T = \sum_{j=1}^{n} I_j = 1^T[I] \tag{4.11}$$

and

$$R = \frac{V}{I_T} \tag{4.12}$$

This method bears the name " matrix method " because it involves the matrix Voltage Distibution Factor[VDF][5]. The entries of this matrix will be called voltage distribution factors [VDFs] because they provide the voltage at a given point due to the flow of a specific current source. The voltage distribution factors have dimensions of resistance (ohms). For this reason, they are often referred to in the literature as transfer resistance, mutual resistances, and self-resistances. However, their physical meaning is not related to the concept of resistance. Thus, it is more appropriate to give them a different name. This shall be referred as the voltage distribution factor.

4.2 Combined Integration/Matrix Method

The matrix method is conceptually simple. However, it is impractical because it involves the inversion of a large matrix. In this section we discuss another method that is suitable for practical applications.

The matrix method provides the electric current distribution along the conductors of a grounding system. Such analyses indicate that the distribution of electric current is more or less uniform along the conductor except at the end of the conductor or where there are conductor crossings. The actual current distribution along the conductors of a grounding system can be approximated with a staircase function. This approximation is equivalent to assuming that the current density is constant along small segments of the conductor. Since the current density along the conductors is not known a priori, a method will be developed for the computation of the current density. For this purpose the conductors of a grounding system are partitioned into a number of finite segments. The electric current density along a given finite segment is assumed constant but unknown. Next, expressions are developed relating the voltage at a point to the total current emanating from the finite segment. Then the matrix method is applied to yield the unknown values of the electric current. The size of the involved matrix is equal to the number of selected segments. Thus the size of the matrix can be kept relatively small by appropriate segmentation of the grounding system conductors. It should be emphasized that the number of segments determines how accurately the actual current distribution will be represented by a staircase function. More segments will result in a better approximation but in a larger matrix (and, therefore, more computations). Appropriate application of this method provides a good compromise between accuracy and efficiency. The method bears the name "combined integration/matrix method" because it involves integration along the length of a finite segment and subsequent application of the matrix method, as will be shown subsequently.

From the previous discussion it is obvious that application of the combined integration/matrix method requires the development of relationships between the total electric current emanating the surface of a finite length of conductor and the voltage at a given point in earth. These relationships will be developed next.

Consider two conductor segments of length $2L_l$ and $2L_2$, respectively, as in Fig.4.2. The two conductor segments are part of a grounding system. The coordinates of the center of the conductor segments are $(x_1,\ y_1,\ z_l)$ and $(x_2,\ y_2,\ z_2)$, respectively. Assume that a total electric current,I_1, emanates from the outside surface of conductor segment 1 and flows into earth. Also assume that the flow of current is uniform over the outside surface of the conductor segment (constant surface density). The following three elementary problems are defined:

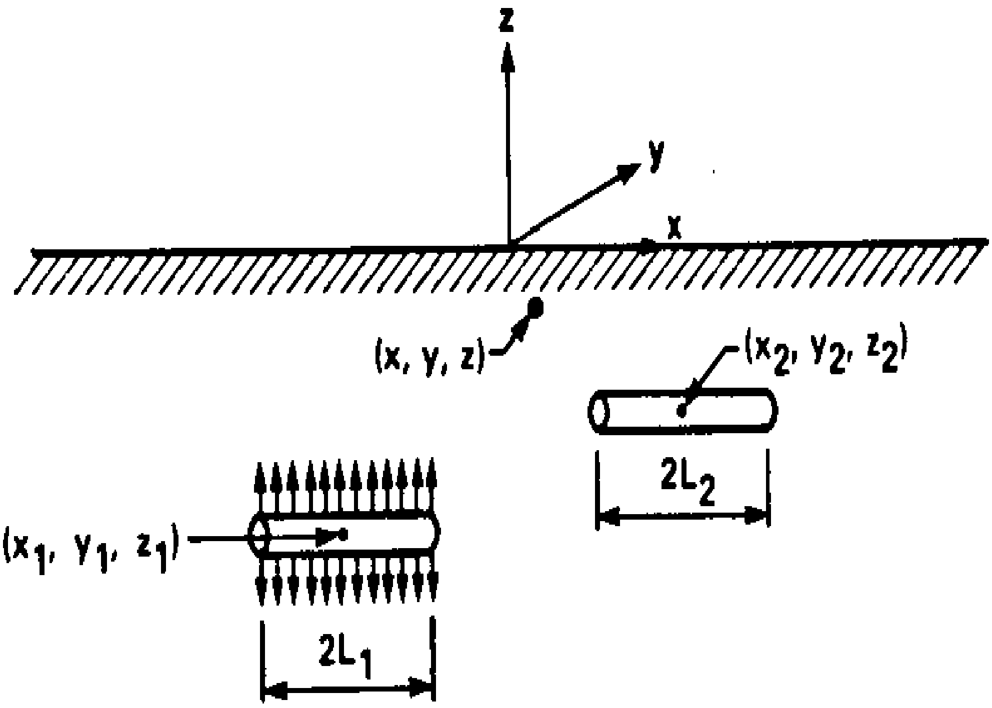

Figure 4.2: Two earth embedded conductor segments of lengths $2L_1$ and $2L_2$ respectively.

Problem 1: Compute the voltage at a point (x,y,z) in the earth du to the flow of the electric current I_1 (current of conductor segment 1).

Problem 2: Compute the voltage "transferred" to conductor segmen 2 because of the flow of the electric current I_1 (current of conduct segment 1).

Problem 3: Compute the voltage of the conductor segment 1 due to the flow of its own current, I_1.

lt is shown later that the voltage at any point (x, y, z) or the " transferred " voltage to another conductor or the voltage of the conductor itself is proportional to the total electric current emanating the conductor, that is,

$$V = R_t I \tag{4.13}$$

where

I=total electric current emanating the surface of the conductor under consideration

R_t=a function depending on the geometry of the system and the conductivity of the soil (this function, which has dimensions of resistance, is a generalization of the voltage distribution factors introduced earlier); it will be also referred to as VDF

Because of the large number of configurations that earth -embedded conductors may' assume, the number of possible geometric arrangements for the three problems is large. To limit the possibilities, assume that earth-embedded conductors are oriented only along the three coordinate axes x, y, or z. In this case only three distinct geometric arrangements need to be considered for problem 1, leading to three distinct expressions for the VDF between a conductor segment and a point. These expressions are summarized. Similarly, only six distinct geometric arrangements need to be considered for problem 2, leading to six distinct expressions for the VDF between two conductor segments. These equations are summarized. Finally, for problem 3, only three distinct geometric arrangements need to be considered, leading to three distinct expressions, which are summarized. The derivation of these expressions is illustrated with four sample calculations:

(a):VDF between an x-directed conductor segment and a point (x,y,z)

(b):VDF between two x-directed conductor segments

(c):VDF between an x-directed conductor segment and a y-directed conductor segment

(d):self-VDF of an x-directed conductor segment.

4.3 VDF Between an x-Directed Conductor Segment and a Point (x,y,z)

Consider the conductor segment 1 illustrated in Fig.4.2 and an arbitrary point (x ,y, z) in the earth. Our objective will be to compute the voltage at point (x ,y, z) , due to the flow of current I_1, neglecting all other sources of electric current (i.e., neglecting the presence of other conductor segments). The electric current I_1 is assumed to be uniformly distributed on the surface of the conductor. Typically, the radius of the conductor is small (less than 1/2 in.). In this case it is reasonable to assume that the source of this current is an ideal line source located on the axis of the conductor segment. The line current density is $I_1/2L_1$ (amperes per meter). The electric current of an ifinitesimal length of the line source, dx_s' is $I_1\ dx_s\ /2L_l$. The contribution of this current to the voltage at point (x,y,z) is

$$dV(x,y,z) = \frac{I_1 dx_s}{8L_1\pi\sigma}\{[(x-x_s)^2 + A_-^2]^{-0.5} + [(x-x_s)^2 + A_+^2]^{-0.5}\} \tag{4.14}$$

where

$$A_\pm^2 = (y-y_1)^2 + (z \pm z_1)^2 \tag{4.15}$$

Figure 4.3 illustrates the geometry of the infinitesimal current source and the point of interest (x ,y, z). For simplicity, the conductor segment length will be denoted as 2L and the total current as I. The voltage at point (x, y, z) results from the contributions of all infinitesimal current sources, that is,

$$V(x,y,z) = \int dV(x,y,z) \tag{4.16}$$

$$V(x,y,z) = \int_{x_s=x_1-L}^{x_1+L} \{[(x-x_s)^2 + A_-^2]^{-0.5} + [(x-x_s)^2 + A_+^2]^{-0.5}\} dx_s \tag{4.17}$$

The result is

$$\begin{aligned} V(x,y,z) = \frac{I}{8L\pi\sigma}\{&F_1(x-x_1+L, A_-) - F_1(x-x_1-L, A_-) \\ &+F_1(x-x_1+L, A_+) - F_1(x-x_1-L, A_+)\} \end{aligned} \tag{4.18}$$

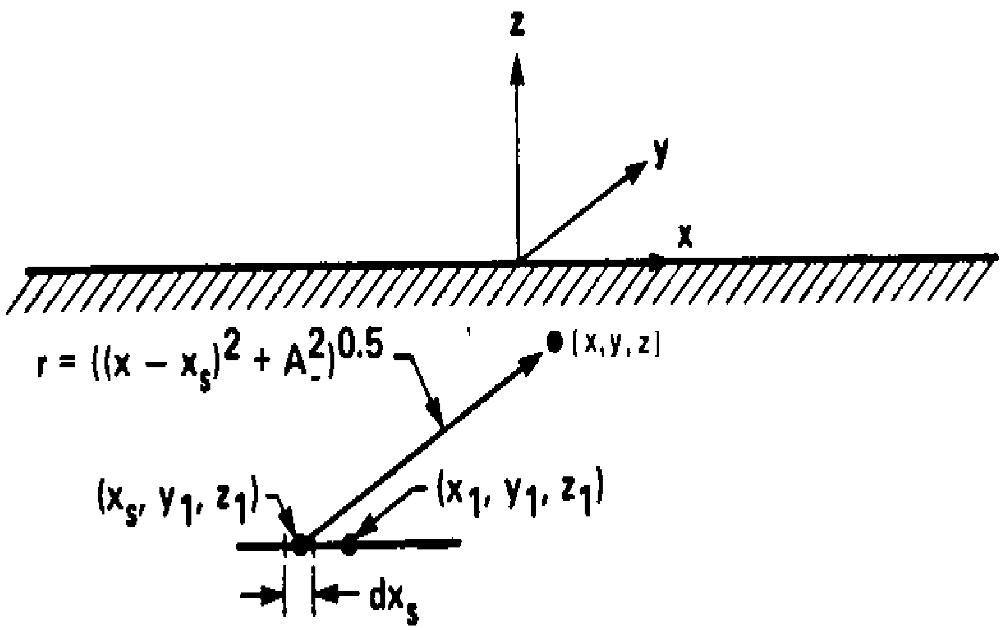

Figure 4.3: Illustration of a conductor segment represented with a line current source of constant current density.

Comparison of the derived formula to the one defining the VDF yields

$$VDF = \frac{I}{8L\pi\sigma}\{F_1(x - x_1 + L, A_-) - F_1(x - x_1 - L, A_-) \\ +F_1(x - x_1 + L, A_+) - F_1(x - x_1 - L, A_+)\} \quad (4.19)$$

In summary, Eq.(4.19) provides the voltage distribution factor (other wise known as transfer resistance) between a conductor segment of length 2L, oriented parallel to the x axis, and a point (x ,y, z) .

Similar

(a):VDF Between Two x-Directed Conductor Segments

As a result

$$VDF = \frac{1}{16L_1L_2\pi\sigma}\{F_2(x_2 - x_1 + L_1 + L_2, B_-) + F_2(x_2 - x_1 + L_1 + L_2, B_+) \\ -F_2(x_2 - x_1 + L_1 - L_2, B_-) - F_2(x_2 - x_1 + L_1 - L_2, B_+) \\ -F_2(x_2 - x_1 - L_1 + L_2, B_-) - F_2(x_2 - x_1 - L_1 + L_2, B_+) \\ +F_2(x_2 - x_1 - L_1 - L_2, B_-) + F_2(x_2 - x_1 - L_1 - L_2, B_+)\} \quad (4.20)$$

In summary, Eq. (4.20) provides the voltage distribution factor (otherwise known as mutual resistance) between two x-directed conductor segments of length $2L_l$ and $2L_2$, respectively.

(b):VDF Between an x-Directed and a y- Directed Conductor Segment

As a result

$$\begin{aligned} V_2 = \frac{I_1}{16L_1L_2\pi\sigma}\{ & F_3(x_2 - x_1 + L_1, y_2 - y_1 + L_2, z_2 - z_1) \\ & -F_3(x_2 - x_1 + L_1, y_2 - y_1 - L_2, z_2 - z_1) \\ & +F_3(x_2 - x_1 + L_1, y_2 - y_1 + L_2, z_2 + z_1) \\ & -F_3(x_2 - x_1 + L_1, y_2 - y_1 - L_2, z_2 + z_1) \\ & -F_3(x_2 - x_1 - L_1, y_2 - y_1 + L_2, z_2 - z_1) \\ & +F_3(x_2 - x_1 - L_1, y_2 - y_1 - L_2, z_2 - z_1) \\ & -F_3(x_2 - x_1 - L_1, y_2 - y_1 + L_2, z_2 + z_1) \\ & +F_3(x_2 - x_1 - L_1, y_2 - y_1 - L_2, z_2 + z_1)\} \end{aligned} \tag{4.21}$$

The voltage distribution factor (VDF) (or transfer resistance) equals the voltage V_2 divided by the current I_1.

(c):Self-VDF of an x-Directed Conductor

As a result

$$\begin{aligned} VDF = \frac{I_1}{16L^2\pi\sigma}\{ & F_2(2L, a) + F_2(-2L, a) - 2a + F_2(2L, |z_1|\sqrt{2}) \\ & +F_2(-2L, |z_1|\sqrt{2}) - (2|z_1|\sqrt{2})\} \end{aligned} \tag{4.22}$$

4.4 Discussion on Numerical Techniques

In this section we have discussed numerical techniques for grounding system analysis. The basic analytical result is Eq (4.1) which provides the voltage at a point in earth due to a point current source. This equation is the basis for all numerical analysis techniques of grounding systems. We discussed the matrix method as well as the combined integration/matrix method. Other ramifications of these methods can be found in the literature. The combined integration/matrix method is based on the concept of voltage distribution factors, defined as the transferred voltage to a point or conductor segment due to the electric current of an earth-embedded conductor segment. Typical VDFs have been derived. A summary of VDFs for conductor segments oriented parallel to anyone of the three coordinate axes (x, y, or z) is given can be used for the analysis of most practical grounding systems. The voltage distribution functions are valid under the assumption that the earth is a semi-infinite conducting medium of constant conductivity σ. This is far from being true. The conductivity of soil exhibits spatial and seasonal variations. Analysis that will take these variations into account is practically impossible. On the other hand, the effects of variations of soil resistivity are substantial. In any case, the soil conductivity below a certain distance from the surface of the earth remains approximately constant (practically in- variant with time). The conductivity of the top layer may vary with weather conditions (e. g. higher conductivity after a rainy day). It is expedient to model the earth as a stratified semi-infinite medium. This earth model makes the analysis complex and impractical. As a compromise between modeling simplicity and the need to model stratified earth, a two-layer soil model is typically assumed.

Chapter 5

FE Methodology for Grounding Design

5.1 Design Objectives and Safety Criteria

5.1.1 Design Objectives

(1) To provide means to carry electric currents into the earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service.

(2) To assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.

A practical approach to safe grounding system strives for controlling interaction of two grounding systems viz.
Intentional ground consisting of ground electrodes buried at some depth below the earth surface and
Accidental ground circuit temporarily established by a person exposed to a potential gradient in the vicinity of a grounded facility.

The circumstances that make electric shock accidents possible are as follows

- Relatively high fault current to ground in relation to the area of grounding system and its resistance to remote earth.
- Soil resistivity and distribution of ground currents such that high potential gradients may occur at points at the earths surface.
- Presence of an individual at such a point, time, and position that the body is bridging two points of high potential difference.
- Duration of the fault and body contact, and hence of the flow of current through a human body for a sufficient time to cause harm at the given current intensity.

To provide a safe condition for personal within and around the substation area, the grounding system is designed to limit potential difference, that a person can come in contact with, to a safe value.

5.1.2 Safety Criteria

Before 1960s the design criterion for substation earthing system was low earthing resistance alone. However during 1960s the new criterion for design and evaluation of substation earthing system was evolved which included ***Low step voltage, Low touch voltage and Low earth resistance*** [15]. Safety criterion for substation grounding system design is based upon tolerable body current limits. The magnitude and duration of the current flowing through a human body at power frequency should be less than that value which can cause ventricular fibrillation of the heart[2].

Tolerable body current for human body are given by following formulas
For person weighing 50 Kg

$$I_B = \frac{0.116}{\sqrt{t_s}} \tag{5.1}$$

For person weighing 70 Kg

$$I_B = \frac{0.157}{\sqrt{t_s}} \tag{5.2}$$

Safety of a person depends on preventing critical amount of shock energy from being absorbed by human body before the fault is cleared and system is de-energized.

Thus main safety objective can be stated as ***" Actual step and touch (mesh) voltages must not exceed the maximum permissible step and touch voltages, established in safety criteria, even in the worst case in order to limit the shock current below a level that can cause ventricular fibrillation. "***

5.2 Finite Element Method for Grounding System Design

Design procedure described here is aimed at achieving safety from dangerous touch and step voltages within a substation. Figure 5.1 shows block diagram representation of FE methodology for grounding system design.

5.2.1 Step by Step Methodology for Design of Grounding System

1. Before starting actual grounding system design, it is necessary to **obtain data regarding site of the substation.** Property map and general location plan provides estimate of area to be covered by the grounding grid. Soil resistivity test is necessary to find out soil resistivity profile and soil model to be used for calculations i.e. uniform resistivity model.

2. Following equation is used to **evaluate ampacity of the conductor** for which material constants are known or can be determined

$$A_{mm^2} = \frac{I}{\sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_f \cdot \alpha_r \cdot \rho_r}\right) ln\left(\frac{K_0 + T_m}{K_0 + T_{amb}}\right)}} \tag{5.3}$$

   Various material constants for standard conductor types are given in table 5.1. Fault current is the maximum expected future fault current that will be conducted by any conductor in the grounding system. Time t_f should reflect the maximum fault clearing time including backup.

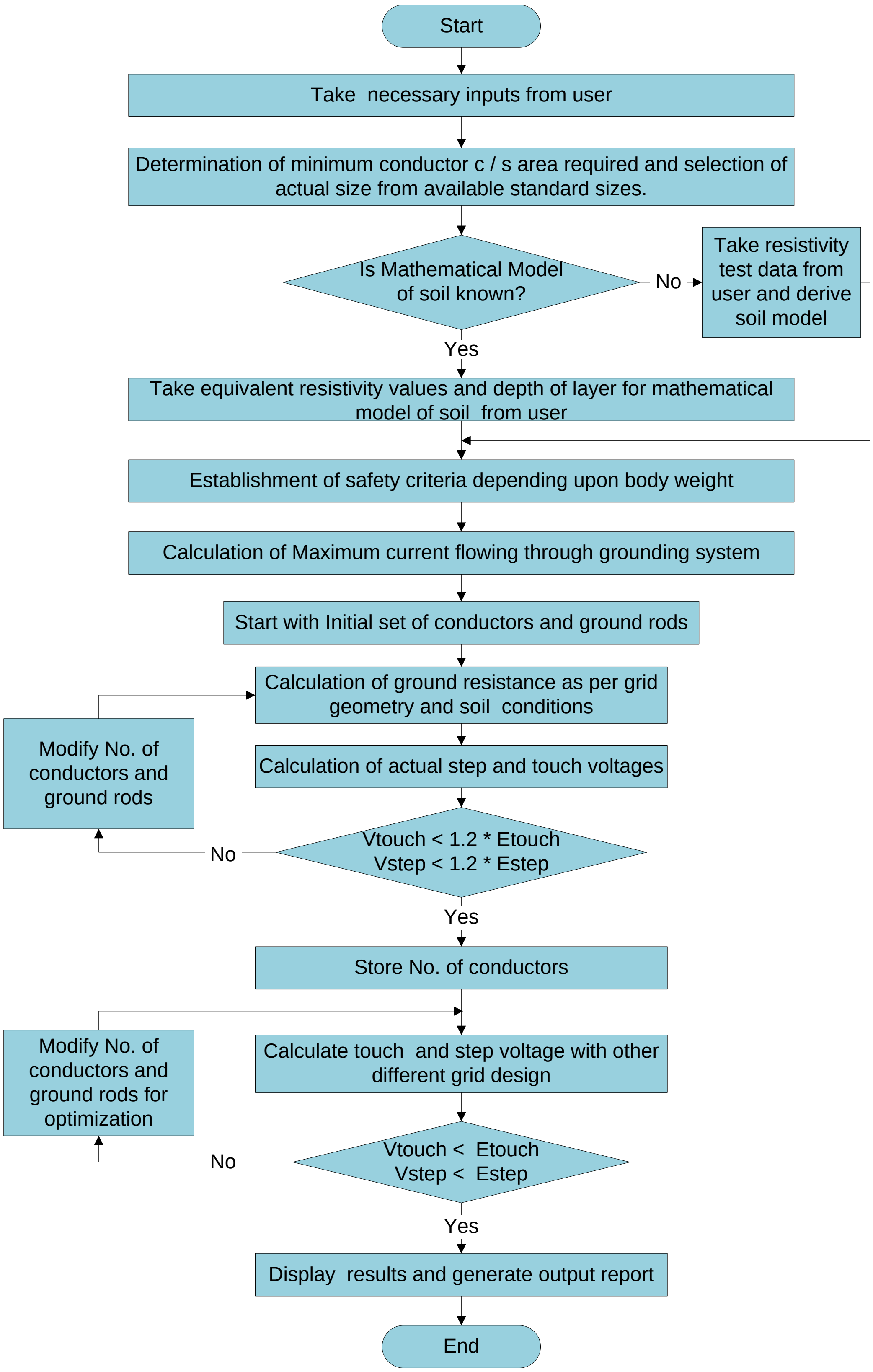

Figure 5.1: Substation grounding system design methodology as per FE Method

Table 5.1: Standard Material constants

Description	Material conductivity (%)	α_r factor at $20°C$ $(1/°C)$	K_0 at $0°C$ $(°C)$	Fusing temp. T_m $(°C)$	ρ_r at $20°C$ $(\mu\Omega \cdot cm)$	TCAP thermal capacity (J/$(cm^3 \cdot° C)$)
Copper annealed soft drawn	100	0.00393	234	1083	1.72	3.42
Copper commercial hard-drawn	97	0.00381	242	1084	1.78	3.42
Copper-clad steel wire 1	40	0.00378	245	1084	4.40	3.85
Copper-clad steel wire 2	30	0.00378	245	1084	5.86	3.85
Copper-clad steel rod	20	0.00378	245	1084	8.62	3.85
Aluminum, EC grade	61	0.00403	228	657	2.86	2.56
Aluminum, 5005 alloy	53.5	0.00353	263	652	3.22	2.6
Aluminum, 6201 alloy	52.5	0.00347	268	654	3.28	2.6
Aluminum clad steel wire	20.3	0.00360	258	657	8.48	3.58
Steel, 1020	10.8	0.0016	605	1510	15.9	3.28
Stainless-clad steel rod	9.8	0.0016	605	1400	17.5	4.44
Zinc-coated steel rod	8.6	0.0032	293	419	20.1	3.93
Stainless steel 304	2.4	0.0013	749	1400	72	4.03

3. **Safety criteria for tolerable touch and step voltages are established using equations as shown below.**

   For person Weighing 50 Kg

$$E_{step50} = (1000 + 6\rho_s C_s) \cdot \frac{0.116}{\sqrt{t_s}} \tag{5.4}$$

$$E_{touch50} = (1000 + 1.5\rho_s C_s) \cdot \frac{0.116}{\sqrt{t_s}} \tag{5.5}$$

   For person Weighing 70 Kg

$$E_{step70} = (1000 + 6\rho_s C_s) \cdot \frac{0.154}{\sqrt{t_s}} \tag{5.6}$$

$$E_{touch70} = (1000 + 1.5\rho_s C_s) \cdot \frac{0.154}{\sqrt{t_s}} \tag{5.7}$$

4. **Calculation of Grid using Finite Element Method**[5, 13]

   The program was based on the method described by Meliopoulos for grounding system analysis.

   Basically, it consists on getting the system partitioned into n finite conductor segments (means in one conductor n no. of small segment) and assuming that the current on each one of the segments is uniformly distributed along the finite element. The transfer resistances, mutual resistances and self-resistance for the segments are represented as VDFs(Voltage Distribution Factors)and the voltage and currents in the conductor segment i, is:

$$V_i = \sum_{j=1}^{n} R_{tij} I_j \tag{5.8}$$

   where

   R_{tij} VDF between segments i and j (self is i=j)

   V_i Potential at conductor segment i

   I_j Current flowing into earth from segment j

   n Total segment number

Due to the low resistance of the conductor material,generally it is assumed that the entire ground grid is at the same potential;thus,the voltage of all the segments wiil be approximately equal,so:

$$V_0=V_1=V_2....=V_n=V$$

and then,the equations for each conductor segment will be as follow:

$$V = \sum_{j=1}^{n} R_{t1j} I_j$$
$$V = \sum_{j=1}^{n} R_{t2j} I_j$$
$$V = \sum_{j=1}^{n} R_{tnj} I_j$$

With the equations system above, the value for the potential V is assumed to calculate the current flowing into earth.

Once obtained currents, other parameters,as the ground resistance,GPR and the surface potential at any point,can be calculated:

$$R_g = \frac{V}{I_1 + I_2 + I_3 + ... + I_n} \tag{5.9}$$

$$GPR = I_g R_g \tag{5.10}$$

$$V_A = \sum_{j=1}^{n} R_{t1j} I_j \tag{5.11}$$

where R_{tAj} is the VDF (or transfer resistance) between the conductor segment j and point A.

Maliopoulos present VDFs tabulated by transfer resistances, mutual resistances and self resistances for conductor segments oriented along the three coordinate axes x,y,or z.

For two-layered soil models the procedure is the same, but the VDFs equations are relatively more complex, due to the multiples images produced by boundary conditions between layers, however, the equations used for these cases start from the same principle described by Meliopoulos.

5. **Calculate R_g,GPR ,Absolute potential,V_{touch}, V_{step} value**
   Using FE method evaluate the value of Ground resistance , GPR , Touch ,Step and Absolute potential for the comparison with safety criteria.

6. (a) If computed touch voltage is more than the tolerable touch voltage, revision in design is necessary.
   (b) If computed touch voltage is less than tolerable touch voltage, grid is safe as per touch voltage criteria. Now check for step voltage criteria.

7. (a) If computed step voltage is more than the tolerable step voltage, design revision is necessary.
   (b) If computed step voltage is less than the tolerable step voltage, design is safe as per step voltage criteria and now final detailed design can be carried out.

8. If either V_{touch} or V_{step} is greater than 1.2times corresponding tolerable value, design of grounding grid has to be revised. Revision may include closer grid conductor placement,, addition of ground rods, increased grid area , chemical treatment of soil, use of deep driven rods etc.

9. After satisfying both the safety criteria, additional grid conductors and ground rods may be required if the designed grid does not include conductors near equipment to be grounded and ground rods near the base of the surge arrestor, transformer neutral etc.

10. Above all step completed then same no.of conductor check with different grid design like change the design of conductor placement and if either V_{touch} or V_{step} is greater than corresponding tolerable value ,design of grounding grid has to be revised with increase no. of conductor or ground rod.This step proceed for optimization of grid based on safety and cost.
    Necessary risers are to be provided for equipment body earthing and at some

places earthing pits are necessary for pouring water from time to time in order to keep the ground resistance at a low value

5.3 Application of Optimization to Grounding System Design Problem

Meaning of Optimization as applied to mathematics is to determine the maximum or minimum values of a specified function that is subject to certain constraints. Optimization finds the most suitable value for a function within a given domain. In engineering design optimization is used for maximizing or minimizing some function relative to some set, often representing a range of choices available in a certain situation. The function allows comparison of the different choices for determining which might be best. Common applications of optimization include minimal cost, maximal profit, best approximation, optimal design, optimal management or control, variational principles etc.

Optimization problem may be linear, non linear, quadratic, integer linear, fractional stochastic optimization and so on, based on type of objective function and constraints. Global optimization is a wide subject that can be studied separately.

Grounding system is one of the most important elements inside transmission and power distribution systems. Poor design methods and simplified calculations can lead to high construction costs and / or unsafe conditions. Hence optimization is applied in order to make design not only economical but also safe. The concept of optimization of a grounding grid has been the focus over the years by researchers who attempted to reduce the amount of copper placed into the earth to form the grounding system design without compromising electrical safety[1].

This section introduces a method to design a grounding grid while minimizing time and cost of construction. In this work software named Ground Grid Designer (GGD) has been such designed that it solves grounding system design problem that is linear optimization problem defining cost as objective function subjected to safety and geometrical constraints. It involves no. of conductors in the ground grid along x and y direction, No. of vertical ground rods and length of ground rods as decision variables.

Effects of various parameters on actual touch and step voltages and grounding system resistance or GPR should be analyzed thoroughly before applying optimization techniques. Following parameters have been found to have substantial effect on ground grid design and performance [4].

- Maximum grid current
- Fault duration
- Shock duration
- Soil resistivity
- Surface layer resistivity
- Thickness of surface layer
- Area occupied by the grid conductors
- Depth of burial of grid
- Spacing between grid conductors
- No. and location of vertical ground rods

5.3.1 Factors to be Considered in Optimization of Grounding System Design

Out of above mentioned parameters following have dominating effect on the grid performance among the others. Detailed description can be found from[4], and [16].

(1) Conductor spacing (D) and/or No. of ground grid conductors (N_x and N_y)

(2) Number of vertical ground rods (N_r)

(3) Depth of grid (h) and

(4) Area of grounding system (A)

Effect of Conductor Spacing and Number of Conductors:
Spacing between the adjacent conductors and No. of conductors are certainly dependent on each other for fixed area of grid. The more conductors are installed, the smaller the distance between the conductors. As seen from fig 5.2, with reduced separation and increased no. of conductors, mesh voltage (Em) decreases but at the same time step voltage (Es) increases. However effect of reduction in Em is more than that of increase in Es. So, designer has to carefully decide no. of conductors and separation between them to keep both voltages below tolerable limits. Also physically, there is a limit on how close conductors can be installed and should be a design consideration [4].

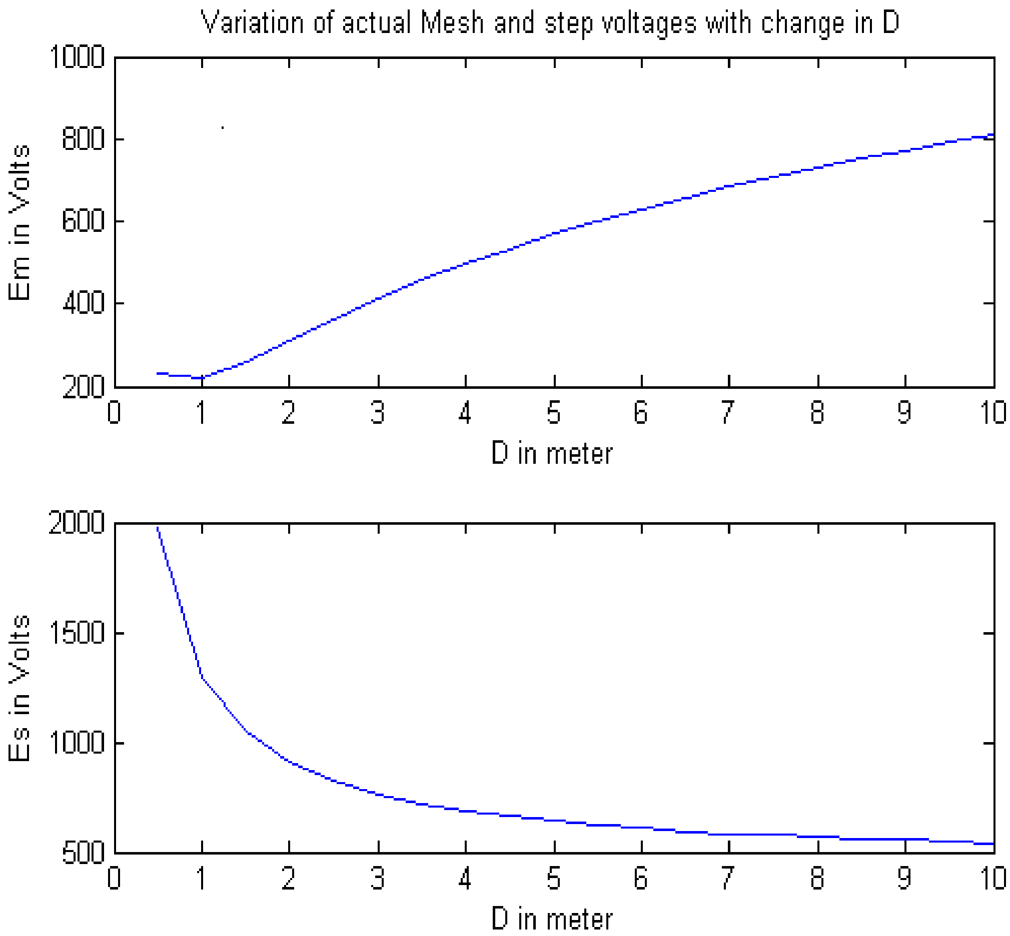

Figure 5.2: Effect of change in No. of conductors and conductor spacing on Em and Es

Effect of Depth of Burial of Grid:

Depth of burial of grid does not have great effect on mesh voltage but has drastic effect on step voltage as seen from fig 5.3. With increased depth of grid, step voltage decreases significantly because as current flows up toward surface most of the voltage is dropped in the soil itself and at the surface of earth less step voltage is experienced. Also, GPR reduces with increased depth of burial until and unless lower layer earth has higher resistivity than upper layer. This is because with higher resistivity layers in the lower portion more current tends to flow toward lower resistivity earth surface thereby increasing potential at the earth surface[17].

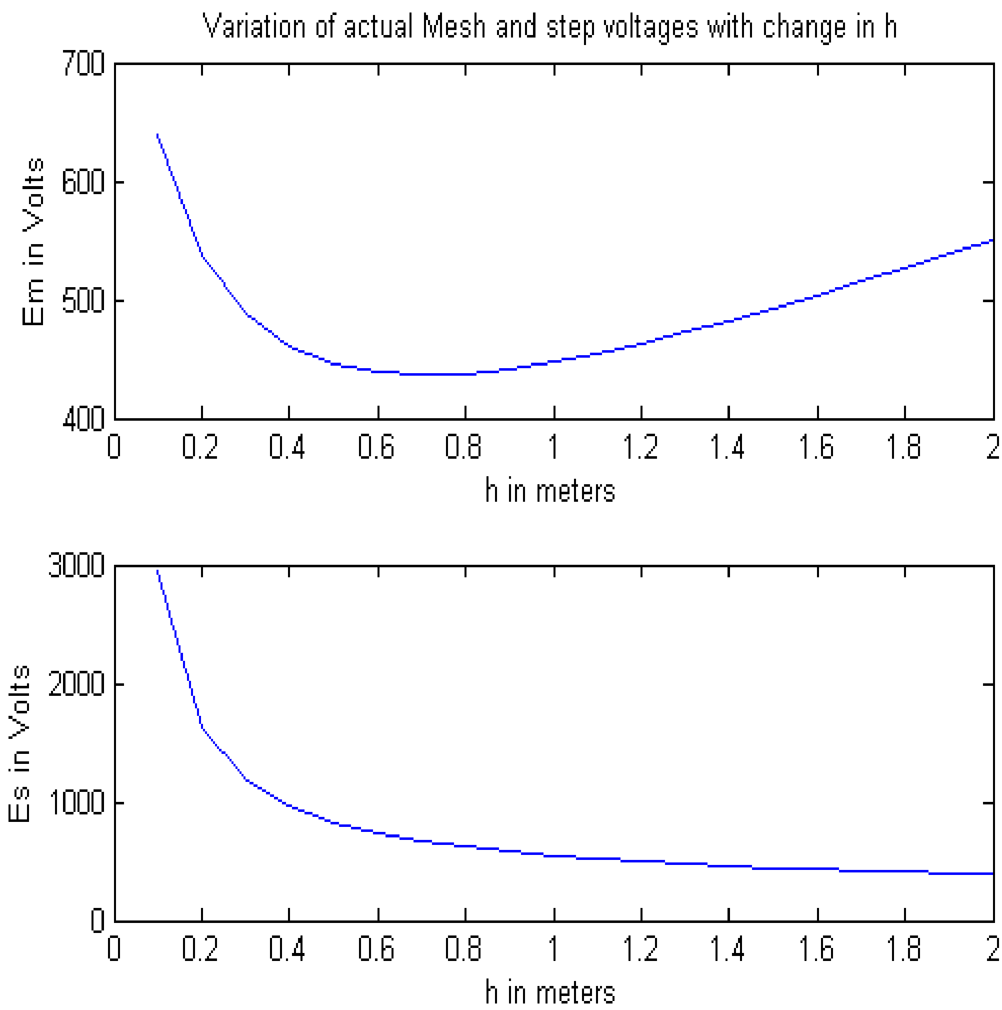

Figure 5.3: Effect of change in depth of burial of grid on Em and Es

Effect of Ground Rods:

Vertical ground rods discharge the grid current in the soil at sufficient depth. Thus, they effectively reduce grounding system resistance and GPR. Also, with more number of ground rods, total length of conductors buried in the earth increases thereby decreasing step and mesh voltages which can be observed from fig 5.4. In actual practice, ground rods are considered to be an effective means of reducing grid resistance and also actual mesh and step voltages whenever design modifications are necessary. For the same total length of conductor to be installed vertical rods are more cost - effective than horizontal grid conductors [10, 19, 20].

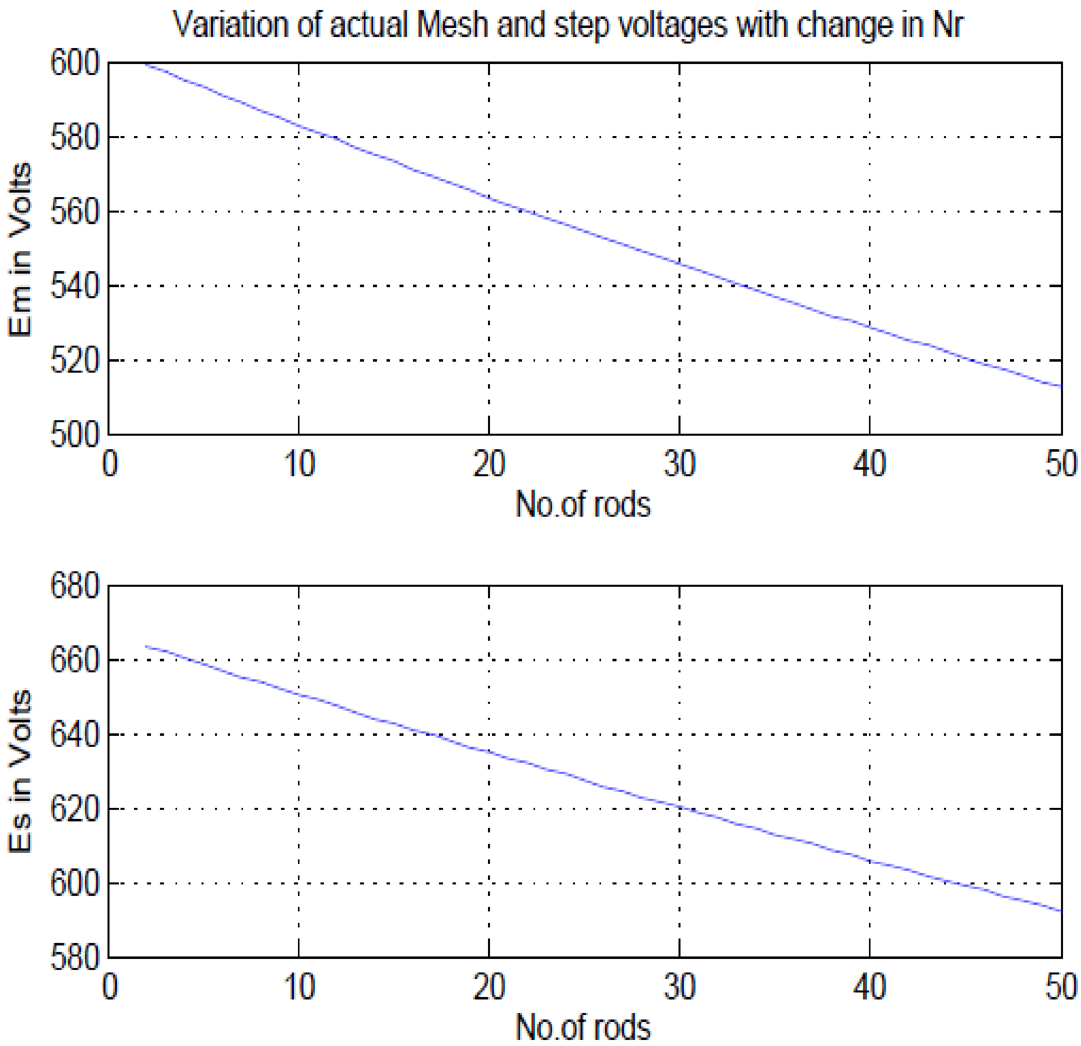

Figure 5.4: Effect of change in Number of ground rods on Em and Es

Effect of Area of Grounding Grid:

Area occupied by the grounding grid has major effect on GPR, step voltage as well as on mesh voltage as can be seen from fig 5.5. With increased area all the three types of potentials reduce significantly. Area contributes to reduction in grid resistance and thus GPR directly as is apparent from the relevant equations given in [2], also with increased area, the length of buried conductors increases and thus actual step and touch voltages reduce.

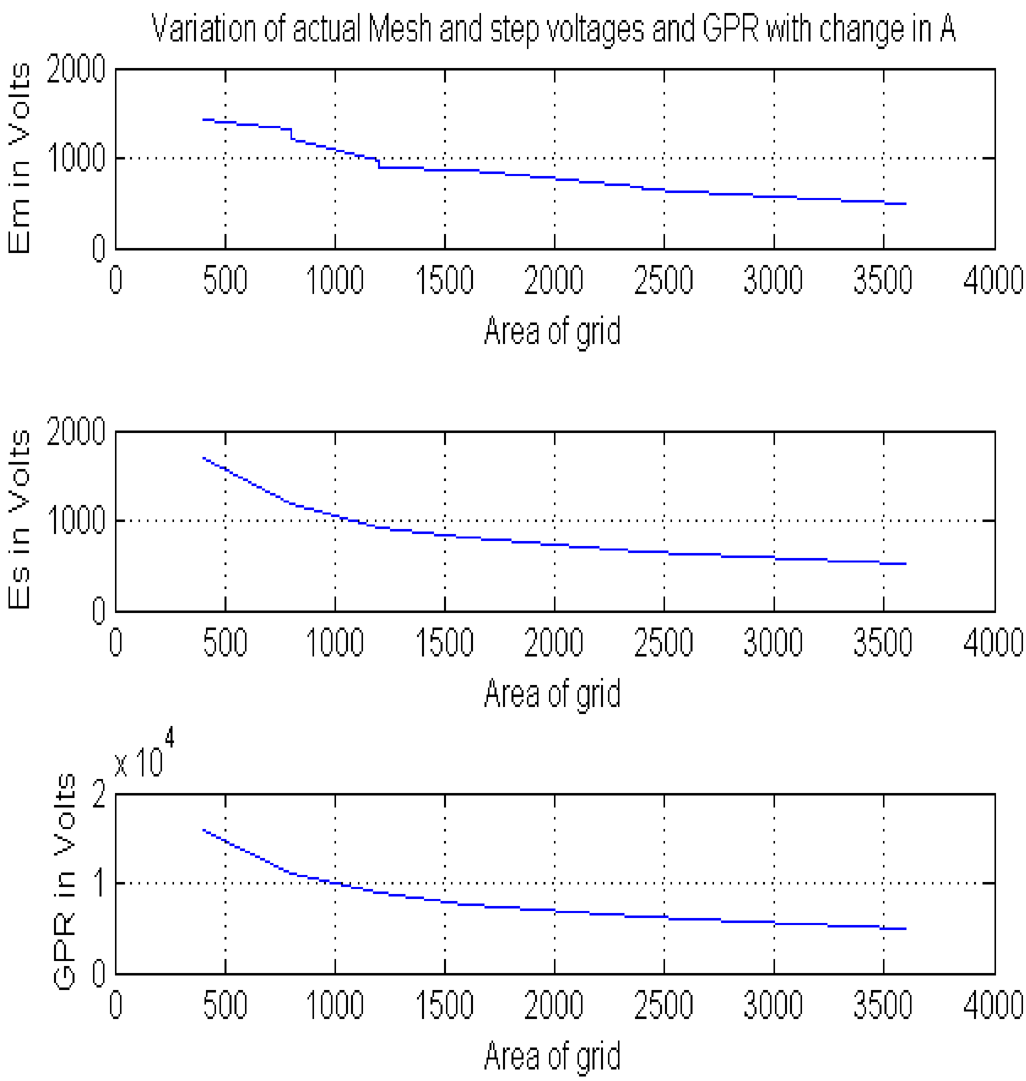

Figure 5.5: Effect of change in Area of grounding system on GPR, Em and Es

At least two, if not all, of the above four parameters must be decision variables while formulating the optimization problem. Hence, for the purpose of optimization, first two dominating parameters affecting grounding system performance viz. no. of conductors in horizontal ground grid and no. of vertical ground rods, have been considered to be variable. Hence for obtaining optimal design of grounding system, no. of ground grid conductors are varied thereby altering separation between them for fixed grounding system area. Also no. of ground rods and length of ground rods are varied to get most appropriate design at minimal cost. Depth of burial is assumed to be constant and is not varied for optimization.

Chapter 6

Software deployment

Subsequent to learning theoretical concepts of substation grounding system design procedure, it is time to implement these concepts in the form of software. The equation find formulas used are as per IEEE 80-2000[2], book by A.P.Sakis Meliopoulos[5] and paper L.M. Coa[13].The formulation used is in FE domain so as to get the results in a narrow gap distance with improved accuray.The software is limited to single layer soil model. Relevant mathematical equations are converted in MATLAB code and integrated with GUI developed with the help of MATLAB guide [21, 22]. This gives resultant software named ***" Ground Grid Designer (GGD) "*** . Figure 5.1 shows flowchart depicting algorithm used to develop GGD.

- Main program in the designed software has been divided into 10 sub-programs (modules) each performing different task. As seen from the flow chart, in first step necessary inputs are taken from user and stored in memory for calculations of various parameters.

- Second step determines most appropriate conductor size.

- Next, if mathematical model of soil is known, the software takes soil parameters to be used for further calculations. However if soil model is not known, the software will take the data obtained from Earth Resistivity Testing (ERT) and it will extract the soil model from the ERT data and communicate it to other modules of the software for further calculations of various parameters.

- After entering all data related to grounding grid geometry, soil parameters and system data, the software proceeds to establish safety criteria as per IEEE - 80 standard.

- Then the software calculates maximum grid current taking into account various factors given in IEEE guide.

- Then analysis to be performed i.e. simple equally spacing conductor performance analysis or optimal design of grounding grid has to be selected. In both the cases performance analysis the software proceeds as per FE methodology, however if optimal design option is selected software proposes unequally spaced conductor option leading to optimal design of the grounding system based on safety and cost benefit.

- Next, grounding system resistance, GPR, actual touch and step voltages is calculated as per the grid geometry selected and soil conditions. Then comparison of these voltages is made with tolerable touch and step voltages established in the safety criteria established above.

- If design is found safe then suggestions for detailed design are given otherwise recommendations for modifying the grid design are provided in substation grounding system design methodology Fig 5.1. Finally results are displayed and report is shown in a separate .doc file. GGD software provides optimal design with minimum no. of conductors and iteratively calculates performance and cost parameters. Calculation is made for all possible combinations of ground grid conductors and ground rods. i.e. that meets all the safety and geometrical constraints and yet gives economical design is given as the final optimal solution.

- Also grid conductors layout is displayed on the main page of the software as per grid geometry and no. of conductors in both directions as entered in grid layout module.

6.1 Description of the Software Modules

Various modules of GGD include three input modules, one analysis modules and one output modules as shown below.

(1) Main page allowing access to all the input - output modules

(2) Grid data module

(3) Soil data module

(4) System input module

(5) Analyze module

(6) Report generation module

Following is description of various input modules and results given by output modules are shown in the subsequent sections.

These all modules are actually GUI files designed with the help of MATLAB GUI Development Environment. Some of them are designed to take input data in a user friendly manner. Call backs are provided in the GUI files generated by GUIDE in order to make multiple GUIs work together. As already said this software is designed as windows standalone application in order to make it work on the systems where MATLAB is not installed. Now in order to make multiple GUIs working for standalone application deployment special data transfer mechanism has to be adopted instead of using MAT files. Following is the description of how data transfer is facilitated to make the program independent of MATLAB.

(1) Data to be shared within GUI or among GUIs is set as application data with the help of setappdata

(2) Handle of the GUI from which data is to be taken is passed to the GUI to which the data is to be sent

(3) Application data is retrieved using appropriate graphic handle and getappdata

6.1.1 Main Page

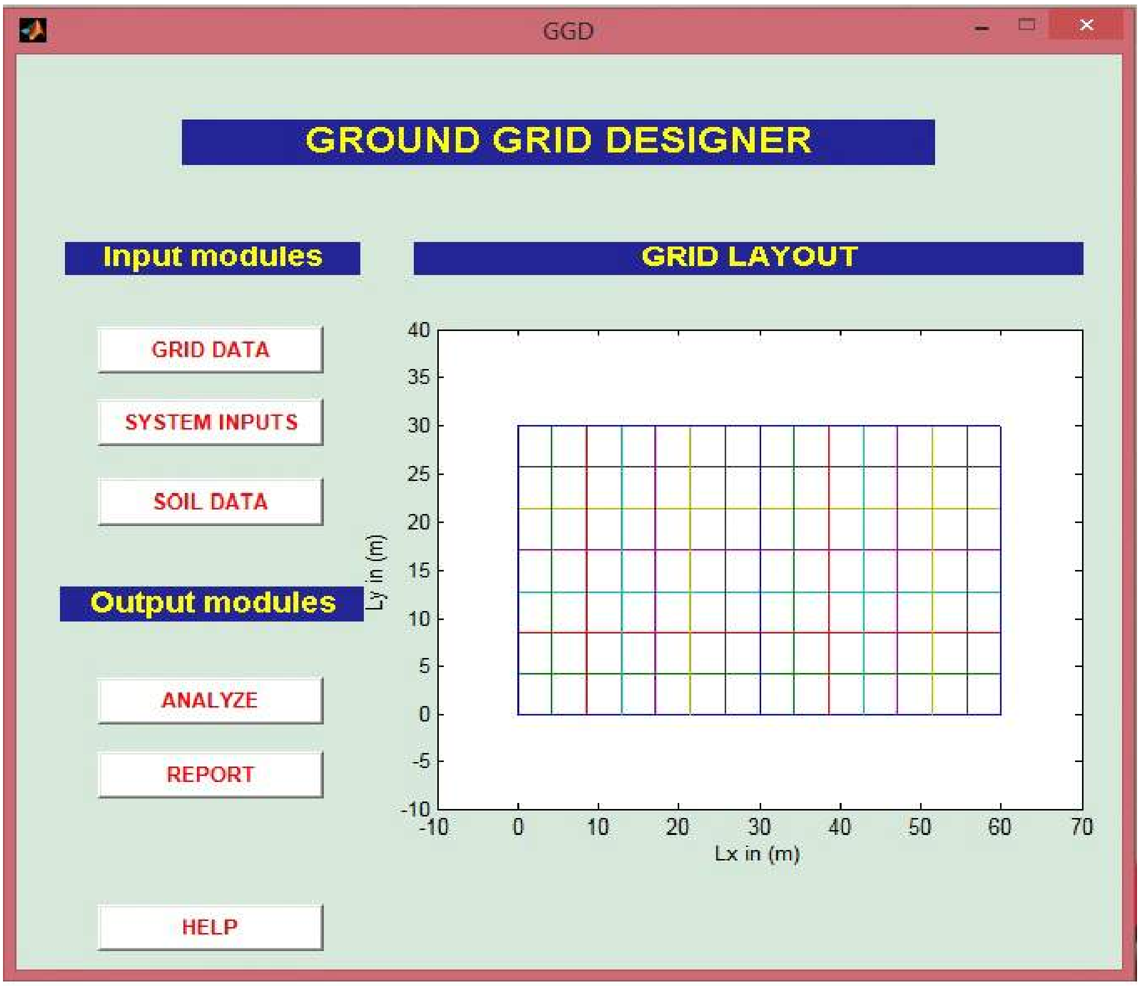

Figure 6.1: Main page of GGD showing various options

Figure 6.1 shows main module of GGD which shows all of the optimization options and also the shapes of ground grid it is capable of analyzing and giving optimal design for. It allows access to all the input, processing and output modules. It takes main details related to substation grounding system design such as shape of ground grid. By accessing various other input pages like grid data, soil data and system input, further details about grounding system design can be entered as shown in following subsections. Also analysis and optimization of the proposed grounding system . Report for the designed grounding system can also be generated from here which will be Microsoft word document.

6.1.2 Grid Data

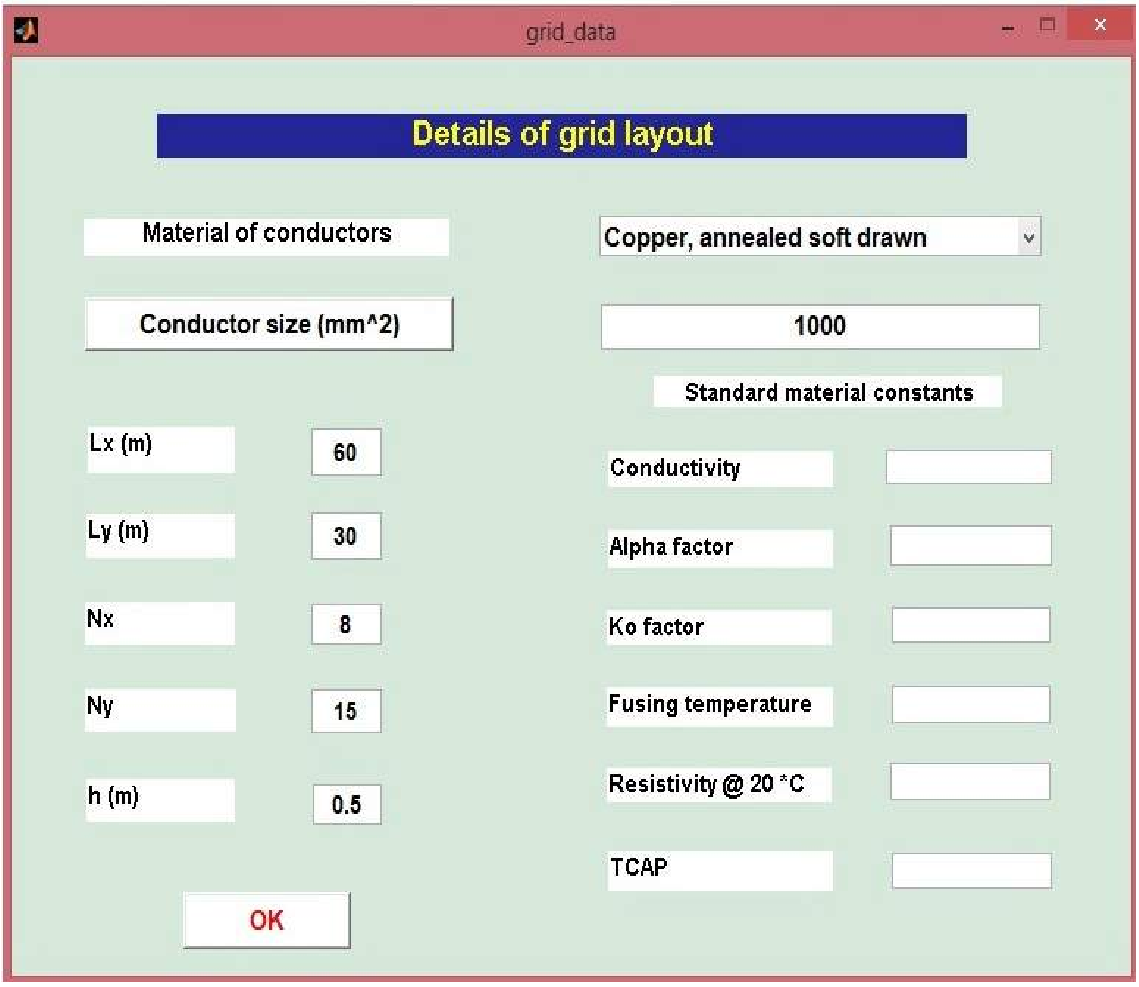

Figure 6.2: Grid data page of GGD

This page asks for parameters related to general grid design like length of grid in both directions, number of conductors, depth of grid, type of conductor material for horizontal conductors and vertical ground rods, arrangement of ground rods, cost of conductors etc. Standard material constants for selected conductor type are also shown which are decided by software itself implicitly based on values given in standards. Here option for calculation of the minimum required size of the conductor according to the fault current value is provided. However, if needed user can select any other value of the size of the ground grid conductor from available list of standard values. Size of the ground rod is to be specified explicitly.

6.1.3 Soil Data

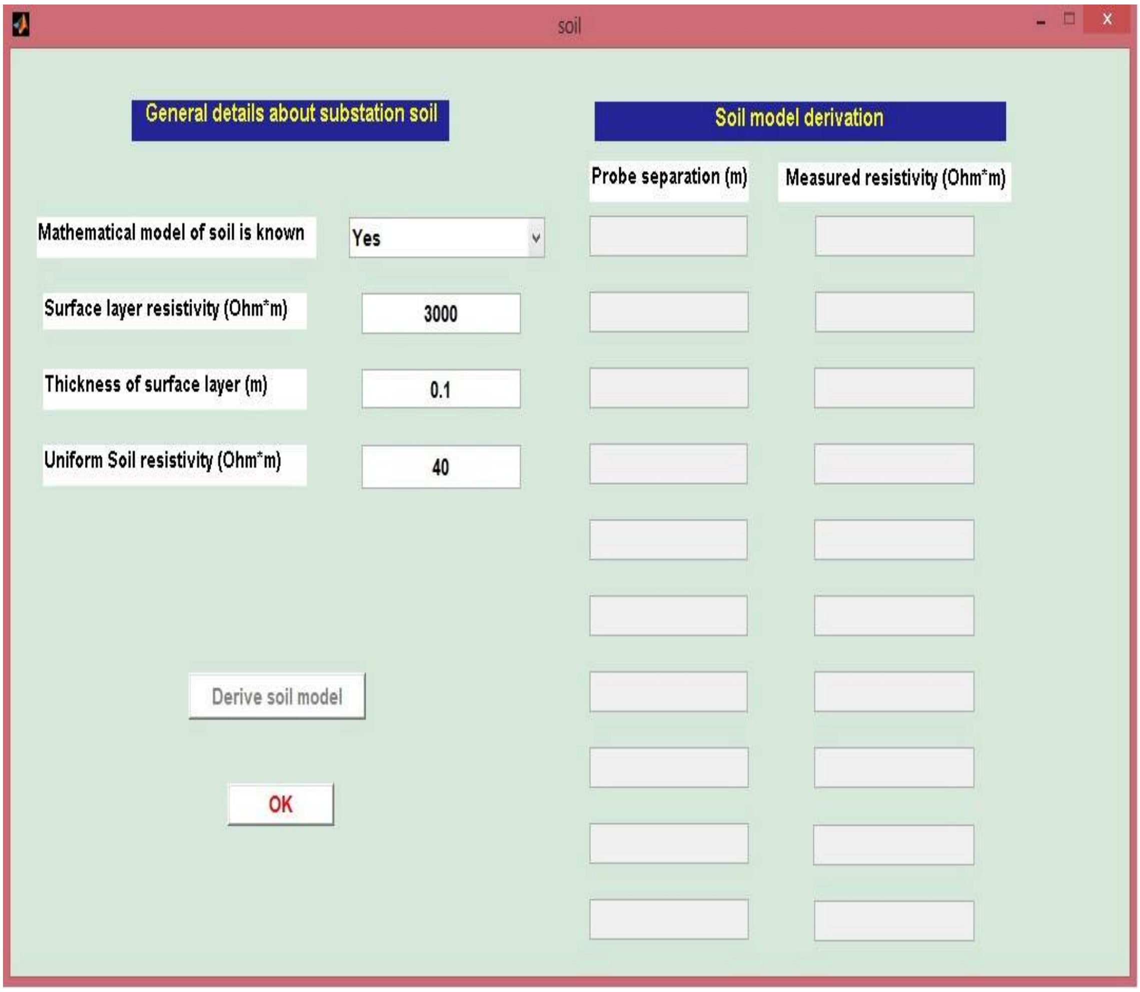

Figure 6.3: Soil data page of GGD

This page is soil modeling module and takes input data required for deriving actual mathematical model of soil at substation site in order to design grounding grid in one layer or two layer soil. Soil resistivity, surface layer resistivity, thickness of surface layer and type of soil model decide resistance of grounding grid and actual voltages within substation. Here, user has two options.

(1) If mathematical model of soil is already known, values of the soil parameters can be entered directly for any of the selected soil model.

(2) If soil model is not known soil model derivation algorithm help user in extracting the soil model from available ERT data.

6.1.4 System Input Data

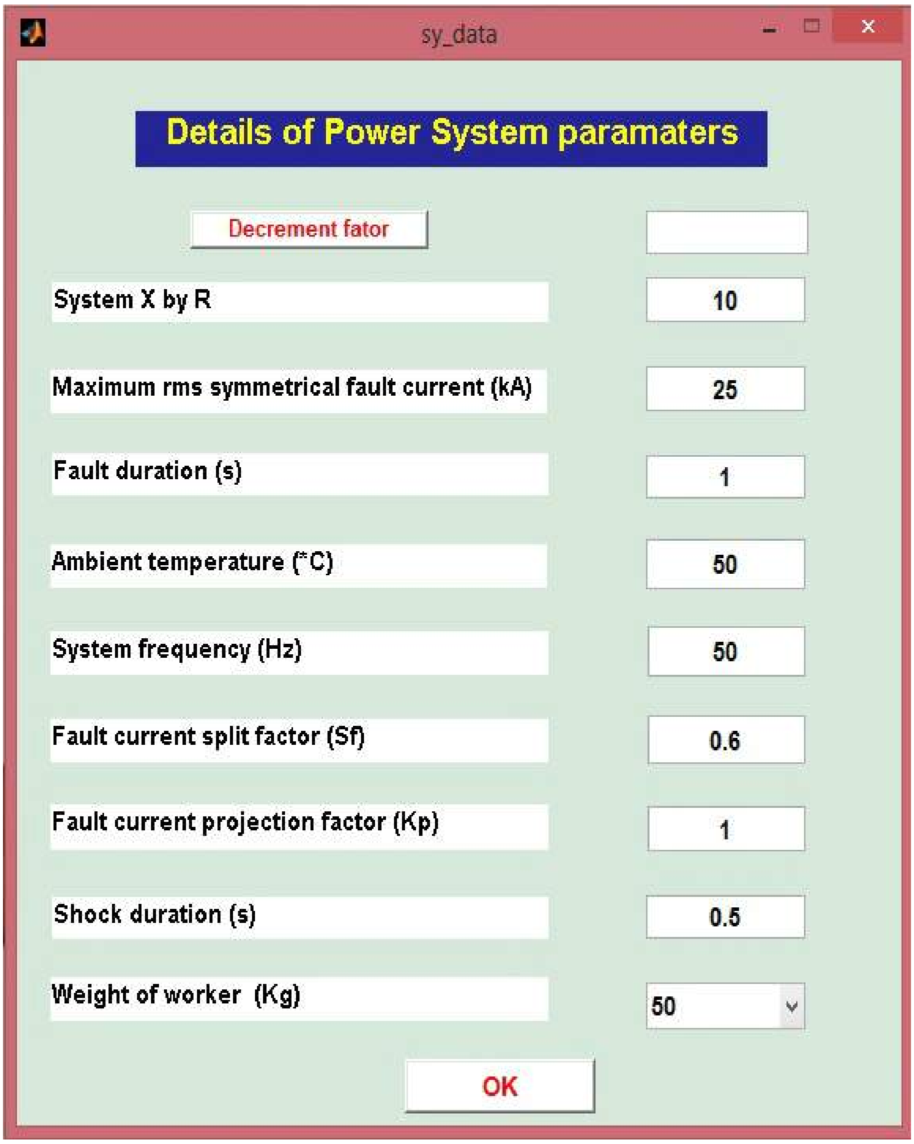

Figure 6.4: System input page of GGD

This system data page takes inputs of general system related data, ambient conditions and fault current related data. These data are necessary for establishment of safety criteria and designing the grounding system such that it does not violate the safety criteria.

6.2 Salient Features of the Software

- GUI developed with the help of MATLAB makes the software quite user friendly and any novice user can also work with it without going for detailed literature study Only thing the user should be aware of is basic design methodology as per IEEE guidelines and related terminology.

- A list of commonly used conductor materials is provided and program automatically takes the standard values of material constants for the selected conductor material.

- This software calculates required conductor size and automatically chooses the most appropriate standard conductor size available in the market; however manual entry is also possible.

- It is capable of handling two grid geometries like square, rectangular, grounding grids supplemented by vertical ground rods.

- It can analyze technical performance of any proposed grounding system in terms of grounding system resistance, tolerable and actual values of touch and step voltages and safety as per standard guidelines in uniform soils layered.

- Results obtained here are found to be more accuracy with those given by Ground Grid Systems module of ETAP 4.7.0 professional software used for solving problems related to power system by many utilities.

- GGD also give result in 3D graph for step potential , touch potential , absolute potential with the actual potential value of the of the grid at abnormal condition and we can easily seen the every point of ground potential.

- Option for derivation of soil model from earth resistivity testing (ERT) data is available when mathematical model of soil is not known in advance. This is an additive feature compared to ETAP 4.7.0. By implementing the standard procedure given in appendix of IEEE standard 81 and using steepest descent algorithm soil model has been derived for uniform soil layered.

- It gives well formatted output in the form of Microsoft Word file.

- This software has been deployed as standalone application with the help of MATLAB compiler, hence it can work satisfactorily even in absence of MATLAB just by installing MATLAB run time compiler which is available with the packed application itself and running the application of GGD.

Chapter 7

Validation Performance of GGD Software

7.1 Validation Performance of GGD as per IEEE 80-2000 and ETAP 4.7 GGS Module.(Software Testing)

Before accepting any newly developed software one important stage is its testing. In order to check performance of any software and declare it as reliable one, the results obtained by it need to be verified against some standard or widely used expert software. The same thing is also true for “Ground Grid Designer (GGD)” software developed herein. For the purpose of checking the validity of the results given by GGD for various problems, same are solved by “Ground Grid Systems” FE method module of ETAP 4.7[24, 25] and IEEE 80-2000 Annex-B (Example-1,2,3). Results obtained by both the software and IEEE design are compared for variety of cases. Tables given in subsequent sections show the relevant data used for problems under consideration and corresponding results obtained by aforementioned software tools.

As already mentioned GGD allows performance evaluation of any proposed grounding system by taking data related to grid geometry, soil characteristics and system data. Also it gives optimal design of the grounding system as per user requirements. Hence in order to illustrate its capabilities following design problems are solved considering various analysis options and results given by GGD are compared with those obtained from ETAP 4.7 - GGS module and IEEE 80-2000 Annex-B (Example-1,2,3).

7.1.1 Design of Grounding Systems Located in Uniform Resistivity Soils by GGD and ETAP 4.7 - GGS

This section analyzes simply the performance of grounding system as per given data for all the types of grid shapes namely Rectangular, Square, with Unequally space and extra four conductor grid with Equally space grids in uniform soil.

Certain parameters are common while analyzing all the eight problems. these data are as follows

- ρ_s : 2500 $\Omega \cdot m$
- ρ : 400 $\Omega \cdot m$
- h_s : 0.102 m
- h : 0.5 m
- t_f : 0.5 sec
- I_g : 1908 Amp
- Square Area : 70 × 70 m
- Rectangular Area : 84 × 63 m
- Conductor Radius : 0.005 m.
- Arrangement of ground rods : Through out grid area
- Conductor material for ground grid and rods : Copper annealed soft drawn

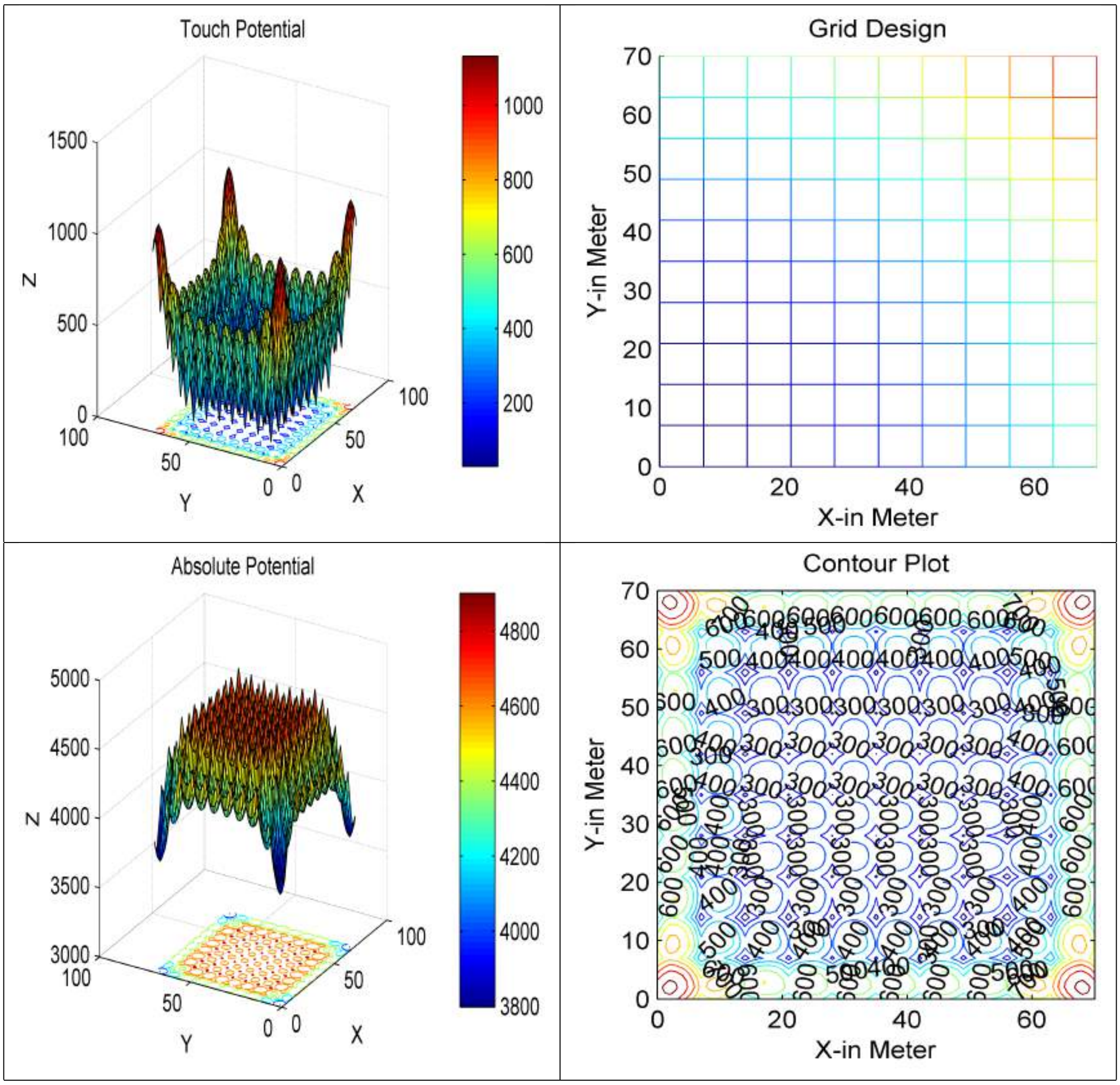

Figure 7.1: Square-Equally spaced design

Table 7.1: Result of Square-Equally spaced design

Particular	IEEE 80-2000	FE method	ETAP
$E_{touch70}$ (V)	838.2	838.2	838.2
$L_x \times L_y$	70 × 70	70 × 70	70 × 70
$N_x \times N_y$	11 × 11	11 × 11	11 × 11
L_c	1540	1540	1540
R_g $(\Omega \cdot m)$	2.78	2.5844	2.65
GPR (V)	5304	4931.1	5556.7
$V_{touch(max)}$ (V)	1002.1	1132.7	1123.2
$V_{touch(min)}$ (V)	-	30.03	-
V_{touch} (Point measure)	1	5041	7322
Safety	Not safe	Not safe	Not safe

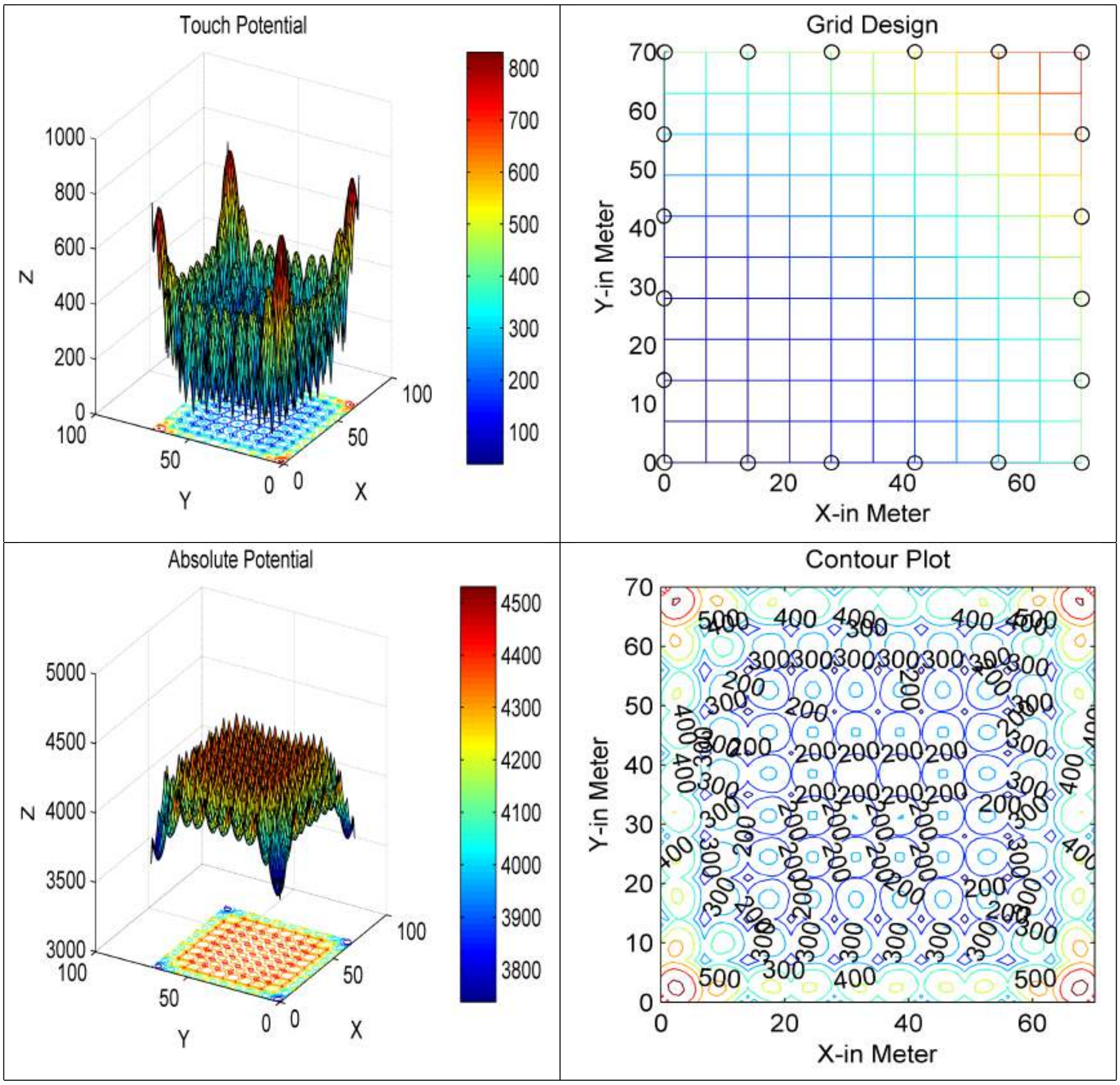

Figure 7.2: Square-deeprod-equally spaced design

Table 7.2: Result of Square-deeprod-equally spaced design

Particular	IEEE 80-2000	FE method	ETAP
$E_{touch70}$ (V)	838.2	838.2	838.2
$L_x \times L_y \times L_r$	70 × 70 × 7.5	70 × 70 × 7.5	70 × 70 × 7.5
$N_x \times N_y \times N_r$	11 × 11 × 20	11 × 11 × 20	11 × 11 × 20
$L_c \times L_R$	1540 × 150	1540 × 150	11
R_g $(\Omega \cdot m)$	2.75	2.3949	2.48
GPR (V)	5247	4569.4	5162
$V_{touch(max)}$ (V)	747.4	830.71	827.2
$V_{touch(min)}$ (V)	-	38.78	-
V_{touch} (Point measure)	1	5041	7322
Safety	safe	safe	safe

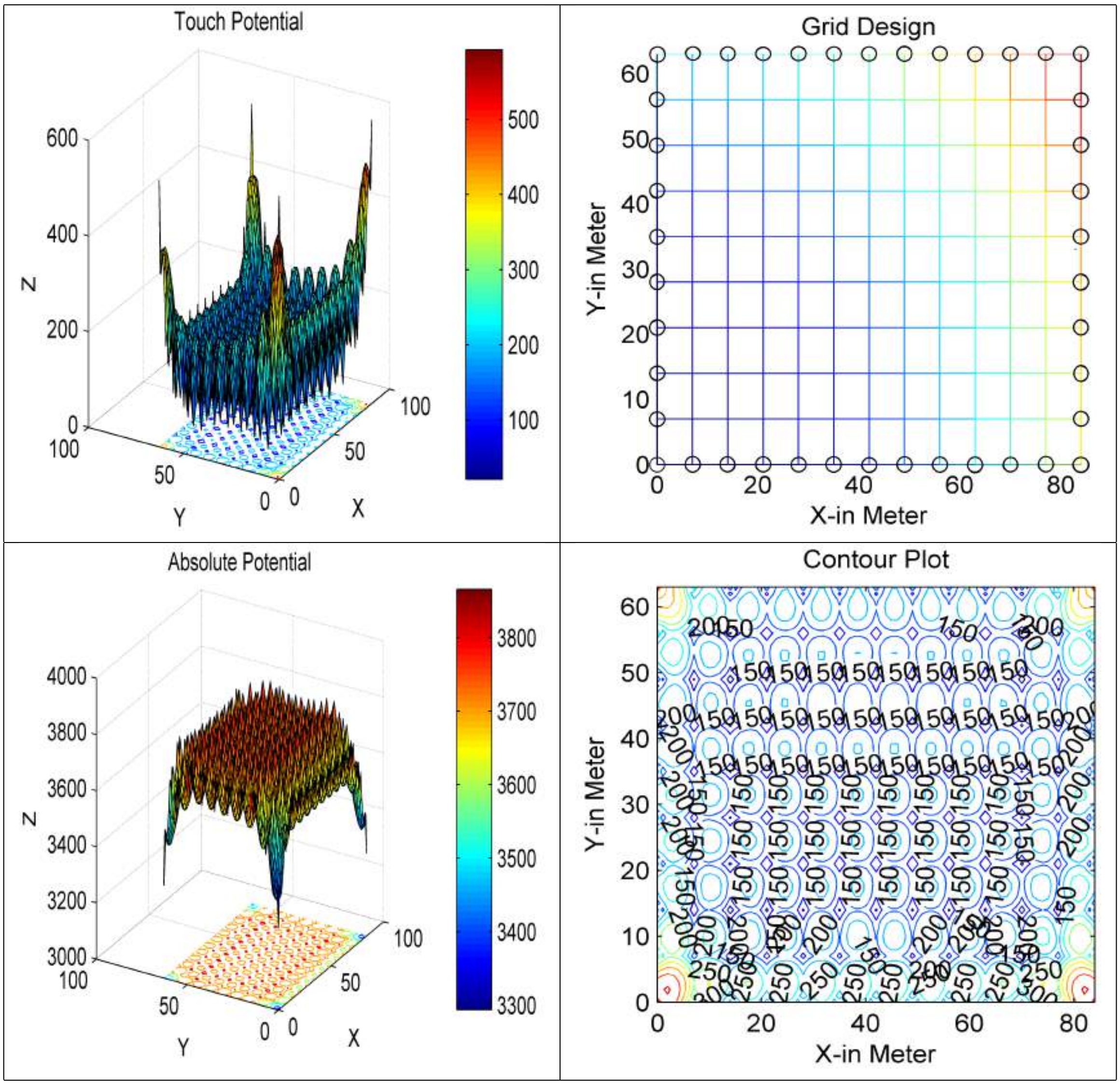

Figure 7.3: Rectangular-deeprod-equally spaced design

Table 7.3: Result of Rectangular-deeprod-equally spaced design

Particular	IEEE 80-2000	FE method	ETAP
$E_{touch70}$ (V)	838.2	838.2	838.2
$L_x \times L_y \times L_r$	$84 \times 63 \times 10$	$84 \times 63 \times 10$	$84 \times 63 \times 10$
$N_x \times N_y \times N_r$	$10 \times 13 \times 38$	$10 \times 13 \times 42$	$10 \times 13 \times 38$
$L_c \times L_R$	1659×380	1659×420	1659×380
R_g $(\Omega \cdot m)$	2.62	2.0371	2.12
GPR (V)	4998.96	3886.8	4749.6
$V_{touch(max)}$ (V)	595.8	592.9	612.5
$V_{touch(min)}$ (V)	-	21.11	-
V_{touch} (Point measure)	1	5440	8442
Safety	safe	safe	safe

7.2 Analysis of Different Design

Above all eight design there are four figure for each design.That four fig. show the Grid design, Touch potential, Absolute potential, Contour plot of the output of FE methodology.By all fig easily possible to observe the different location potential of the grid area.Here step potential graph is not show because step potential safety criteria is greater then touch potential safety criteria when the max touch potential under safety limit then the step potential also under safety limit.

7.2.1 Different Graph

(1): Grid design :- Grid design graph given the idea between two conductor spacing , no. of conductors , ground rod location and x and y direction conductor length.

(2): Absolute Potential :- The potential measure at every one meter distance horizontally as well as vertically point calculation shown in table. It is also possible to smallest distance calculation inside and out side the grid area.

(3): Touch Potential :- Touch potential is difference between absolute potential and GPR because GPR is only one value of the grid area as compare to isolate place and absolute potential depend on the current distribution in each segment of grid.In different conductor spacing grid design the maximum touch potential location is different observe by 3D touch potential and 2D contour plot.

(4): Contour plot :- This 2D graph describe the location wise touch potential level in grid area .

7.2.2 Different Design

(1): Square-Equally spaced design :- Square-Equally design is a general design a preliminary design . In this design, space between two conductors space is equal through out the grid. High touch potential is found in equally spaced design near the grid corner and periphery by graphical representation.

(2): Square-Unequally spaced design :- The max. touch potential is grater then tolerable value in (1) so the design is modified with same no. of conductors using unequal spacing between two conductors.By using unequal spacing the max. touch potential is under the safety criteria.In unequal spacing the potential distribution is unequal at corner minimum potential and at centre of grid potential level rises.

(3): Square-Extraconductor-Equally spaced design :- One more solution to the first design is extraconductor equall spacing. In this design, the stating and ending space is half for both the x and y direction.Using this concept the touch potential at corner and end of the grid conductor is decrease. Touch potential almost equal through out the grid and also under the certain safety limit.

(4): Square-deeprod-equally spaced design :- Vertical deeprod equally space design is mostly used for more reliable and for different geometry requirement like two layer soil resistivity when lower layer resistivity is low, less area and high rating of substation. In all the above cases it is always possible to achive good results with the use of deep rod. It is more costly compared to above three designs.

(5): Rectangular-Unequally spaced design :- Rectangular-unequally spacing design is compare with deeprod design IEEE 80-2000 Annex-B (ex.-3). Here we analyse the little more touch potential level is high compare to IEEE example but reliability is almost same for safety margin and cost is reduce because no ground rod.

(6): Rectangular-Changeconductor-Unequally spaced design :- Hear, one more new design concept introduce, generally x direction length and y direction no. of conductor is more as compare to other direction length and no. of conductor. Now, hear design change means x direction length and conductor both are more compare to y direction. By this design getting more uniformly increase or decrease the potential level compare to nearest point location in grid area and also decrease the max. touch potential. Here little more total conductor length will be increase because x direction no. of conductor is more compare to y direction.

(7): Rectangular-Extraconductor-Equally spaced design :- Extraconductor-equally spacing design is better compare to other design because of good safety margin and low cost means max. optimization getting in this design.

(8): Rectangular-Deeprod-Equally spaced design :- Hear, Changing the deep rod location and the few no. of rod increase which will given in IEEE 80-2000 Annex-B (ex.-3) and getting much better result as compare to IEEE 80-2000 Annex-B example.

7.2.3 Analysis

Above all eight design comparison with each other and also compare with ETAP 4.7- GGS module [24]and IEEE 80-2000. The change the design of arrangement of conductor getting more reliable for cost and safety margin optimization with same time. As per requirement change the design or mesh size at different location of the grid area and the control the all type of potential.Minimum mesh size potential level low seen in above design so corner and periphery make a design minimum mesh size.

These design problems are solved by using GGD and ETAP 4.7 - GGS module and the results are as shown in tables 7.1 to 7.8. As seen from the tabulated results. GGD produces results quite comparable to those given by ETAP and IEEE 80-2000. Thus GGD is found to give reliable performance analysis for grid having various basic shapes.

As seen from the figures, results obtained by both software and IEEE 80-2000 are quite comparable for square and rectangular shaped grid in uniform soil. Also the design is safe as per step as well as touch potential criteria hence preliminary design is fully safe. Now detailed design can be prepared based on practical knowledge and site specific requirements.

This was all about simple performance analysis of grounding systems located in uniform soil layered and having various grid designs. Here performance GGD is found more satisfactory.

In previous eight examples optimization for square and rectangular shaped grids located in uniform soil layered respectively is shown by keeping cost benefit as main objective. Also results given by GGD are confirmed with those given by ETAP 4.7 - GGS module. However GGD offers optimization considering variation in ground rods only without varying ground grid conductors and also keeping safety margin as the main objective of optimization for various optimization options involving different design variables. This feature is not available in ETAP 4.7 - GGS module.

Hence as seen from all above cases it is inferred that the newly developed software is quite efficient in analyzing simple performance and optimizing design for ground grid having square and rectangular shapes and located in uniform soil layered considering various decision variables for optimization. GGD can give design that is safe and economical i.e. optimal design in a true sense as per user requirements of keeping either cost or safety margin as dominating parameter. This proves technical soundness of this novel software and the results are also verified with GGS - module of ETAP 4.7 and IEEE 80-2000 design criteria.

Here only few sample problem have been solved to demonstrate the capabilities of the software. Also as said before, GGD is superior to ETAP 4.7 - GGS in certain cases as it offers more optimization design options and also handles almost all the cases by giving realistic results.

Up till now sample problems have been solved using GGD in order to validate its technical performance as compared with ETAP 4.7 - GGS and IEEE 80-2000. Now application of the software for solving the real world problem will be shown.

Chapter 8

Conclusion

Important Findings

- **Related to FE method**

  1. FE methodology calculation is grid conductor segmentwise calculation for Ground resistance , GPR , touch potential , step potential due to this reason the calculation is more accurate compare then other method for grounding design.
  2. At abnormal condition each segment current rms value level we can observe in FE method.
  3. It is possible to minimize distance calculation of different type potential.
  4. Grid area and Out side the grid area any point of ground potential easily find in FE method.
  5. FE method smallest distance calculation done same time and 3D graphical representation give the idea of changes of grid design and abnormal condition behavior of grid.
  6. Unequal spacing design accurate calculation possible in FE method due to conductor segmentwise calculation.

- **Related to grounding system design procedure**

    1. In majority of cases, grounding systems are intentionally made overdesigned to take into account future growth and to cope up with any unexpected scenario in order to ensure safety of people. Hence in such cases by judiciously designing the grounding system, great amount of saving can be incurred.
    2. Merely using uniform soil model may not prove satisfactory in all the cases unless soil is chemically treated. Hence soil characteristics need to be studied in detail and appropriate soil model must be used for the purpose of grounding system design and analysis calculations.
    3. In critical cases where soil has quite high resistivity, safe and reliable grounding system can be designed by applying chemical treatment to the soil for lowering soil resistivity. Occasionally use of chemically treated ground rods is a good choice to improve grounding system performance.
    4. Deep driven ground rods are excellent means to avoid hazardous scenarios. Few ground rods near periphery of the ground grid when driven into the soil upto sufficient depth, reduces grid resistance and limits hazardous voltages to a safe level by discharging fault current in lower layers of soil which generally have less resistivity.

- **Related to Software development procedure**

    1. GGD designed here gives reliable results for optimal design of grounding systems for any rating substation. These are also verified by GGS module of ETAP and IEEE 80-2000.
    2. MATLAB GUIDE provides excellent environment for software development. By developing GUIs code becomes more user friendly.
    3. MATLAB runtime compiler addon helps in making the application standalone so that it can run on any system even where MATLAB is not installed. All the thing that is needed is installing MATLAB compiler which is available in the application itself.

4. Here MATLAB is used for fist time for such extensive application development which is quite useful for educational purpose as well apart form its conventional use for coding and simulations.

5. By using these facilities those engineers who are not expert in professional programming languages but can manage with MATLAB for routine coding and simulation can now develop nice software using MATLAB GUIDE without relying on software engineer.

Conclusion

In the due course of the major project, standalone application named ***" Ground Grid Designer (GGD) "*** has been developed using MATLAB as mathematical computing tool as well as programming platform. It has been packed and deployed as windows standalone application using MATLAB compiler add on, hence it is capable of working satisfactorily even in absence of MATLAB. GGD implements safe grounding system practices described in IEEE standard 80 2000. Additionally it allows modeling of soil uniform layered structure. Also by selecting appropriate changing different design options for optimization , GGD gives optimized grounding system design which is safe and cost effective. Technical performance of the software is validated by comparing results given by it with those obtained from GGS module of ETAP , professional software. This shows reliable performance of GGD for all types of analysis thereby declaring it as trustworthy tool in the area of substation grounding system design. Moreover it is found to be superior than ETAP in certain situations where ETAP gives unrealistic results or fails in optimizing the grounding system different types of design. Hence this project has given reliable and effective solution for optimal design of grounding system for electrical substations. This can serve as excellent tool in educational field for students of electrical engineering and can also be used by professionals for getting optimal design of substation grounding system.

Future Scope of Work

1. In this work grounding system has been designed as per FE guidelines only. However it does not give rigorous analysis for complex shaped grids. In order to analyze grids having shape that is other than the basic shapes defined in IEEE standard, one has to implement method of images using FD analysis techniques. Implementation of that concept will enable the user to analyze grounding system of any complex shape by entering the required data which will be quite complicated as compared to what it is at present.

2. Also this software takes into account only the power frequency performance of the grounding system. Hence the option giving analysis of lightning impulse or switching impulse behavior of the grounding system can be incorporated that will help in analyzing the grounding system performance in dynamic conditions

3. If it is intended to expand this project itself, inclusion of options for inherent calculations of fault current for the substation and split factor determination based on the power system configuration to which the substation is connected can be attempted.

4. Right now it gives soil model extraction form Wenner resistivity test only however it can be extended for other methods also like driven rod method or Schlumberger Palmer method etc.

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[25] N. M. Tabatabaei and S. R. Mortezaeei, " Design of Grounding Systems In Substations By ETAP Intelligent Software ", International Journal on Technical and Physical Problems of Engineering, March 2010, Issue 2, Vol. 2, No. 1, pp. 45 - 49.

Appendix A

ETAP 4.7 Ground Grid Systems - An introduction

The Ground Grid Systems software utilizes the following four methods of computation:

- FEM - Finite Element Method
- IEEE 80-1986
- IEEE 80-2000
- IEEE 665-1995

The Ground Grid Systems software calculates the following:

1. The Maximum Allowable Current for specified conductors. Warnings are issued if the specified conductor is rated lower than the fault current level.
2. The Step and Touch potentials for any rectangular/triangular/L-shaped/T-shaped configuration of a ground grid, with or without ground rods (IEEE Standard 80 and IEEE Standard 665).
3. The tolerable Step and Mesh potentials and compares them with actual, calculated Step and Mesh potentials (IEEE Standard 80 and IEEE Standard 665).
4. Graphic profiles for the absolute Step and Touch voltages, as well as the tables of the voltages at various locations (Finite Element Method).

5. The optimum number of parallel ground conductors and rods for a rectangular - triangular - L-shaped or T-shaped ground grid. The cost of conductors/rods and the safety of personnel in the vicinity of the substation/generating station during a ground fault, are both considered. Design optimizations are performed using a relative cost effectiveness method (based on the IEEE Standard 80 and IEEE Standard 665).

6. The Ground Resistance and Ground Potential rise (GPR).

A.1 Main features of the Ground Grid Systems Analysis Study

- Calculate the tolerable Step and Touch potentials
- Compare potentials against the actual, calculated Step and Touch potentials
- Optimize number of conductors with fixed rods based on cost and safety
- Optimize number of conductors and rods based on cost and safety
- Calculate the maximum allowable current for specified conductors
- Compare allowable currents against fault currents
- Calculate Ground System Resistance
- Calculate Ground Potential Rise
- User-expandable conductor library
- Allow a two-layer soil configuration in addition to the surface material
- Ground grid configurations showing conductor rod plots
- Display 3-D/contour Touch Voltage plots
- Display 3-D/contour Step Voltage plots
- Display 3-D/contour Absolute Voltage plots
- Calculate Absolute, Step and Touch potentials at any point in the configuration
- Conductor can be oriented in any possible 3-Dimensional direction
- Handle irregular configurations of any shape

A.2 Ground Grid System (GGS) presentation

The GGS presentation is composed of the **Top View**, **Soil View**, and **3D View**.

• The Top View is used to edit the ground conductors/rods of a ground grid.

• The Soil View is used to edit the soil properties of the surface, top, and lower layers of soil.

• The 3D View is used for the three-dimensional display of the ground grid. The 3D View also allows the display of the ground grid to rotate, offering views from various angles.

The GGS presentation allows for graphical arrangement of the conductors and rods that represent the ground grid, and to provide a physical environment to conduct ground grid design studies. Following figure A.1 shows main page of GGS presentation.

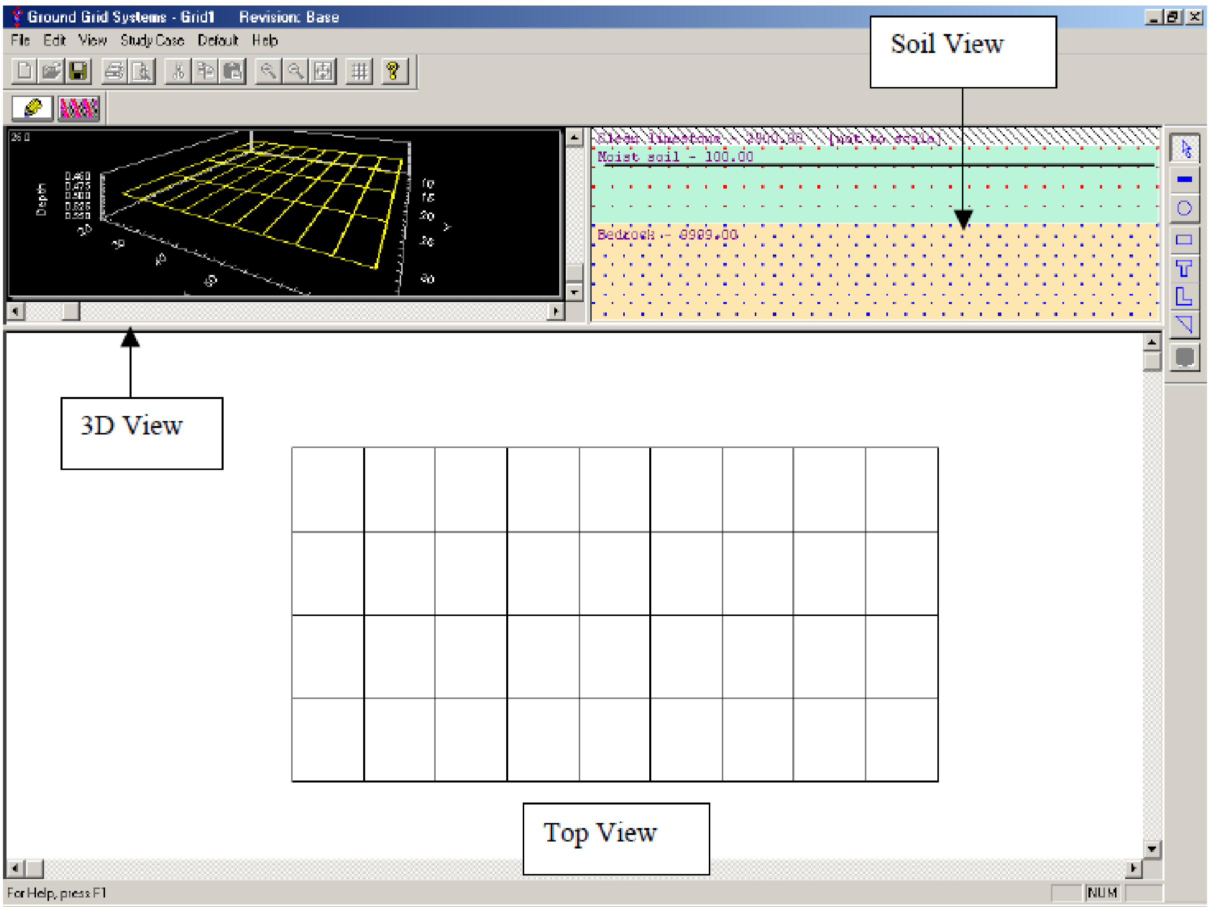

Figure A.1: Main page of ETAP GGS presentation

Various data related to grid conductors and ground rods are entered with the help of grid editor in ***top view***. FE group grid editor is shown in following figure A.2. This page takes as input all the data related to horizontal ground grid and Vertical ground rods.

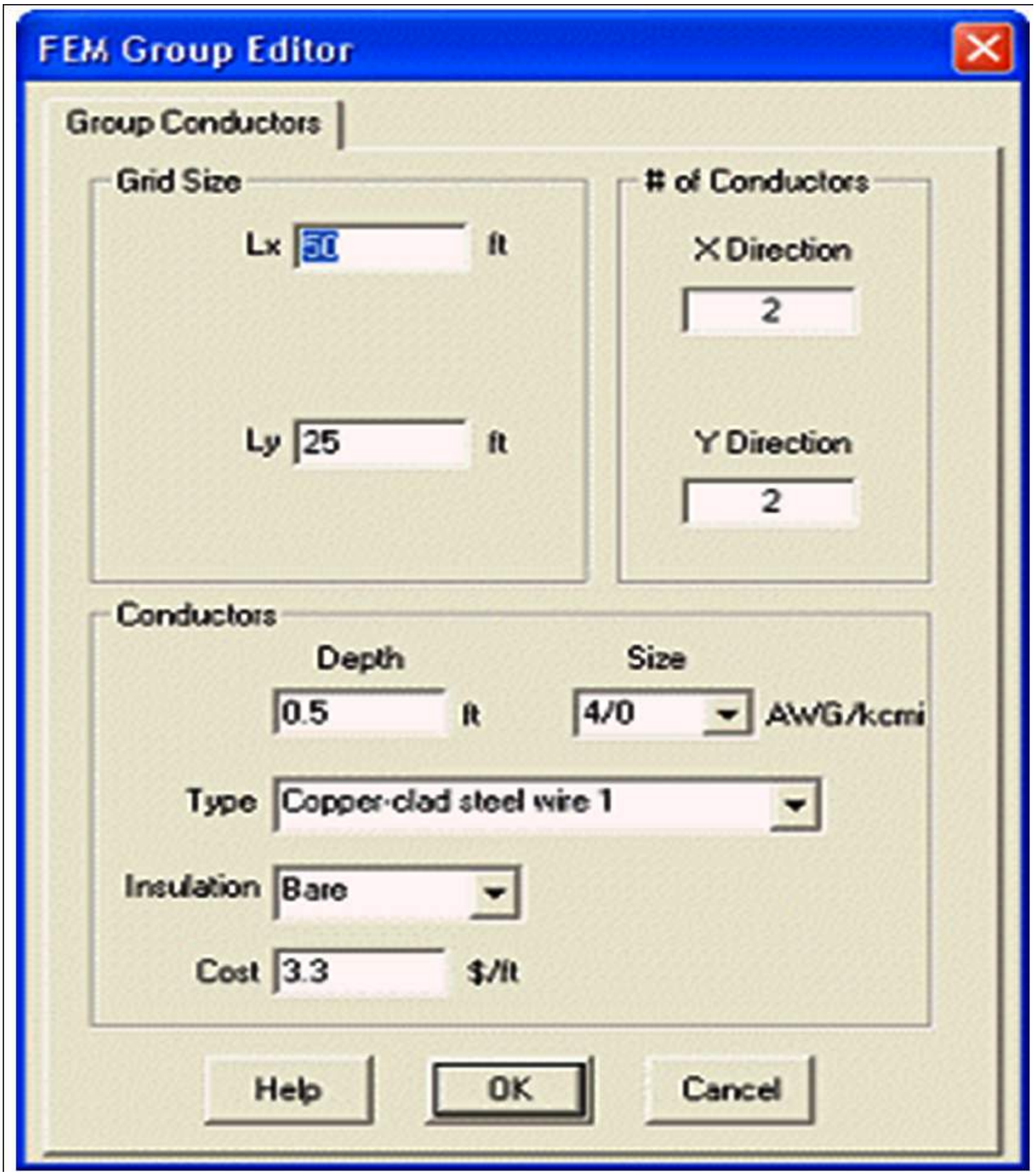

Figure A.2: Grid and Rod editor of ETAP FE method

Soil view is used for entering data related to substation soil. It allows modeling of soil structure as uniform resistivity soil or as two layered soil. Following figure A.3 shows soil editor page of ETAP.

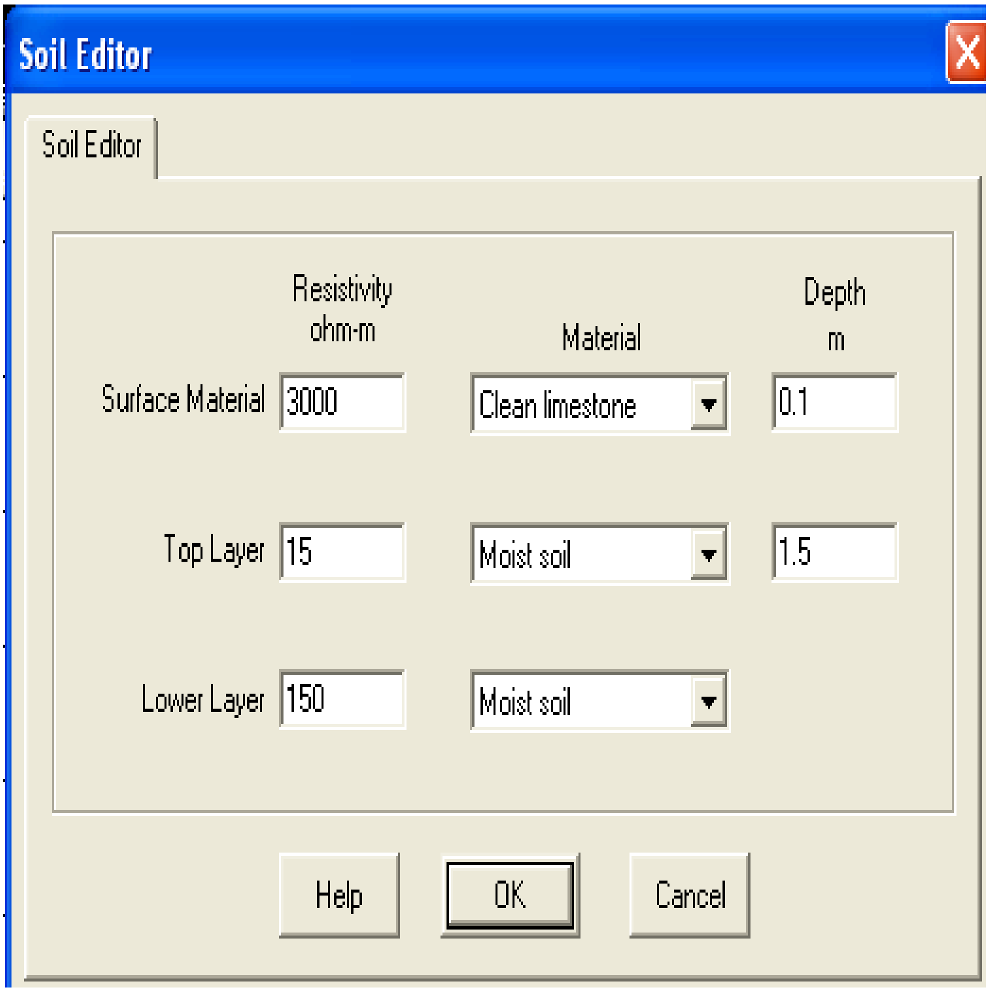

Figure A.3: Soil editor of ETAP FE method

A.2.1 Study case Editor

The GGS Study Case Editor contains

Average Weight

Ambient Temperature

Current Projection Factor

Fault Current Durations and

Option to input or compute Fault Current Parameters (i.e., zero-sequence fault current, current division factor, and X/R ratio)

Power Station allows for the creation and saving of an unlimited number of study cases for each type of study. Following figure A.4 shows screen shot of IEEE study case editor in ETAP ETAP is a professional software used by hundreds of power

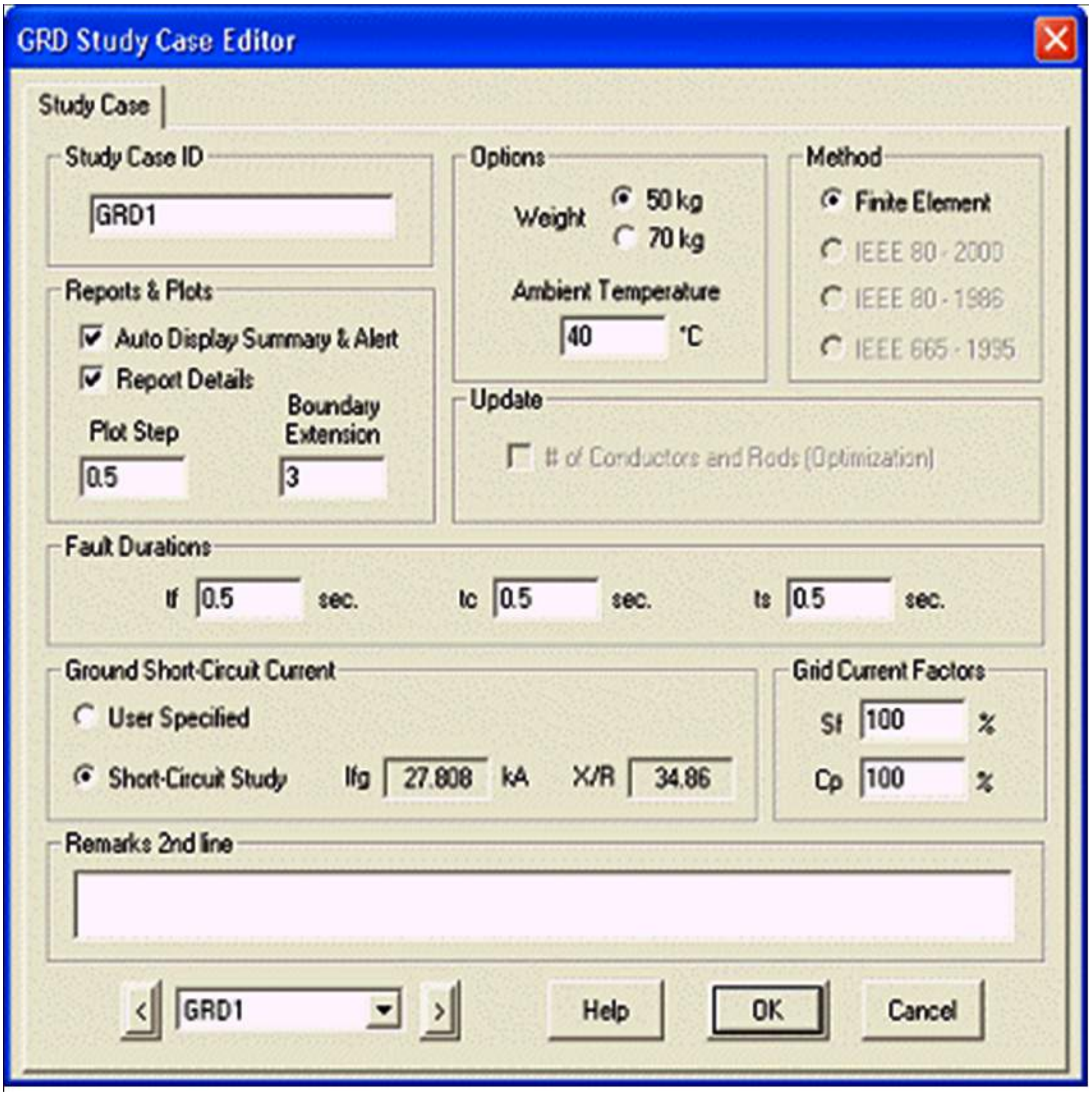

Figure A.4: Study case editor of ETAP FE method

system engineers through out the world. After analyzing various problems it gives very nice looking and well formatted report as PDF document following figure A.5 shows such a screen shot of report generated by ETAP - GGS module.

Project:	ETAP	Page:	1
Location:	4.7.0	Date:	05-04-2014
Contract:		SN:	12345678
Engineer:	Study Case: GRD1	Filename:	square

Electrical Transient Analyzer Program

Ground Grid Systems

Finite Element Method

Number of Ground Conductors:	22
Number of Ground Rods:	0
Total Length of Ground Conductors:	1540.00 m
Total Length of Ground Rods:	0.00 m

Frequency:	50.0
Unit System:	Metric
Project Filename:	square
Output Filename:	C:\ETAP 470-a\square\Grid1_SquareGrid.GR1

Figure A.5: Output report of grounding system analysis generated by ETAP

Appendix B

Introduction to MATLAB GUI

GUIDE, the MATLAB graphical user interface development environment, provides a set of tools for creating graphical user interfaces (GUIs). These tools simplify the process of laying out and programming GUIs.

B.1 Why MATLAB for GUI Development ?

In addition to simple coding, MATLAB also allows creation of graphical user interfaces [8, 9]. Though there are many advanced programming tools available for GUI based programming systems that allow creation of GUI applications, there are numerous persuasive arguments that support MATLAB as GUI development tool. Following are some significant reasons that describes encouraging applicability of MATLAB for GUI development.

- High level script based development
- Seamless integration with existing MATLAB computational power
- Operating system independent GUI applications
- User inter activity and real time measurements
- Code developed by MATLAB work on various platforms such as MS Windows, UNIX, Linux and Mac OS-X
- Also GUI developed by MATLAB works satisfactorily on various operating systems with little or no modifications. However if needed , MATLAB GUI offers simple solution using common script language.

Previously in order to develop a software, toolbox or standalone applications, one had to rely on C++, Visual basic, or Java. For a computer science or information technology student it is easy to program in these environments but for other science and engineering students this pose a problem since they are not familiar with these programs and may not have excellent programming expertise. Nevertheless MATLAB also has very nice inherent GUI development environment called as GUIDE that allows creation of GUI so that the code becomes more user friendly. It is includes low-level commands that allow user to fully customize the appearance of graphics as well as to build complete Graphical User Interfaces on MATLAB applications. Also it has access to other programming environments such as C, C++, JAVA etc. It allows user to write C and FORTRAN programs that interact with MATLAB. It includes facilities for calling routines from MATLAB (dynamic linking), calling MATLAB as a computational engine, and for reading and writing MAT files. Also with the help of deployment tool it can deploy windows standalone application so that the application can be used even in absence of MATLAB.

B.2 Salient Features of MATLAB GUIDE

Math Works has provided MATLAB programmers with a set of structured event driven components in the form of user interface controls (uicontrols) and menus (uimenus) that can easily be assembled and used to create GUIs. The fundamental power of GUI is that they provide a means through which individuals can communicate with the computer without programming commands. The components have become quite standardized and developed into a user friendly and intuitive set of tools. These tools can be used to increase the productivity of a user or to provide a window to the sophistication and power of a MATLAB application for people with little or no MATLAB programming experience [1]. MATLAB contains functions for low level GUI development that allow creation of GUI programmatically, also high level GUI development using graphical layout tool with inbuilt properties defined is available which is more convenient tool for GUI application development. When one already uses MATLAB for solving the problems in the field of engineering and

/ or science and has number of functions and scripts for solving specific problems on hand, MATLAB GUI development Environment (GUIDE) offers quite efficient and easy opportunity for building GUI by directly using the already available code within the GUI and thus saving large programming effort. This integration of MATLAB script and function files with the figure files can prove priceless and programmer friendly also in addition to being user friendly. No doubt script files and function files in MATLAB are quite efficient in solving majority of problems in various fields of engineering, technology and science; often situations arise where user interactivity is essential for understanding or solving particular problem. List of various applications can be found form In certain situations such as video applications, audio signal processing, control system analysis and circumstances where repeated analysis with modifying only few parameters is necessary, MATLAB GUIDE can serve useful in the terms of user friendliness and programming ease altogether. GUIDE allows construction of GUIs simply in drag and drop manner and also allows managing component properties with the help of property inspector. It has option for automatic generation of M file code for the GUI application. Also it has capability to handle and create most common events required to architect advanced GUI applications. Last but not the least MATLAB compiler add-on tool allows conversion of GUI into standalone executable application that may be used even in the absence of MATLAB.

GUI development environment in MATLAB allows creation of GUIs simply in drag and drop manner. Properties of various GUI components can be managed by property inspector tool. Also m file containing code for displaying the components on GUI and callbacks that handle the behavior of GUI can be generated from the GUIDE itself. Next step is inclusion of code in the m -files for various callbacks depending upon which actual functioning of the entire GUI will be decided. When one has solved certain problem(s) with the help of MATLAB coding and has script and / or function files already available, these can be directly used with the m file generated by GUIDE for GUI designed therein Following figureB.1 shows the main form that is used for GUI development Various tools to be used for developing GUIs and their use are shown in table B.1 Detailed information on GUI development using MATLAB GUIDE can be found from [2]and [3]

Table B.1: GUI tools and their use

Layout Editor	Select components from the component palette, at the left side of the Layout Editor, and arrange them in the layout area.
Figure Resize Tab	Set the size at which the GUI is initially displayed when it is run.
Menu Editor	Create menus and context, i.e., pop-up, menus.
Align Objects	Align and distribute groups of components. Grids and rulers also enables alignment of components on a grid with an optional snap-to-grid capability.
Tab Order Editor	Set the tab and stacking order of the components in the layout.
Toolbar Editor	Create Toolbars containing predefined and custom push buttons and toggle buttons.
Icon Editor	Create and modify icons for tools in a toolbar.
Property Inspector	Set the properties of the components in the layout. It provides a list of all the properties that can be set and displays their current values.
Object Browser	Display a hierarchical list of the objects in the GUI.
Run	Save and run the current GUI.

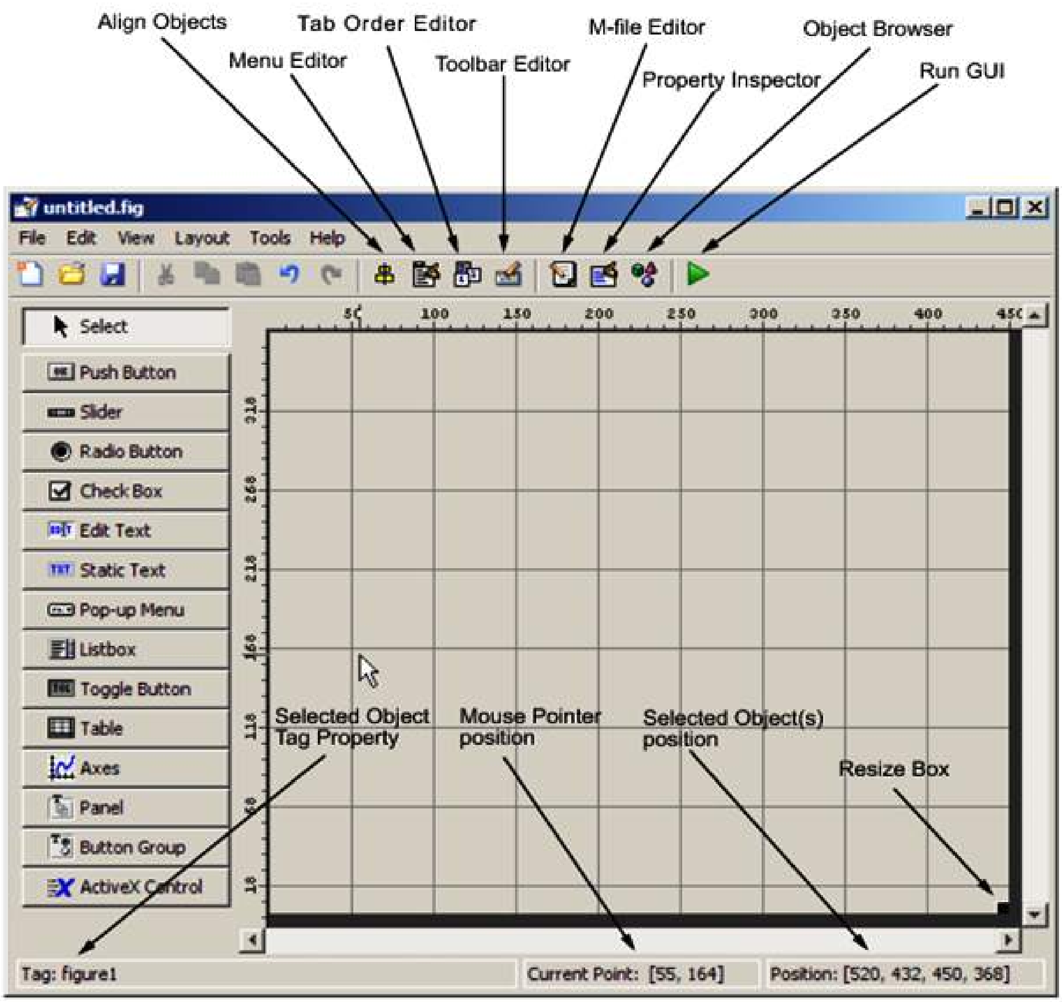

Figure B.1: Layout of GUI creation form in MATLAB GUIDE

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