A COST OPTIMIZATION METHODOLOGY FOR DESIGN OF SUBSTATION EARTHING SYSTEM

D.P.C.T.W. Gunaratne

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Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa
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Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree
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Abstract

Current practice for earthing grid design for AC substations is mainly guided by IEEE 80 ; 2000 standard. This practice is an iterative process of changing design variables until safety requirments for step and touch voltages and maximum earth grid resistance are met. During this iterative process, the assignment of values for design variables is mainly based on the experience and assumptions of designers.

However, this practice is not guided by concerns about cost minimization. Since the earth grid construction occupies a large part of the total cost of AC substation construction, an appropriate cost optimization methodology for the earth grid design for AC substations should be fully identified.

The aim of this work is to develop a cost optimization methodology based on a Genetic Algorithm using Microsoft Excell based on IEEE guidelines. This paper analyzes the effect of each earth grid design parameter on the total cost of constructing earth grid and formulation of the optimization problem. This work is also supported by a few sample calculations for a few real-time applications. The calculations show that the developed methodology ensures cost savings of between 30% and 40%.

***Keywords**: IEEE 80 :2000, Cost optimization , Earthing grid design, AC substaions, GA*

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List of Abbreviations

Abbreviation	**Description**
IEEE	*Institute of Electrical and Electronics Engineeers*
MATLAB	*Matrix Laboratory*
IEEE Std 80 (2000)	*Guide for Safety in AC Substation Grounding*
RMS	*Root Mean Square*
AC	*Alternating Current*
DC	*Direct Current*
GPR	*Ground Potential Rise*
EHT	*Extra High Tension*
GA	*Genatic Algorithm*
EC	*Evolutionary Computation*
PES	*Power Engineering Society (IEEE)*
IEC	*International Electromechanical Commission*
ICEE	*International Conference on Engineering Education*

CHAPTER 1

1. INTRODUCTION

Electricity benifits are numerous, but they can lead to fetal injuries and severe losses without adequate safety and protection. The most importantant concern when designing an electrical installation is the earthing system. The main purpose of the earthing system is to provide a way to earth for currents caused by some fault or disturbance. It enables the identification of the earth faults that ensures the operation of protective equipments and reduces the overvoltages that may occur in the system. The circulation of these currents in the earth produces voltages between the earth at various points that are potentially dangerous to humans.

To avoid theses hazardous effects , any earthing system needs to be designed to meet a number of requirements. Those requirments include ensuring the living beings in the proximity of earth structures are not exposed to danrgerous potentials under normal conditions or faulty conditions (lightning, switching surges and phase to earth short circuits), keeping system voltages within reasonable limits under faulty conditions to ensure that insulation breakdown voltages are not exceeded, the compatibility of electromagnetic effects and providing sufficiently low impedance to make electrical protection equipments easier to operate.

1.1 Background

Vertical ground rods are the easiest and most widely used type for electrical earth termination. When vertical ground rods are combined with the earthing grids, it allows a convenient earthing system design to improve its efficiency by reducing not only the grid resistance but also the step and touch voltages to human-safe value. Typically; an effective substation earth system consists of earth rods, connecting cables from the buried earth grid to metallic parts of structures and equipment, connections to earth system neutrals, and earth surface insulating material.

Earth rods , conecting cables and earth grid provide a designated low ressistance path to earth fault currents, while surface insulating materials increase human safety by increasing the contact resistance between earth and feet.

People often assume that it is possible to safely touch any grounded object. However, low resistance to substation ground is not in itself a guarantee of safety. Step and touch voltages should be measured for safety criteria within and around the substation. [1] In practice, safety criteria mean that the magnitude and duration of the current through the body of a person exposed to a potential gradient does not result in ventricular fibrillation.

High construction costs and unsafe conditions will result from unreliable design methods and simplistic field measurements. The appropriate design methods reduce the construction time and costs and offer great reliability in the results obtained.[2] Nowadays, with well-defined and reliable earthing grid design methods, safety factors can be achieved by almost 100 per cent and therefore cost effectiveness is given similar importance as safety in earthing grid designs.[3] When focusing on cost effectiveness, it was highlighted that safety constraints must be overcome without having an over-dimensioned earth grid design that is more costly than necessary.

1.2 Problem Statement

Current practice in the Electrical Earthing System Design is mainly focused on complying with all safety criteria such as step voltage, touch voltage and allowable grid resistance limits. Over the past few years, these protection dimensions of variables have been thoroughly updated to improve safety. In common practice, if initial design does not follow the safety criteria, the highest step voltage and touch voltage and earth grid resistance are usually reduced by decreasing the gap between the horizontal grid conductors, increasing the number of earth rods etc. which simultaneously increase the material cost and the earth grid construction cost. Due to the lack of guidance in this procedure in revising the initial design to meet the safety limits, this cost increase may be in terms of millions rupees which is not actually necessary. Due to this lack of guidance for cost effectiveness in current practice, the cost of the earth grid design depends on designer’s experience and approximate assumptions.

Reducing the cost of earthing grid construction means, in turn, reducing the cost of material and the cost of construction labour. Reducing earth grid material and construction labour will simultaneously increase maximum step voltage and touch voltage and earth grid resistance. Therefore, designing an earthing grid in compliance with safety constraints while reducing the cost is in conflict and a compromise solution needs to be found.

Design of substation earthing system involves setting values for number of design variables while reducing costs and meeting all safety parameters. Number of grid configurations can be obtained by setting values for all variables that can fully define grid characteristics while meeting the IEEE std 80 2000 safety criteria. Selecting the most cost-optimized grid configuration from all of these possible configurations is a time consuming and very complex process.

It is getting simpler if one can use an optimization methodology with well-defined objective function and constraints and in such methodology has the potential to save millions of rupees. When using in an optimization process, these design variables shall include in a comprehensive objective function to compute the cost of the complementary system.

1.3 Objectives and Scope

1.3.1 Objectives

The main objective of this research is;

- To develop a methodology to design a cost-optimal substation earthing system that incorporates a genetic algorithm for cost optimization**.**

Sub objectives of the research are;

1. To generate a relationship between the design variables of the substation electrical earthing design and total construction cost of the design.
2. To determine a cost optimization methodology for electrical earthing systems that meets all the safety criteria.

1.3.2 Scope

Installation of the earthing grid, which meets all safety requirements, will cover a considerable amount of a substation's overall construction cost. Since the common practice of IEEE 80:2000 does not involve in optimizing the cost of earth grid design, this design procedure may end up with over-designed earth grid design in terms of cost. Therefore cost optimization of substation earth grid design has the potential to save a considerable amount of money.

This paper aims at optimizing the design of earth grid by obtaining cost optimized values for design parameters such as;

- Spacing between horizontal earth grid conductors
- Number of vertical earth rods
- Length of earth rods
- Grid burial depth
- Surface layer thickness

to obtain a cost-optimized substation earth grid design while ensuring IEEE 80:2000 safety criteria for Step and Touch Voltages and complying with minimum earth grid resistance requirements for uniform soil conditions with uniform conductor spacing.

1.4 Research Methodology

The main focus of this work is to develop a cost optimizing methodology for earthing design of AC substations. Although alternative approaches have been used in the past to optimize earthing grid design with a limited number of optimization variables and using the finite element method for earth grid design, almost all design variables have been implemented in this study and the design process described in IEEE std 80 2000 has been used, which is widely used in practice. Those alternative approaches will be discussed in the literature review

1. **Identify all cost components associated with substation earthing construction.**

   All the cost comptometers should be correctly identified in order to identify the total cost that may incur during construction of earthing grid. This was done by conducting interviews with industry practitioners (Electrical contractors and technicians) and by closely reviewing the earthing construction method statements.

2. **Establish a relationship between the IEEE design parameters and those cost components (Cost Function).**

   Earthing grid design variables that can be used to define both grid configuration and cost of earth grid construction such as distance between horizontal conductors, number of earth rods , length of earth rod, thickness of the surface layer and grid burial depth are considered as optimization variables to minimize the objective function of total earth grid construction cost. Upper and lower boundary values were also defined for these variables in order to achieve more realistic grid configuration. After analyzing the effect of each design parameter on grid performance and construction cost, a comprehensive cost function was developed. This expression was used as the objective function during the cost optimization process. In-depth review of literature was helpful to develop a comprehensive cost function (Objective function) for the study.

3. **Determine the most suitable cost optimization method that can be adopted to optimize substation earthing.**

   Number of optimization methods was available. Genetic Algorithm (GA) was selected as the best method of optimization for use in this problem, considering the characteristics of constraints and objective function, the number of variables involved in the optimization process, the computation time and ability to reach the best optimal solution.

4. **Develop a spreadsheet for designing substation earthing system as a cost optimization problem**

   An Excel sheet is created to do the calculations according to the IEEE Std 80 2000 design procedure for the AC substation earth grid design. This Excel sheet is referred by the optimization add-in during the optimization process. When the field data is entered on the excel sheet, all the safety criterions , actual grid performance parameters (maximum step voltage and touch voltage, maximum grid resistance, GPR) and the total construction cost are calculated based on the values assigned by the optimization add-in for the design variables.

   An excel add-in of the GA optimization is used in this study. GA settings were defined to obtain the most optimized solution within reasonable duration according to problem variables and constraints. Constraints for Step and Touch voltages and Maximum grid resistance were defined as constraints for the optimization problem.

   Therefore, the minimum construction cost and associated optimized design variable values can be achieved from this excel sheet when optimization process is terminated. Also values for design variables were assigned based on the past experience and assumptions to obtain a value for total earth grid construction cost in the case of normal condition (scenario when optimization is not used). From those two cost values, the cost saving is assesd.

5. **Apply the developed spreadsheet for a few sample calculations.**

   In order to analyze cost savings from the developed methodology, few real-time cases with different site parameters have been considered. Labor rates and material prices have been obtained from the market price lists and by obtaining labour rates for installation from industrial contractors.

6. **Evaluate the numerical results.**

   Then the results obtained for the studied cases for standard IEEE design procedure and the cost optimization methodology adopted by this study were compared in terms of cost saving to demonstrate the appropriateness of the developed method.

   The cost saving values obtained were analyzed by means of a cost-sensitivity analysis for changes in market prices of material due to changes in taxes , variations in foreign currency exchange rates and variation in raw material prices. Also sensitivity of labour rates was also analyzed considering variations in labour wages. The reliability of the proposed method was ensured from the results of the cost sensitivity analysis.

CHAPTER 2

2. LITERATURE REVIEW

In the early stages of this research area in earth grid cost optimization, researchers have tried to consider a single grid parameter at a time in order to achieve optimum performance in the earth grid.

In the research undertaken A. Datta, R. Taylor and G. Ledwich, a method to determine the **earth grid installation depth** based on soil model is described to increase grid performance, hence reducing the amount of conductor material and thus the cost. Although they did not consider optimizing the earth grid in relation to cost , they concluded that by optimizing the grid burial depth by their method,they could reduce the material quantity of the earthing grid conductors, which could lead to reduction in the cost of earthing grid.[4]

A study was carried out to understand effective grounding strategies for high resistivity soil in order to minimize cost increases caused by **backfilling** the grid area. [5]

Another research was carried out to obtain the best possible **position for vertical earth rod** to reduce grid resistance, step voltage and touch voltages. This research also shows that the grid mesh sizes can be kept larger to achieve lower material cost on horizontal conductors by placing the vertical earth rod at best possible location.[6]

A Research was conducted as a basis for the economic design of grounding grids by varying the **grid area** and the **distance of external grounding grid** in order to achieve minimum grid resistance.[7]

Numerous research works have also been carried out on the use of **unequally spaced ground grid** design to equally distribute the electrical voltage difference between points on earth grids in order to minimize material cost horizontal mesh by making optimal use of the mesh to obtain safety criteria.[8],[9],[10] In addition, few remarkable case studies have also paved the way for optimizing the cost of earth grids. A case study was conducted in an attempt to reduce the cost of earth grid construction by replacing commercial hard drawn copper with aluminium 505 alloy material and significant cost saving was obtained.[11]

The CYMGRID software base method and mathematical method based on IEEE 80 2000 were compared to analyze possible shortcomings resulting from over dimensioning or underestimating the ground grid in design of electrical earth grid. [12]

A case study was performed for 275 kV Betung Substation to optimize the earth grid according to IEE 80-2000 standard. [13]

The paper presented by another group of researchers demostrate a secure and economic earthing system design using genetic algorithm optimization (GAO) for a substation located in Algeria. [14]

Another effort to reduce the earth grid construction cost is illustrated by the work using a mixed integer linear programming to evaluate pre identified, grid configurations from possible conductor sizes, excavation depths and number of rods in terms of cost. The number of binary variables was used to store the variable values for each configuration during the cost optimization method. [15]

In order to increase the level of safety of the earthing grid, a method for optimal arrangement of conductors in the grounding grid was proposed by another study.[16]

In the field of earthing grid optimization, several researches have been conducted utilizing innovative methods for calculating earth grid performance parameters, such as grid resistance, step and touch voltages, using approaches other than those empirical formulas described in the IEEE standards.

For a two-layer soil model, an equivalent circuit of the grid mesh and earth rods has been designed for the node voltage calculation in the study another study.[17]

Another author proposes a nested evolutionary method which uses genetic algorithms to design an earthing grid with a pre-arranged number of conductors. In all design steps the maximum touch voltage is controlled, the value of which must be lower than the safety values set out in the IEEE Standards. This maximum touch voltage is calculated using a method based on the genetic algorithm. The proposed evolutionary method allows the design unequally spaced grounding grids that produce a more uniform distribution of touch voltage distribution than the equally spaced earthing grids.[18]

There are also few other studies that have used few variables to optimize the earthing grid without taking into account all possible variables and parameters. In the study conducted by A. Covitti, G. Delvecchio, A. Fusco, F. Lerario, and F. Neri, the cost of supply and installation of earth rods and horizontal conductors was considered by limiting only the touch voltage of the earth grid to a safe value.[9]

The aim of another study using Charge Simulation Method (CSM) is to calculate the Earth Surface Potential due to discharge of current into the grounding grid using a scaled model with an electrolytic tank. Parameters used for cost optimization in this analysis are the length of the grid and the length of the rod. The cost of the optimized design is higher than the initial design, but still lower than the proposed cost. [19]

Based on the Electromagnetic Field (EMF), the paper studies the calculation of grounding grid parameters and uses genetic algorithm studies to optimize the design of the grounding grid, under the condition of that the highest touch potential of grounding grid is less than the specified IEEE defined value.[20]

In the reserch done by Z. He, X.Wen, K.Zhang et al Genetic algorithm was used to optimize the earthing grid by calculating the highest touch potential to determine the safety of the earthing grid under the condition that the grounding grid's highest touch potential is less than the IEEE guide provision value. The goal is to optimize the level conductor configuration and uniform leakage current density distribution of conductor in order to achieve a uniform surface potential and make best use of the conductors, reduce the potential surface gradient and protect the safety of people and equipment. Althought the research focused on optimizing the grid configuration in terms of safety , it didn’t aim to reduce the cost.[20] The paper presented by S. Patel and A.K. Kori discuss a method to improve the soil resistivity to achieve safe, reliable and economical earth design. This paper also discussed about various alternatives to achieve low grid resistance and safe step and touch potential [21]

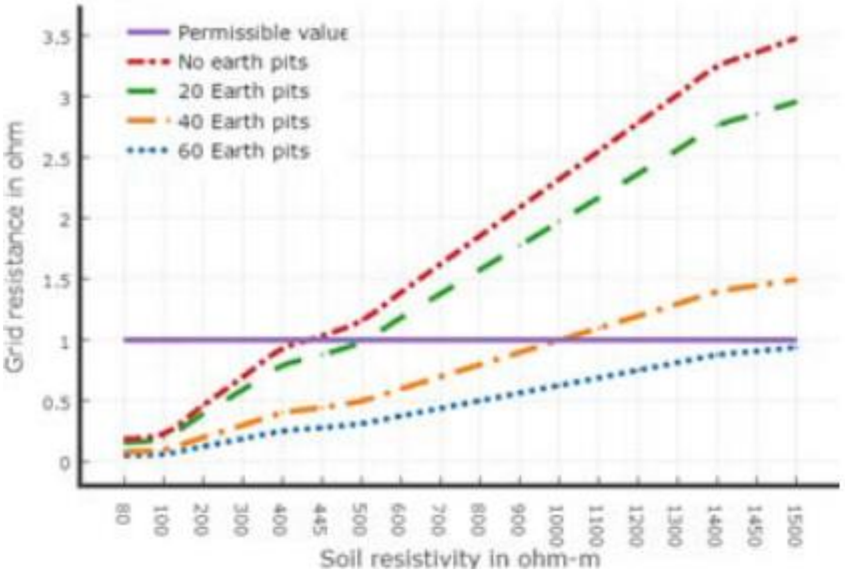


Figure 2.1: Grid resistance curve for different soil resistivity with modification

Source: Comparison between Earthing System Designing Parameters for Different Types of Soil Resistivity Area and Minimization of Limitation[21]

An evolutionary algorithem is used in the research by S. Ghoneim, H. Hirsch, A, Elmosshedy et al to optimize the earth grid design based on the grid parameters such as lengths of the grid , grid conductors size and length of vertical rods.[22]

Another research has been carried out using the Random Walk Technique through a MATLAB program to optimize the cost of earthing grids. However, this reserch by G.Gilbert,Y.Chow,D.Bouchard et al. considered only the number of meshes ,the size of the earthing grid and the number and length of the vertical rods as the decision variables for the objective function of cost optimization. [23]

It was concluded that the use of meta heuristic optimization methods has a good effect on the cost minimization of substation earthing grids. A good objective function could achieve a well optimized design using these algoriths with IEEE 80 standard constraints. [24]

The aim of the work done by A. George is to design a cost effective ground grid for a certain set of parameters. Factors affecting cost such as conductor spacing, depth of burial, number of ground rods, length of ground rods and type of grid material are considered for cost minimization purpose. Keeping rest of the parameter constant, one parameter is varied at a time to obtain a set of solutions. The process is repeated for the rest of the parameters and the execution results in a large number of solutions. Just feasible solutions will be kept and the rest will be discarded. An optimal solution or least cost solution is found from the set of feasible solutions. [3] Almost all parameters affecting the cost of constructing the earthing grid in substations have been considered for this study. However manual calculations such as those carried out in this work may take grat deal of time to get the optimum solution.

Most of the above metioned cost optimization approcraches were considered only limited number of design variables in the objevtive functions. It is visble that increasing the number of design variables considered during the optimization process may resulted in higher cost saving in the optimized design. This gap was identified and this work is focused on developing more comprehensive cost function which can be used to optimize the earth grid design.

CHAPTER 3

3. THE EARTHING GRID DESIGN AS IT USUALLY FORMULATED

The common practice of designing AC Substation Earthing Systems is according to IEEE guidlines. Designers can use this guidline to calculate and validate their earthing grid designs in terms of safety.

3.1 IEEE Guide for Safety in AC Substation Grounding, IEEE 80: 2000

This guide focuses on safe grounding practices in the 50 - 60 Hz range for power frequencies. As the initial step to start the earthing design for AC substation, few data related to the site conditions are required. Those are;

3.1.1 Resistivity of Soil, ρ

Soil composition, moisture content and temperature may influence soil resistivity. Most of the time, soil can be considered to be non-homogeneous in terms of soil resistivity.

The most widely used method for measuring soil resistivity is Wenner method, developed by Dr. Frank Wenner of the US Bureau of Standards in 1915. According to this method, earth resistance is measured by the use of the Earth Tester. These measurements can be used to determine the soil resistivity profile and the soil model which is most important in designing earthing grids.

3.1.2 Grid Area, A

The substation earthing grid area shall be measured at the site or otherwise substation property map and general location plan shall provide a good estimate of the grid area. The designed earth grid should meet all the safety criteria within this grid area.

3.1.3 The Maximum Grid Current, I_G

The maximum grid current is defined in IEEE 80 standards by (3.1).

$$I \qquad (3.1)$$

In the equation,

– The Maximum Grid Current in A

- Decrement Factor

- RMS Symmetrical Grid current in A

I_g is the part of the symmetrical earth fault current that flows through the earthing grid to the surrounding soil. The Decrement factor is the adjustment factor used in earthing grid design to include RMS equivalent of the asymmetrical current wave for a given fault duration, t_f, accounting to the effect of initial DC offset and its attenuation during the fault.[25]

3.1.4 Fault Duration, t_f

Table 3.1: Relationship between Voltage Class and Fault Duration Time
Source: Software Development of Optimal Substation Ground Grid Design based on Genetic Algorithm and Pattern Search [17]

Voltage Class (kV)	Time (s)
>250	0.25
200 -250	0.5
22-200	0.58
<22	1.1

After obtaining above data for the considered substation, the minimum conductor size that can be used in the earthing grid should be determined. This depends mainly on the current carrying capacity of the selected conductor type. The current carrying capacity of the selected material for the calculated minimum size should be higher than the maximum grid current to ensure that the earth grid is mechanically and electrically viable to safely conduct the earth fault current to the surrounding soil without failure

In IEEE 80 guidelines, the minimum conductor size is calculated by using equation (3.2)

$$I = A_{mm^2}\sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_c \alpha_r \rho_r}\right)\ln\left(\frac{K_o + T_m}{K_o + T_a}\right)} \qquad (3.2)$$

Where

I - The RMS current in kA

$TCAP$ - The thermal capacity per unit volume from Table 1, in J/ ($cm^3 \cdot °C$)

A_{mm^2} - The conductor cross section in mm^2

t_c – Duration of Fault Current, s

α_0 - The thermal coefficient of resistivity at 0 °C in 1/°C

α_r - The thermal coefficient of resistivity at reference temperature T_r in 1/°C

ρ_r - The resistivity of the ground conductor at reference temperature T_r in μΩ-cm

K_0 - $1/\alpha_o$ or $(1/\alpha_r) - T_r$ in °C

T_r - The reference temperature for material constants in °C

T_m - The maximum allowable temperature in °C

T_a - The ambient temperature in °C

After calculating the minimum conductor size, the initial design of the substation earthing shall be determined by determining the dimensions of the earth mesh, the number of earth rods, the depth of the grid burial, the length of earthing rods and the material used for the surface layer and its thickness. The initial design is then evaluated on the basis of the safety constraints of the Earthing Grid. If the initial design satisfies all the safety constraints, a detailed design shall be carried out.

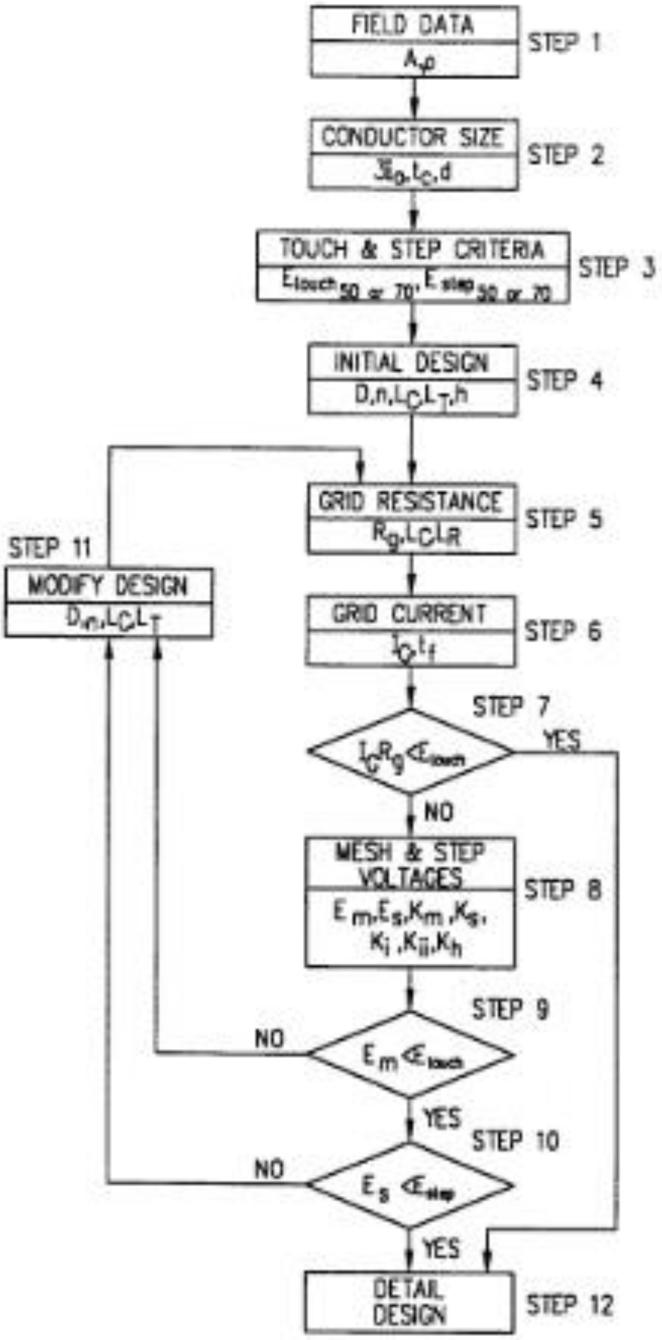


Figure 3.1: Design procedure Block Diagram

Source: IEEE 80 (2000)

CHAPTER 4

4. SAFETY CONSTRAINTS FOR EARTH GRID DESIGN IN AC SUSBTATIONS AND EARTHING RESISTANCE

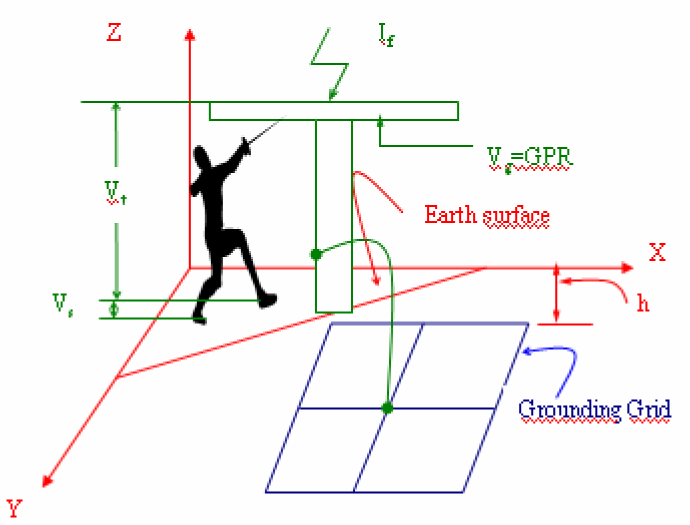


Figure 4.1: Illustatrion of the Earthing System

Sourec : Optimum grounding grid design by using an Evolutionary Algorithm[22]

4.1 Step Voltage

Voltage difference between the feet of a person (approximately a distance of 1m) without contacting any earthed object, but standing near an energized earthed object which causes increase in ground potential. When the earth grid is installed, the maximum step voltage of the person within the earth grid should be lower than the tolerable step volatge based on the body mass of the person and the fault duration. The step volatage is calculated using the equation (4.1) in IEEE 80:2000 design procedure.

$$E_s = \frac{\rho \times K_s \ \times K_i \ \times I_G}{L_S}$$

(4.1)

Where

E_s - Step voltage between a point above the outer corner of the grid and a point 1 m diagonally outside the grid for the simplified method, V

ρ - Soil resistivity, Ω·m

K_s - Spacing factor for step voltage simplified method (IEEE 80 (2000)

K_i - Correction factor for grid geometry, simplified method IEEE 80 (2000)

L_s - Effective length of L_c+L_R for step voltage,m

4.2 Touch Voltage

The voltage difference between two metal parts that can be touched at the same time by a single person. When the bodies of all the energized components are connected, the earth mesh voltage is considered to be the worst touch voltage on the earth's surface above the earthing system. Therefore, the earth mesh voltage should be lower than the tolerable touch voltage of a person. The mesh voltage is calculated using the equation (4.2) as specified in IEEE 80:2000.

$$E_m = \frac{\rho \times K_m \times K_i \times I_G}{L_M}$$

(4.2)

Where

E_m - Mesh voltage at the center of the corner mesh for the simplified method, V

K_m - Spacing factor for meesh voltage, simplified method (IEEE 80(2000)

L_M - Effective length of L_c+L_R for mesh voltage,m

4.3 Resistance of the Earth Grid

Earth Resistance shall be maintained at a minimum level that facilitates proper functioning of the protection equipment. A good earthing system provides a low resistance to remote earth to minimize GPR. For transmission and other large substations, the earth grid resistance is usually about 1 Ω or less. In smaller distribution substations, the usual acceptable range is from 1 Ω to 5 Ω. [26] Minimum earth grid resistance levels are as table (4.1) for specific applications.

Table 4.1 Allowable Earth Resistance Values

Source: Comparison between Earthing System Designing Parameters for Different Types of Soil Resistivity Area and Minimization of Limitation[21]

	Application	**Permissible Value**
1.	Power Stations	0.5Ω
2.	EHT Substations	1.0Ω
3.	33kV Stations	2.0Ω
4.	D/T Centers	5.0Ω
5.	Tower foot resistance	10.0Ω

In this work, Earth grid resistance is calculated by Sverak's equation(4.3), as set out in the IEEE guidelines below.

$$R_g = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20 \times A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] \tag{4.3}$$

Where

R_g - Resistance of grounding system, Ω

L_T - Total effective length ogf grounding system conductor, including grid and ground rods, m

h - Depth of ground grid conductors, m

CHAPTER 5

5. EFFECT OF EACH EARTH GRID DESIGN PARAMETER ON TOTAL COST OF EARTH GRID CONSTRUCTION

Factors for improving earth grid performance also have a significant impact on the overall construction cost of the earth grid. These parameters have a different effect on overall earthing grid construction cost and earthing grid performance.

5.1 Surface Layer Thickness

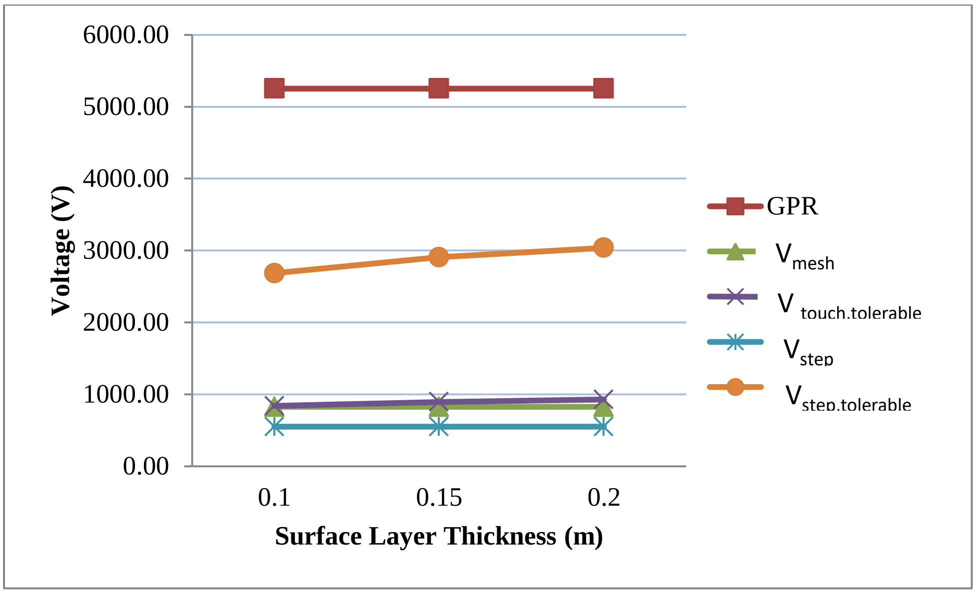


Figure 5.1: GPR,Step & Touch Voltages vs Surface Layer Thickness

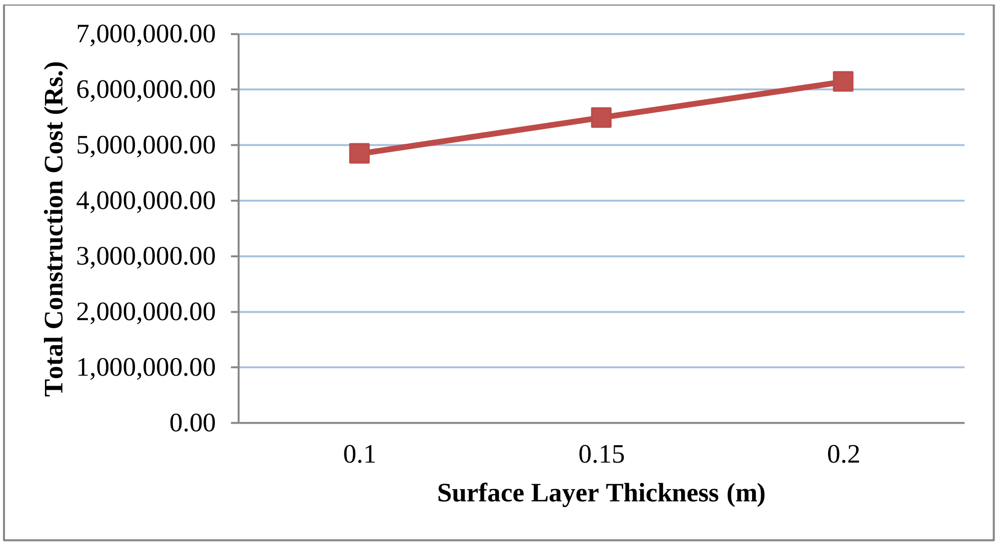


Figure 5.2: Total Construction Cost of Earthing System vs Surface Layer Thickness

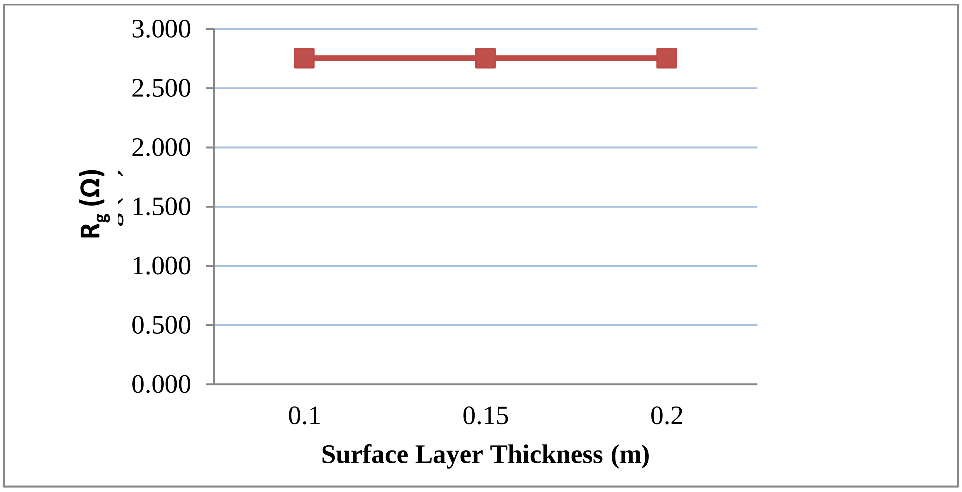


Figure 5.3: Earth Grid Resistance vs Surface Layer Thickness

When the surface layer thickness increases , the tolerable step and touch voltage limits increase. When the thickness of the surface layer material increases supply and installation cost of the surface material also increases, resulting in higher overall cost for the earthing system construction. However ,the thickness of the surface layer material has no effect on Earth Grid GPR, Maximum Step & Touch Voltages and Earth Grid Resistance.

5.2 Length of Horizontal Conductors

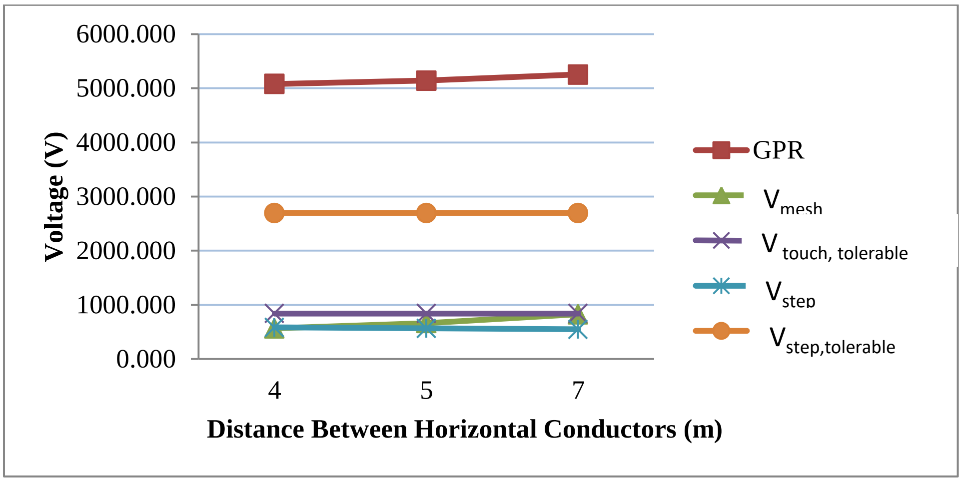


Figure 5.4: GPR,Step & Touch Voltages vs Distance Between Horizontal Conductors of Earth Mesh

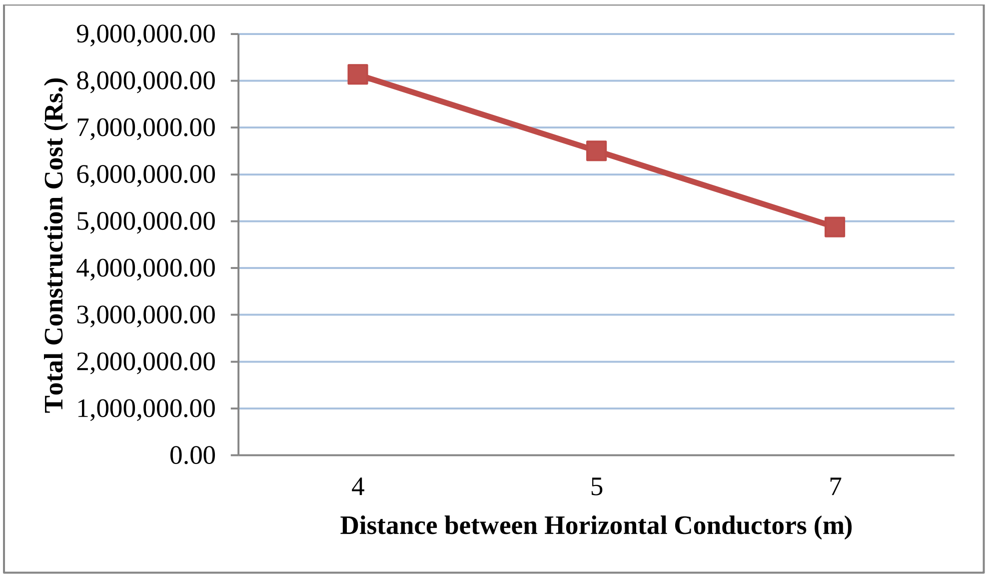


Figure 5.5: Total Construction Cost of Earthing System vs Distance Between Horizontal Conductors of Earth Mesh

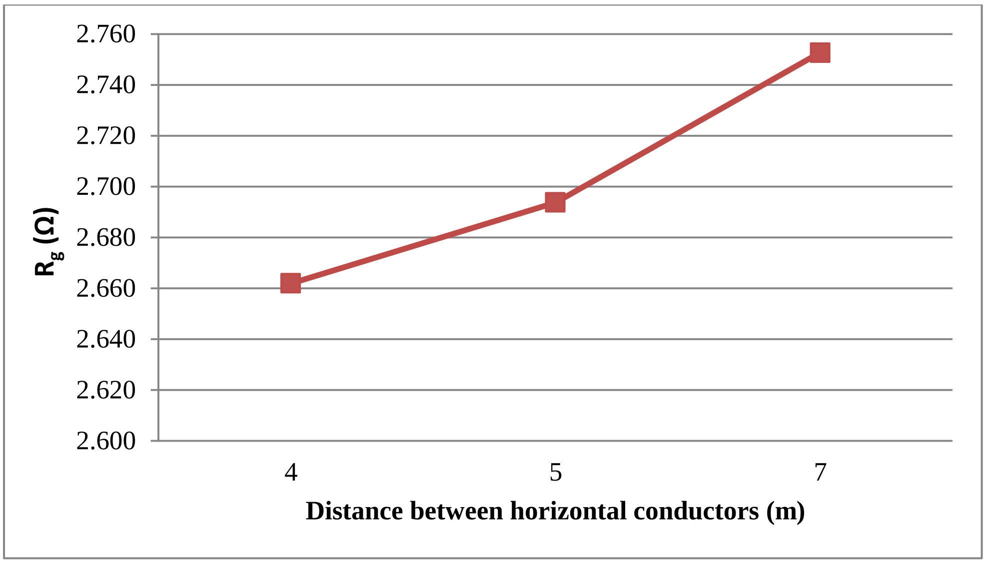


Figure 5.6: Earth Grid Resistance vs Distance Between Horizontal Conductors of Earth Mesh

Distance between horizontal conductors is used to define the mesh size of the earthing grid. With larger earth grid mesh size, GPR, earth grid resistance ,maximum step and touch voltages are also increased. However, when the mesh size increases, the total length of the horizontal conductors reduces causing reduction in total earthing grid construction cost.

5.3 Number of Earthing Rods

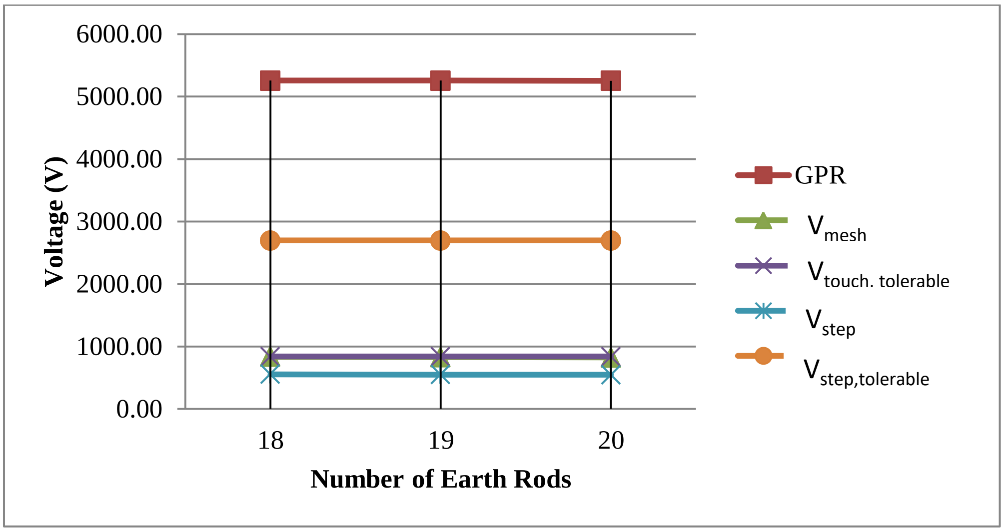


Figure 5.7: GPR,Step & Touch Voltages vs Number of Earth Rods

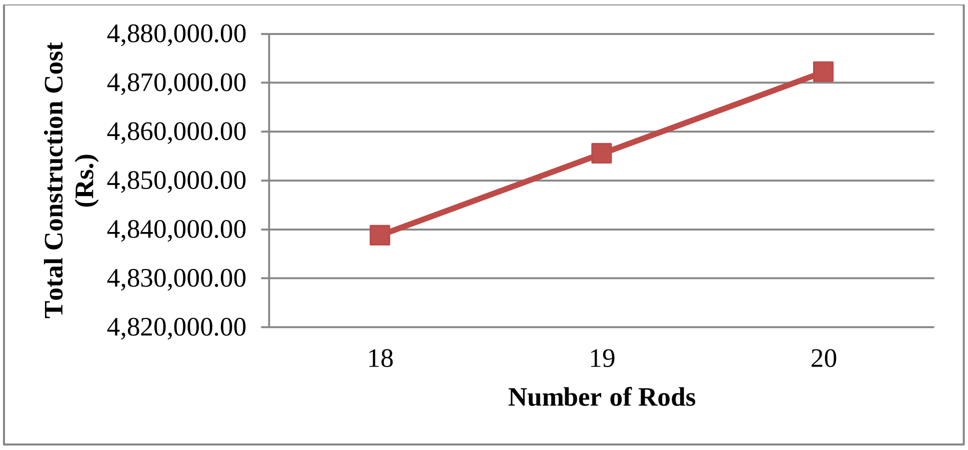


Figure 5.8: Total Construction Cost of Earthing System vs Number of Earth Rods

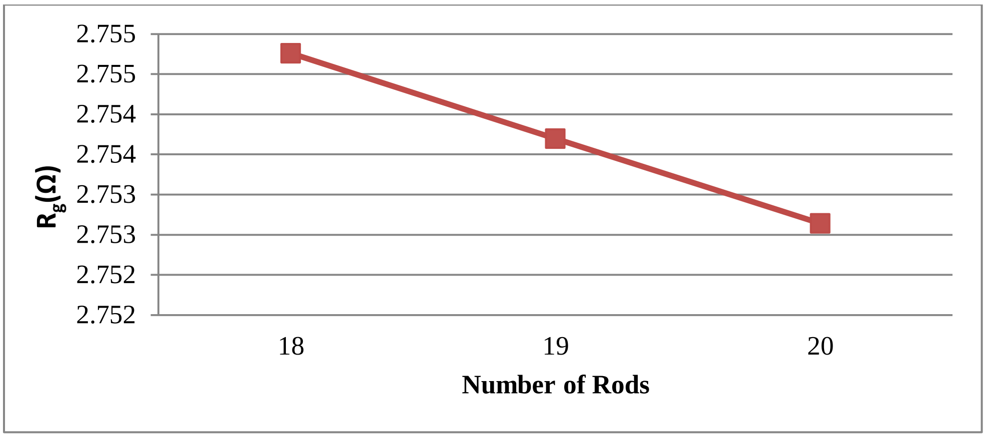


Figure 5.9: Earth Grid Resistance vs Number of Earth Rods

When the number of earth rods is increasing,the GPR and maximum step and touch voltages of the earthing grid are reduced slightly. However, the number of vertical earth rods significantly reduces earth grid resistance. The total cost of earthing grid construction also increases with the number of earth rods.

5.4 Length of Earth Rods

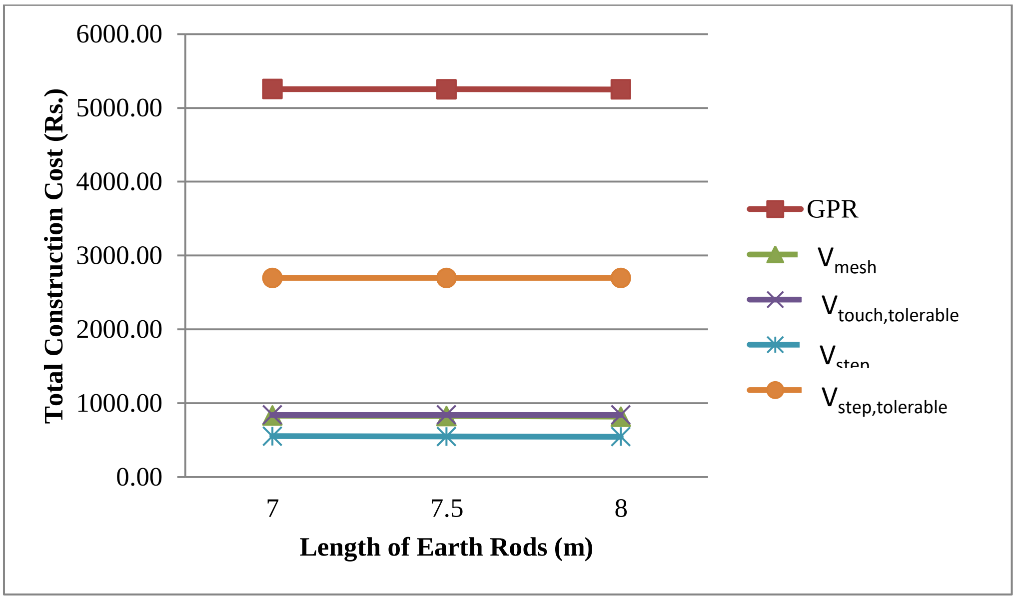


Figure 5.10 : GPR,Step & Touch Voltages vs Length of Earth Rods

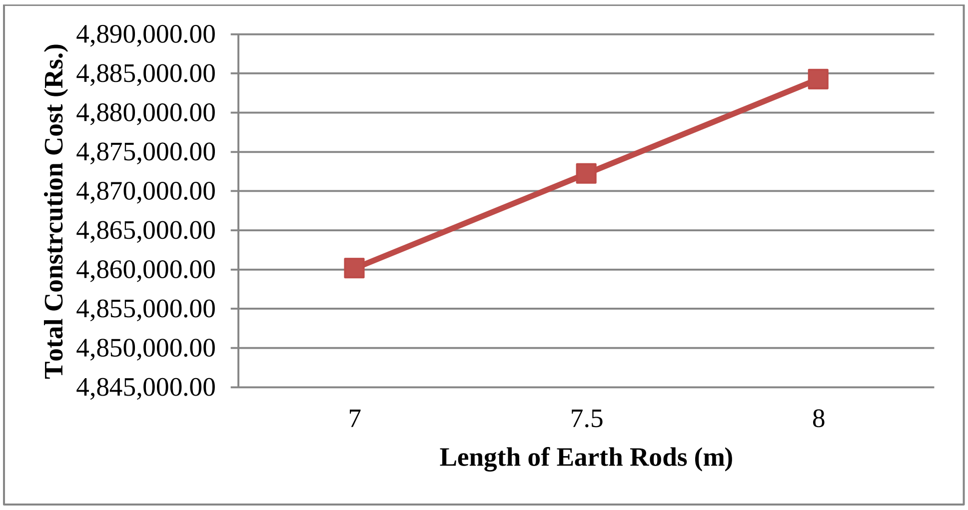


Figure 5.11: Total Construction Cost of Earthing System vs Length of Earth Rods

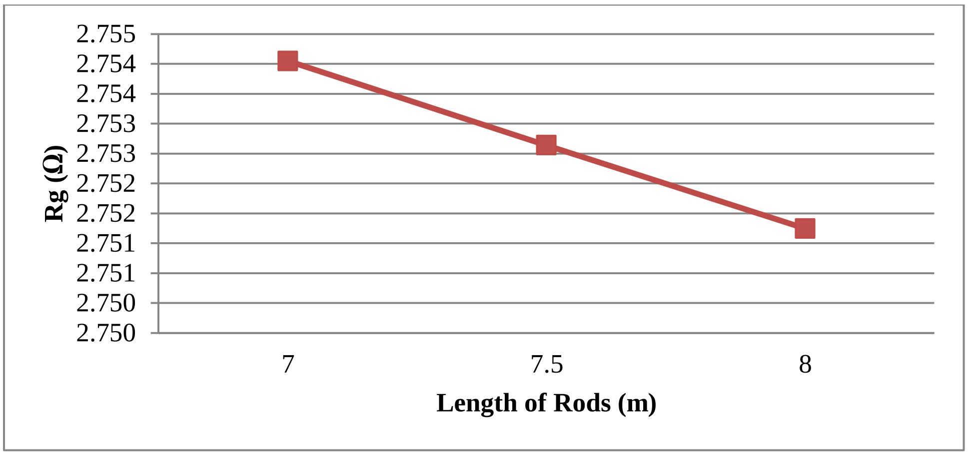


Figure 5.12: Earth Grid Resistance vs Length of Earth Rods

When the length of the earth rods increases,the GPR and maximum step and touch voltages of the earthing grid decreases slightly. Similar to the number of earth rods when the length of earth rods increases the earthing grid resistance incrases significantly.The increase in the length of the earth rods also causes higher cost in construction of the earthing grid.

5.5 Grid Burial Depth

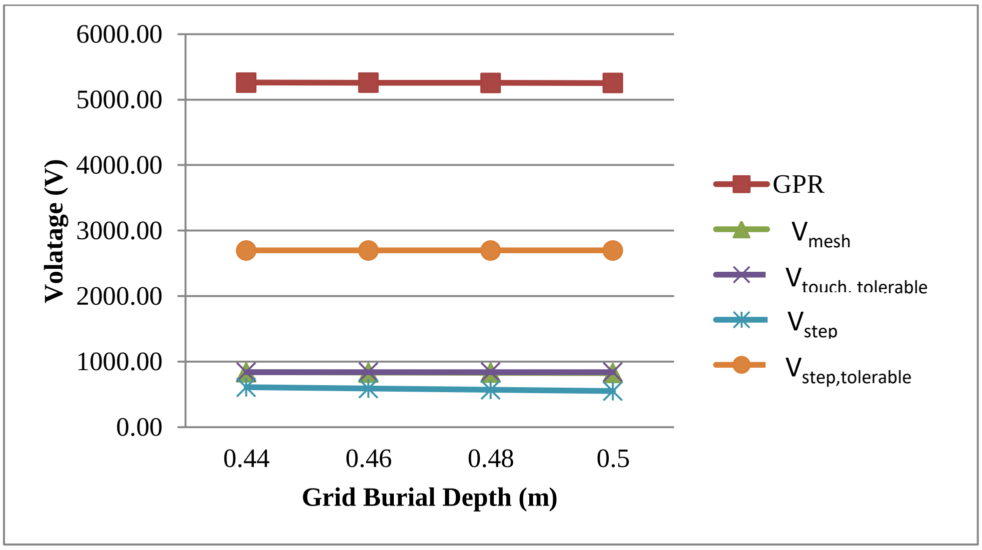


Figure 5.13: GPR,Step & Touch Voltages vs Grid Burial Depth

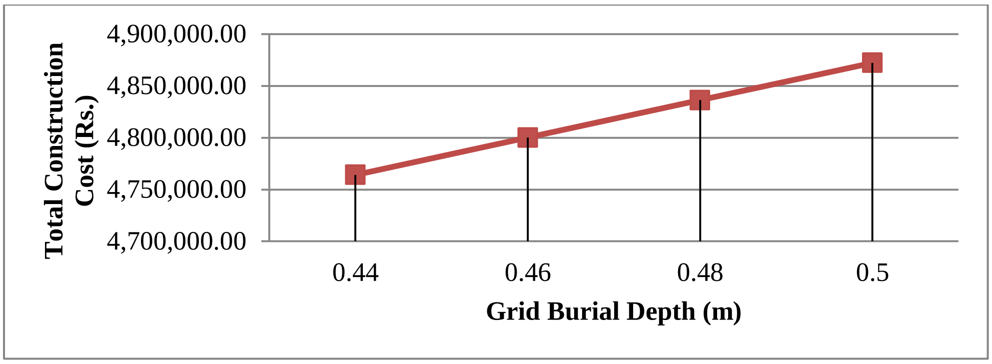


Figure 5.14: Total Construction Cost of Earthing System vs Grid Burial Depth

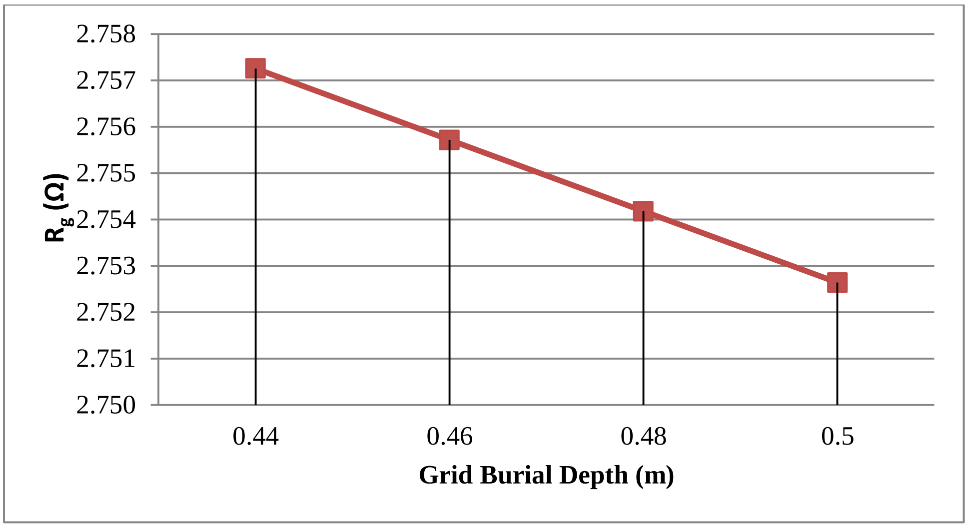


Figure 5.15: Earth Grid Resistance vs Grid Burial Depth

When increasing the grid burial depth, GPR, step and touch voltages and earthing grid resistance are reduced. Higher grid burial depth may result in higher installation cost for the earthing grid, resulting in an increase overall earthing grid construction cost.

5.6 Surface Layer Material

High resistance surface layer material such as granite, limestone, asphalt, concrete, blue metal, gravel, etc. may lead to an increase in tolerable step and touch voltage limits. However surface layer material may not cause or have an effect on earthing grid properties like GPR, step and touch voltages and earthing grid resistance.

5.7 Conductor Material

There are several conductive materials used in earthing grids. Those are solid Copper, Copper clad Steel, Aluminium, Aluminium clad Steel, Galvanized Steel and Stainless Steel, etc. These conductive materials have specific electrical and mechanical properties, which limit their use under different conditions. Solid Copper may provide the highest conductivity and resistance to corrosion, but is more ductile and expensive. Therefore, solid Copper conductors cannot be used in earthing grids with harsh soil conditions and sites with higher theft problems. Stainless steel also provides higher resistance to corrosion, making it more suitable for soil conditions with higher moisture contents. Stainless steel is also a strong material ideal for hard soils. However, Stainless Steel is also an expensive conductor material. Low cost solution can be provided by the use of Stainless Steel conductors. However, Stainless Steel may cause lower resistance to corrosion and lower electrical conductivity. In this way, considering the conditions of the site and the requirement for the earthing grid performance level, the selection of earthing grid conductor material may vary. Conductor material may also have a direct impact on the earthing grid construction cost.

5.8 Cross Sectional Area of the Horizontal Conductors

Higher cross sectional area of the conductors may cause higher material cost. However higher earth fault currents and higher fault durations may cause an increase in the conductor cross sectional area to increase the current carrying capacity of the conductors.

CHAPTER 6

6. THE OPTIMIZATION PROBLEM

This work was carried out in order to find cost-optimized design for the electrical earthing system of AC substations. The cost will be optimized by varying the Earth grid design parameters while satisfying the safety criteria for Step and Touch voltages and Earth grid resistance.

6.1 Objective Function

The cost function (6.1) will be the objective function of the optimization problem that combines the cost of supply and installation of each grid component.

$$\begin{aligned}
\mathit{Total\ Earth\ Grid\ cost}\ = \Big\{ & C_{\mathit{Con}} \\
& \times \left[\left(\frac{\mathit{Grid\ length}}{\mathit{Conductor\ spacing}} + 1\right) \times \mathit{Breadth} \right. \\
& \left. + \left(\frac{\mathit{Grid\ Breadth}}{\mathit{Conductor\ Spacing}} + 1\right) \times \mathit{length}\right]\Big\} \\
& + \{C_{\mathit{Rod}} \times \mathit{No.of\ rods} \times \mathit{Length\ of\ a\ rod}\} \\
& + \Big\{C_{\mathit{Con.\ Inst.}} \times \left[\left(\frac{\mathit{Grid\ length}}{\mathit{Conductor\ spacing}} + 1\right) \times \mathit{Breadth} \right. \\
& \left. + \left(\frac{\mathit{Grid\ Breadth}}{\mathit{Conductor\ Spacing}} + 1\right) \times \mathit{length}\right] \times 1 \times \mathit{Grid\ depth}\Big\} \\
& + \{C_{\mathit{Rod\ Inst}} \times \mathit{No.of\ rods} \times \mathit{Length\ of\ a\ rod}\} \\
& + \Big\{C_{\mathit{Exo.}} \times \left(\frac{\mathit{Grid\ length}}{\mathit{Conductor\ spacing}} + 1\right) \\
& \times \left(\frac{\mathit{Grid\ breadth}}{\mathit{Conductor\ spacing}} + 1\right)\Big\} + \{C_{\mathit{Exo}}\ \mathrm{X}\ \mathit{No.\ of\ rods}\} \\
& + \{(C_{\mathit{surf}} + C_{\mathit{surf,\ install}}) \times \mathit{Surface\ Layer\ Thickness} \\
& \times \mathit{Grid\ Length} \times \mathit{Grid\ Breadth}\}
\end{aligned} \tag{6.1}$$

Where;

$C_{con.}$ - Cost of horizontal earth mesh conductors

C_{Rod} - Cost of vertical earth rods

$C_{con,excav}$ - Cost of labour for trenching, installing and backfilling for horizontal earth mesh

$C_{rod, inst}$ - Cost of labour to install vertical earth rods

$C_{exother}$ - Cost of exothermic weld connection

$C_{surf, inst}$ - Cost of labour to setup the surface layer

$C_{surf,s}$ - Cost of surface layer material

The first term of this cost function is the material cost for the horizontal grid mesh. Second term refers to the material cost of vertical earth rods.Third term gives the installation cost of horizontal earth grid mesh. The fourth term generates installation cost for vertical erath rods. The fifth and sixthe terms introduce the cost of exothermic welding joints in the horizontal mesh of the earth grid and between the earth mesh and vertical rods of the earth grid respectively. Last term represents the cost for the supply and installation of the surface layer material.

Table 6.1:Values for Cost Components of the Objective Cost Function

Component	Cost associated with the parameter	
$C_{con.}$	Cost per conductor size (mm^2)	(Rs./m)
	Copper Tape (25mm× 3mm)	1,450.00
	Copper clad steel tape	
	25mm × 3mm	900.00
	25mm × 4mm	950.00
	Aluminium Tape (25mm× 3mm)	1,800.00
	GI Strips (25mm× 3mm)	
	20mm× 3mm	65.00
	50mm× 6mm	170.00
	Stainless steel tape	
	30mm× 4mm	1,400.00

Coefficient	Cost associated with the parameter	
C_{Rod}	Cost per rod size (dia - mm)	(Rs /m)
	Copper clad steel rod	
	12.7 mm dia	1,100.00
	14.2mm dia	1,775.00
	17.2 mm dia	3,600.00
	Galvanized Steel rod	500.00
	Stainless Steel	905.00
	Solid Copper rod	1,693.00
$C_{con,excav}$	Cost per cubic meter volume	(Rs/ m^3)
	Manual Excavation	1,170.00
	Excavation using Backhoe	945.00
$C_{rod, inst}$	Cost per rod installation	(Rs/m)
		105.00
$C_{exother}$	Cost for exothermic welding per connection	(Rs./Connection)
		7,678.00
$C_{surf, inst}$	Installation cost of gravel	(Rs/m$^{3)}$
		145.00
$C_{surf,supply}$	Material Cost of surface Material	(Rs/m^3)
	Sand	6,360.00
	Msand	2,300.00
	Gravel	2,500.00

6.2 Safety Assessment and constraints

This objective function is minimized subjected to three safety restrictions as defined in the IEEE 80 guidelines. Those are;

$$V_{Mesh} - V_{Touch,tolerable} > 0$$

$$V_{Step} - V_{Step,tolerable} > 0$$

$$R_{Grid} - R_{Grid,allowable} > 0$$

6.3 Optimization Methodology

The optimization problem can be described as assigning values for five design variables: conductor spacing, number of earth rods, length of earth rods, grid burial depth and surface layer thickness by minimizing total construction cost and achieving the required earth grid performance level. The objective function determines how fit the assigned value is. In this case, the objective function for minimization is developed as a cost function by combining design variables which affect total construction cost. To keep the performance level of the earth grid within the required limits, three safety constraints are defined for step and touch voltages limitations and maximum grid resistance. These safety limitations depend on grid design parameters.

It was found after an in-depth literature survey and few sample calculations, Genetic Algorithm provides an optimal global solution to this type of problem.

6.3.1 Basic Steps of Genetic Algorithm

John Holland developed the Genetic Algorithm (GA) in 1975. There are three operators involved in the technical process of the GA:

1) Selection and reproduction,
2) Cross over and
3) Mutation

Compared to traditional optimization algorithms, the reason for choosing the genetic algorithm for ground grid optimization is the ability to deal with complex optimization problems. In the optimization of the earth grid , the objective function involves the integer design parameters, whose number will change with each iterations, include nonlinear constraints on the step and touch voltage and grid resistance.

An initial population of randomly generated particles is generated. Then from each particle, the fitness values of the mesh size, number of rods, length of rods, grid burial depth and surface layer thickness will be determined. If the cost function value is better (lower) than its personal best, the current values of design variables will be saved. [28]

6.3.2 Algorithm selection

The optimization process can be extremely time-consuming when done manually, requiring a lot of analysis at the same time without ensuring acceptable results. The use of an Evolutionary Computation (EC) technique to optimize a grid design algorithm enables optimal fitness to be achieved (i.e. the best choice of parameter values) through an computerized process [29] accomplished by the evolutionary strategy technique. Evolutionary Stratergy is continuous reproduction,trial and selection. Each newly generated resul set is improvement of previous one. [10] The soil is assumed to be homogeneous.

6.4 Flow Chart

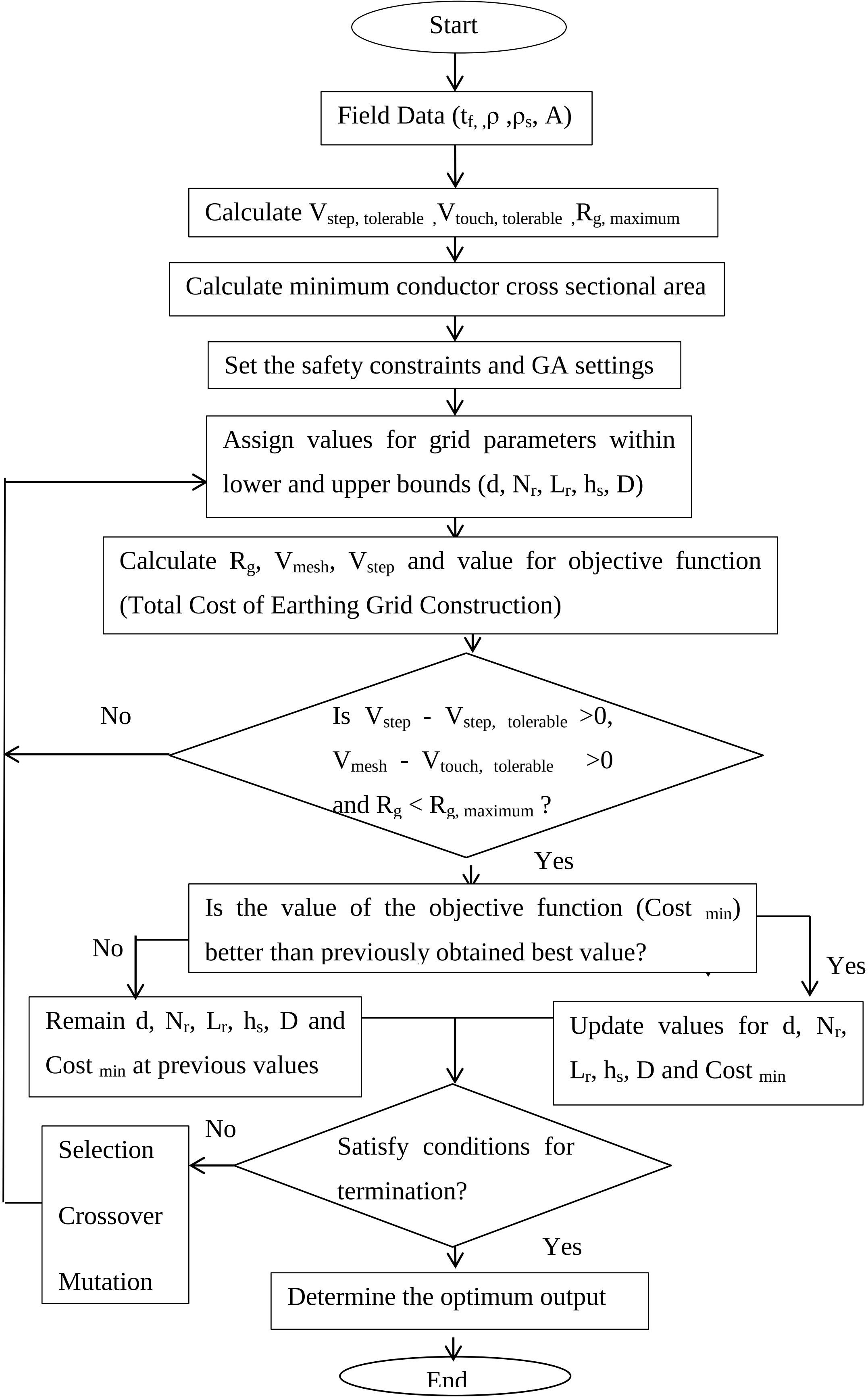
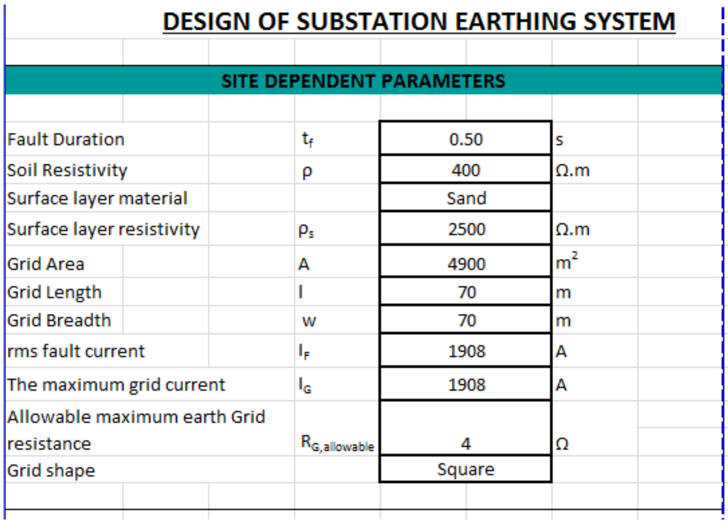


Figure 6.1: Earth Grid Optimization Flow Chart based on GA

6.5 Implementation

As can be seen in Figure 6.2, 6.3 and 6.4, an Excel file, containing the calculation model, can be selected and cell references for the cost function value, all design variables and all constraints can be specified. The GA parameters can be modified as required by the GA optimization add-in. Then the GA algorithm can run and output values can be extracted for design variables (d, N_r, L_r, D and h_s) from the Excel file.

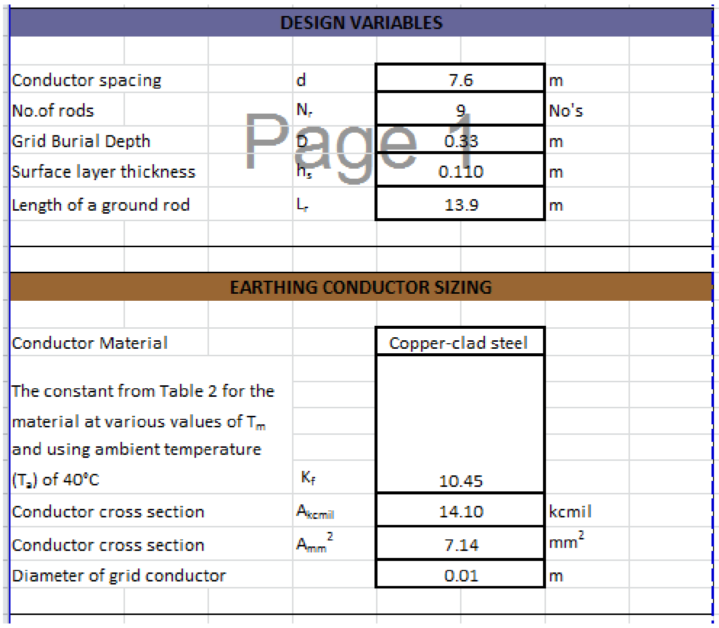


DESIGN OF SUBSTATION EARTHING SYSTEM

SITE DEPENDENT PARAMETERS

Fault Duration	t_f	0.50	s
Soil Resistivity	ρ	400	Ω.m
Surface layer material		Sand	
Surface layer resistivity	ρ_s	2500	Ω.m
Grid Area	A	4900	m^2
Grid Length	l	70	m
Grid Breadth	w	70	m
rms fault current	I_F	1908	A
The maximum grid current	I_G	1908	A
Allowable maximum earth Grid resistance	$R_{G,allowable}$	4	Ω
Grid shape		Square	

Figure 6.2:Screenshot of Earth Grid Design Calculation to based on GA



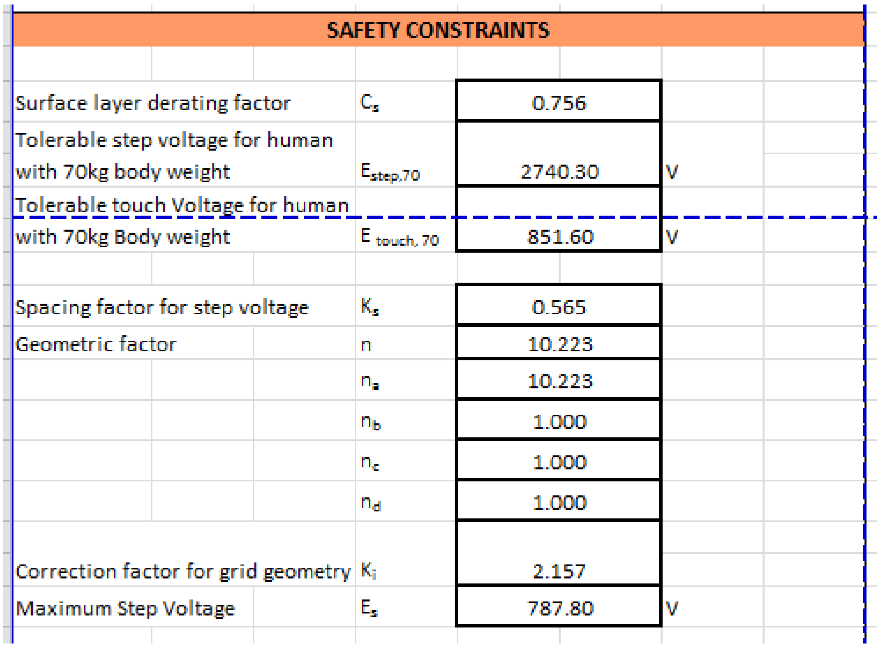
DESIGN VARIABLES

Conductor spacing	d	7.6	m
No.of rods	N_r	9	No's
Grid Burial Depth	D	0.33	m
Surface layer thickness	h_s	0.110	m
Length of a ground rod	L_r	13.9	m

EARTHING CONDUCTOR SIZING

Conductor Material		Copper-clad steel	
The constant from Table 2 for the material at various values of T_m and using ambient temperature (T_a) of 40°C	K_f	10.45	
Conductor cross section	A_{kcmil}	14.10	kcmil
Conductor cross section	$A_{mm}{}^2$	7.14	mm^2
Diameter of grid conductor		0.01	m

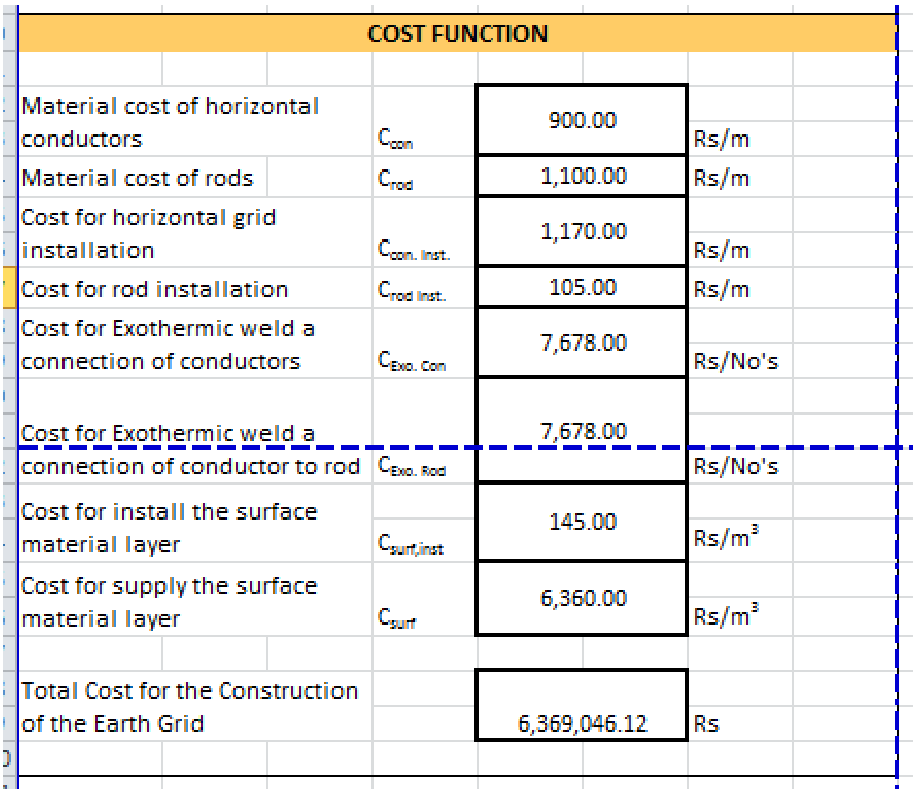
Figure 6.3: Screenshot of Earth Grid Design Calculation to based on GA



SAFETY CONSTRAINTS

Surface layer derating factor	C_s	0.756	
Tolerable step voltage for human with 70kg body weight	$E_{step,70}$	2740.30	V
Tolerable touch Voltage for human with 70kg Body weight	$E_{touch,\ 70}$	851.60	V
Spacing factor for step voltage	K_s	0.565	
Geometric factor	n	10.223	
	n_a	10.223	
	n_b	1.000	
	n_c	1.000	
	n_d	1.000	
Correction factor for grid geometry	K_i	2.157	
Maximum Step Voltage	E_s	787.80	V

Figure 6.4: Screenshot of Earth Grid Design Calculation to based on GA

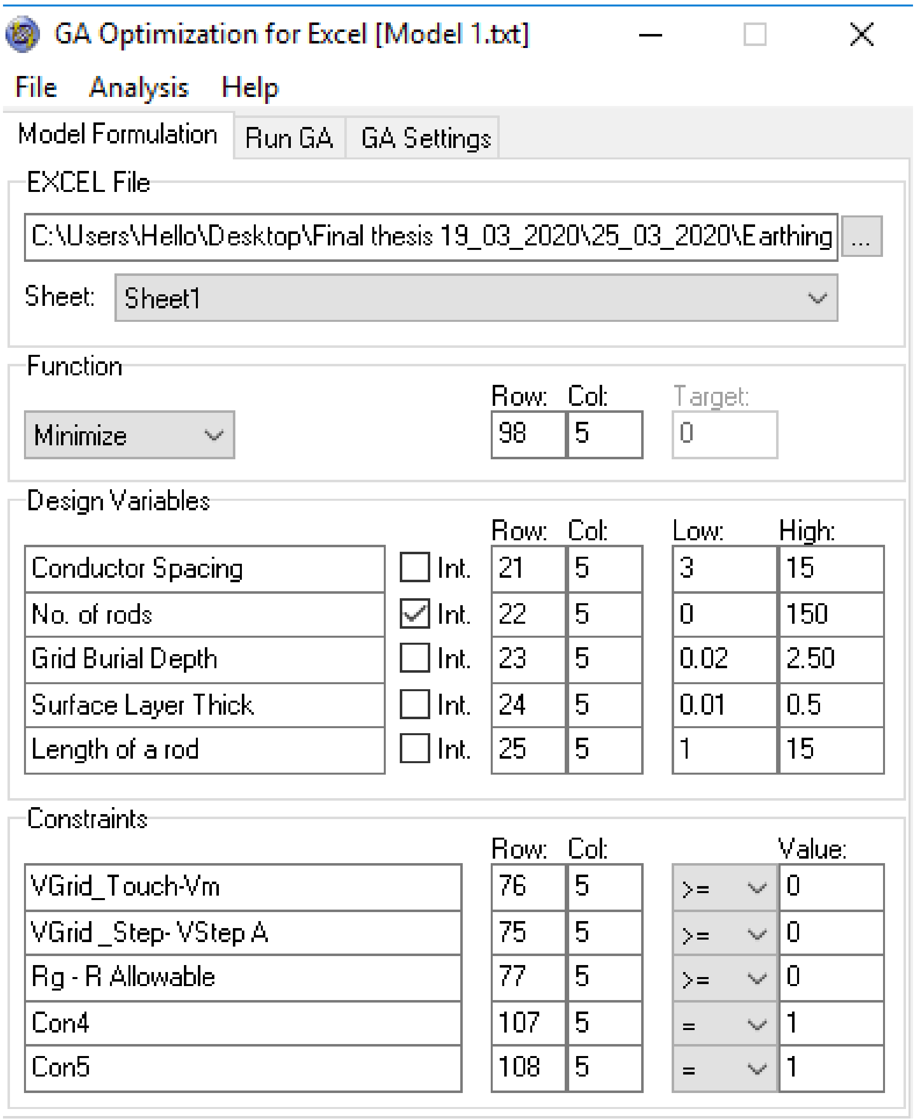


COST FUNCTION

Material cost of horizontal conductors	C_{con}	900.00	Rs/m
Material cost of rods	C_{rod}	1,100.00	Rs/m
Cost for horizontal grid installation	$C_{con.\ Inst.}$	1,170.00	Rs/m
Cost for rod installation	$C_{rod\ Inst.}$	105.00	Rs/m
Cost for Exothermic weld a connection of conductors	$C_{Exo.\ Con}$	7,678.00	Rs/No's
Cost for Exothermic weld a connection of conductor to rod	$C_{Exo.\ Rod}$	7,678.00	Rs/No's
Cost for install the surface material layer	$C_{surf,inst}$	145.00	Rs/m^3
Cost for supply the surface material layer	C_{surf}	6,360.00	Rs/m^3
Total Cost for the Construction of the Earth Grid		6,369,046.12	Rs

Figure 6.5: Screenshot of Earth Grid Design Calculation to based on GA

In order to specify the objective function, the design variables with lower and upper bounds and the safety constraints for the cost optimization of the earth grid in the GA optimization add-in, the relevant cells were referred from the developed excel sheet.



EXCEL File

C:\Users\Hello\Desktop\Final thesis 19_03_2020\25_03_2020\Earthing

Sheet: Sheet1

Function

Minimize

Row:	Col:	Target:
98	5	0

Design Variables

		Row:	Col:	Low:	High:
Conductor Spacing	☐ Int.	21	5	3	15
No. of rods	☑ Int.	22	5	0	150
Grid Burial Depth	☐ Int.	23	5	0.02	2.50
Surface Layer Thick	☐ Int.	24	5	0.01	0.5
Length of a rod	☐ Int.	25	5	1	15

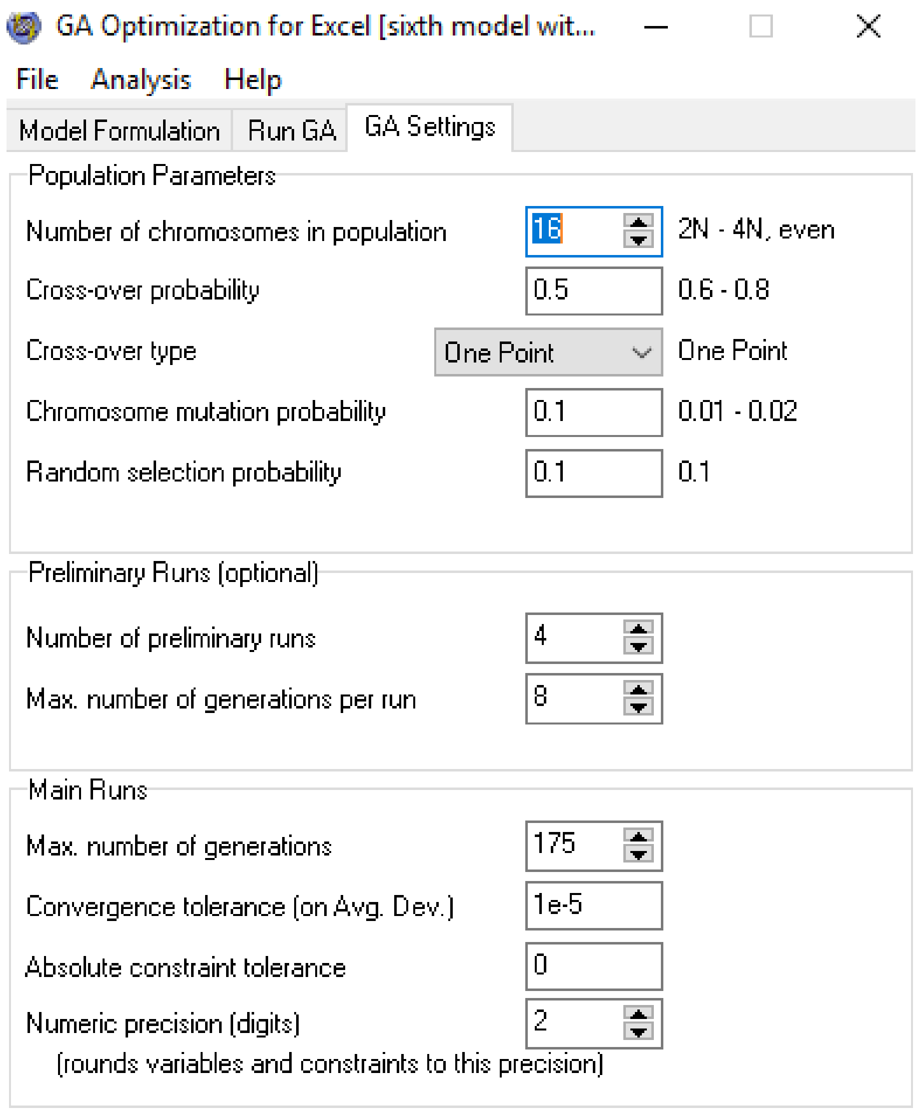
Constraints

	Row:	Col:		Value:
VGrid_Touch-Vm	76	5	>=	0
VGrid _Step- VStep A	75	5	>=	0
Rg - R Allowable	77	5	>=	0
Con4	107	5	=	1
Con5	108	5	=	1

Figure 6.6: Screenshot of Model Formulation Interface in GA Optimization Add-in

Source : GA Optimization for EXCEL © 2005, Alexander C. Schreyer

The GA parameters were specified after several earth grid optimization test and the specified values were selected when the minimum value for the objective function was obtained. It was assumed that the specified GA parameters will provide the most optimized solution for all site conditions.



Population Parameters

Number of chromosomes in population: 16 — 2N - 4N, even

Cross-over probability: 0.5 — 0.6 - 0.8

Cross-over type: One Point — One Point

Chromosome mutation probability: 0.1 — 0.01 - 0.02

Random selection probability: 0.1 — 0.1

Preliminary Runs (optional)

Number of preliminary runs: 4

Max. number of generations per run: 8

Main Runs

Max. number of generations: 175

Convergence tolerance (on Avg. Dev.): 1e-5

Absolute constraint tolerance: 0

Numeric precision (digits): 2

(rounds variables and constraints to this precision)

Figure 6.7: Screenshot of GA Setting Interface in GA Optimization Add-in

Source : GA Optimization for EXCEL © 2005, Alexander C. Schreyer

CHAPTER 7

7. RESULT AND DISCUSSION

Currently IEEE 80 2000 provides the basic guidelines for Earthing design for AC substations. However, current practice is not cost-effective. The cost of the earth grid design depends on designer's experience and presumptions. Designing a substation Earthing system while reducing costs and meeting all safety criteria is a very complicated and time-consuming process.

This was observed by considering a few case studies with the common design procedure without cost optimization and evaluating the same cases with the newly introduced cost optimization method in this paper.

7.1 Comparison of Results

Table 7.1 Grid Design Parameters

Properties	Unit	Case 1	Case 2
Soil Resistivity	**Ωm**	400	100
Surface Layer resistivity	**Ωm**	2500	5000
Fault duration	**s**	0.5	0.5
Maximum Grid Current	**kA**	1.908	24
Grid Size	**m^2**	70*70	134*92

7.2 Simulation Results for Case 1

According to the Table 7.2 the conductor spacing is increased from 7m to 10m in the optimized design, which results in a larger mesh size, thus reducing the overall conductor length for the horizontal grid mesh. The number of meshes in the grid is also reduced and, as a result, the number of exothermic welding points is also reduced, resulting in a reduction in the cost of constructing the horizontal earth grid mesh. However, the grid burial depth, the number of vertical rods and the length of a rod are increased in the optimized design to meet the safety requirements .

However the cost saving of Rs. 410,553.00 (9.2%) is achieved in this case by using the cost optimization methodology introduced in this research paper. Also,when optimizing the design, the total effective buried conductor length (Total conductor length of horizontal grid mesh + Total conductor length of vertical earth rods) is reduced from 1690 m to 1400 m.

In this case, since the surface layer thickness is reduced from 0.102 m to 0.1m, the tolerable step voltage for persons with body weight 70kg is reduced from 2696.1 V to 2684.28 V. Tolerable touch voltage for a person weighting 70kg is reduced from 840.5V to 837.6V.

Table 7.2 Comparison between Original Design and Optimized Design Parameters

	Case 1	
Properties	**Original Design**	**Optimized Design**
Conductor spacing, d	7m	10m
No. of rods , Nr	20	28
Grid Burial Depth, D	0.5m	0.85m
Surface layer thickness, h_s	0.102m	0.1m
Length of a ground rod, L_r	7.5m	10m
Cost	Rs. 4,872,219.00	Rs. 4,461,666.00
GPR	5401.4V	5345.6V
Step voltage , E_s	549V	320V
Mesh Voltage , E_m	764.8 V	784.74V
Earthing grid resistance, R_g	2.83Ω	2.80Ω

7.3 Simulation Results for Case 2

In the second case considered, the distance between horizontal conductors is reduced in the optimal design resulting in smaller mesh sizes. However, the number of vertical rods is considerably reduced. Although the overall effective buried conductor length is higher in this optimized design than in the unoptimized design, the cost saving is mainly achieved by reducing the thickness of the surface layer (Msand layer with a resistivity of 5000 Ωm). The optimized cost saving in this case is Rs. 5,371,212.24 (35.26%).

In this case, since the surface layer thickness is reduced from 0.5 m to 0.02m, the tolerable step voltage for persons with body weight 70kg is reduced from 6343.99 V to 3427.12V. Tolerable touch voltage for a person weighting 70kg is reduced from 1752.52V to 1023.30V.

Table 7.3 Comparison between Original Design and Optimized Design Parameters

	Case 2	
Properties	**Original Design**	**Optimized Design**
Conductor spacing, d	10m	4m
No. of rods , Nr	20	7
Grid Burial Depth, D	0.5m	0.2m
Surface layer thickness, h_s	0.5m	0.04m
Length of a ground rod, L_r	5m	6m
Cost	Rs. 20,604,390.64	Rs. 15,233,178.40
GPR	10431.04V	1001.25V
Step voltage , E_s	1051.78V	2310.55V
Mesh Voltage , E_m	1744.33V	987.96V
Earthing grid resistance, R_g	0.43Ω	0.42Ω

Table 7.4: Cost Sensitivity Analysis of Cost Saving from the Proposed Cost Optimization Methodology

Cost Component		Best Estimated Price	Lowest Price	Highest Price	Cost for design without optimizing			Cost for design after cost optimizing			Cost Saving		
					Best Estimated Price	Lowest Price	Highest Price	Best Estimated Price	Lowest Price	Highest Price	Best Estimated Price	Lowest Price	Highest Price
Material Cost of conductors Rs. per meter	Copper tape	1,450.00	1,377.50	1,522.50	21,446,305.64	21,155,612.84	21,736,998.44	13,678,436.99	13,062,284.99	14,294,588.99	7,767,868.65 (36.22%)	8,093,327.85 (38.25%)	7,442,409.45
	Copper clad steel tape	900.00	792.00	1,008.00									
	Aluminium tape	1,800.00	1,710.00	1,890.00									
	Stainless steel tape	1,400.00	1,330.00	1,470.00									
	GI tape	65.00	61.75	68.25									
Material Cost of rods (Rs. per 1 meter length)	Copper bonded steel rod	3,550.00	3,195.00	3,905.00	21,446,305.64	21,432,105.64	21,460,505.64	13,678,436.99	13,673,466.99	13,683,406.99	7,767,868.65	7,758,638.65	7,777,098.65
	Galvanized steel rod	500.00	475.00	525.00									
	Stainless steel rod	905.00	859.75	950.25									
	Solid copper rod	1,693.00	1,608.35	1,777.65									
Labour rates	Labour rate for clearing grid area Rs. per sqr area	2,230.00	2,007.00	2,453.00	21,446,305.64	21,290,384.44	21,600,881.04	13,678,436.99	13,350,745.66	14,003,275.77	7,767,868.65	7,939,638.78	7,597,605.27
	Manual excavation Rs. per cube	1,170.00	1,053.00	1,287.00									
	Bulk excavation using backhoe Rs. per hour	945.00	831.60	1,058.40									

Cost Component		Best Estimated Price	Lowest Price	Highest Price	Cost for design without optimizing			Cost for design after cost optimizing			Cost Saving		
					Best Estimated Price	Lowest Price	Highest Price	Best Estimated Price	Lowest Price	Highest Price	Best Estimated Price	Lowest Price	Highest Price
	Skilled Labour per 8 hour day per person	3,000.00	2,700.00	3,300.00									
	Unskilled Labour per 8 hour day per person	2,000.00	1,800.00	2,200.00									
Cost for exothermic weld a point		7,678.00	6,756.64	8,599.36	21,446,305.64	21,292,549.08	21,600,062.20	13,678,436.99	13,063,878.50	14,292,995.48	7,767,868.65	8,228,670.59	7,307,066.71
Surface Layer	Installation Rate per Cubic meter	145.00	130.50	159.50	21,446,305.64	21,356,927.64	21,535,683.64	13,678,436.99	13,674,861.87	13,682,012.11	7,767,868.65	7,682,065.77	7,853,671.53
	Supply Rate per Cubic meter	2,500.00	2,375.00	2,625.00	21,446,305.64	20,675,805.64	22,216,805.64	13,678,436.99	13,647,616.99	13,709,256.99	7,767,868.65	7,028,188.65	8,507,548.65
Material Cost of conductors Rs. per meter	Copper tape	1,450.00	1,377.50	1,522.50	21,446,305.64	21,155,612.84	21,736,998.44	13,678,436.99	13,062,284.99	14,294,588.99	7,767,868.65	8,093,327.85	7,442,409.45
	Copper clad steel tape	900.00	792.00	1,008.00									
	Aluminium tape	1,800.00	1,710.00	1,890.00									
	Stainless steel tape	1,400.00	1,330.00	1,470.00									
	GI tape	65.00	61.75	68.25									
Material Cost of rods (Rs. per 1 meter length)	Copper bonded steel rod	3,550.00	3,195.00	3,905.00	21,446,305.64	21,432,105.64	21,460,505.64	13,678,436.99	13,673,466.99	13,683,406.99	7,767,868.65	7,758,638.65	7,777,098.65
	Galvanized steel rod	500.00	475.00	525.00									
	Stainless steel rod	905.00	859.75	950.25									

Cost Component		Best Estimated Price	Lowest Price	Highest Price	Cost for design without optimizing			Cost for design after cost optimizing			Cost Saving		
					Best Estimated Price	Lowest Price	Highest Price	Best Estimated Price	Lowest Price	Highest Price	Best Estimated Price	Lowest Price	Highest Price
	Solid copper rod	1,693.00	1,608.35	1,777.65									
Labour rates	Labour rate for clearing grid area Rs. per sqr area	2,230.00	2,007.00	2,453.00	21,446,305.64	21,290,384.44	21,600,881.04	13,678,436.99	13,350,745.66	14,003,275.77	7,767,868.65	7,939,638.78	7,597,605.27
	Manual excavation Rs. per cube	1,170.00	1,053.00	1,287.00									
	Bulk excavation using backhoe Rs. per hour	945.00	831.60	1,058.40									
	Skilled Labour per 8 hour day per person	3,000.00	2,700.00	3,300.00									
	Unskilled Labour per 8 hour day per person	2,000.00	1,800.00	2,200.00									
Cost for exothermic weld a point		7,678.00	6,756.64	8,599.36	21,446,305.64	21,292,549.08	21,600,062.20	13,678,436.99	13,063,878.50	14,292,995.48	7,767,868.65	8,228,670.59	7,307,066.71
Surface Layer	Installation Rate per Cubic meter	145.00	130.50	159.50	21,446,305.64	21,356,927.64	21,535,683.64	13,678,436.99	13,674,861.87	13,682,012.11	7,767,868.65	7,682,065.77	7,853,671.53
	Supply Rate per Cubic meter	2,500.00	2,375.00	2,625.00	21,446,305.64	20,675,805.64	22,216,805.64	13,678,436.99	13,647,616.99	13,709,256.99	7,767,868.65	7,028,188.65	8,507,548.65

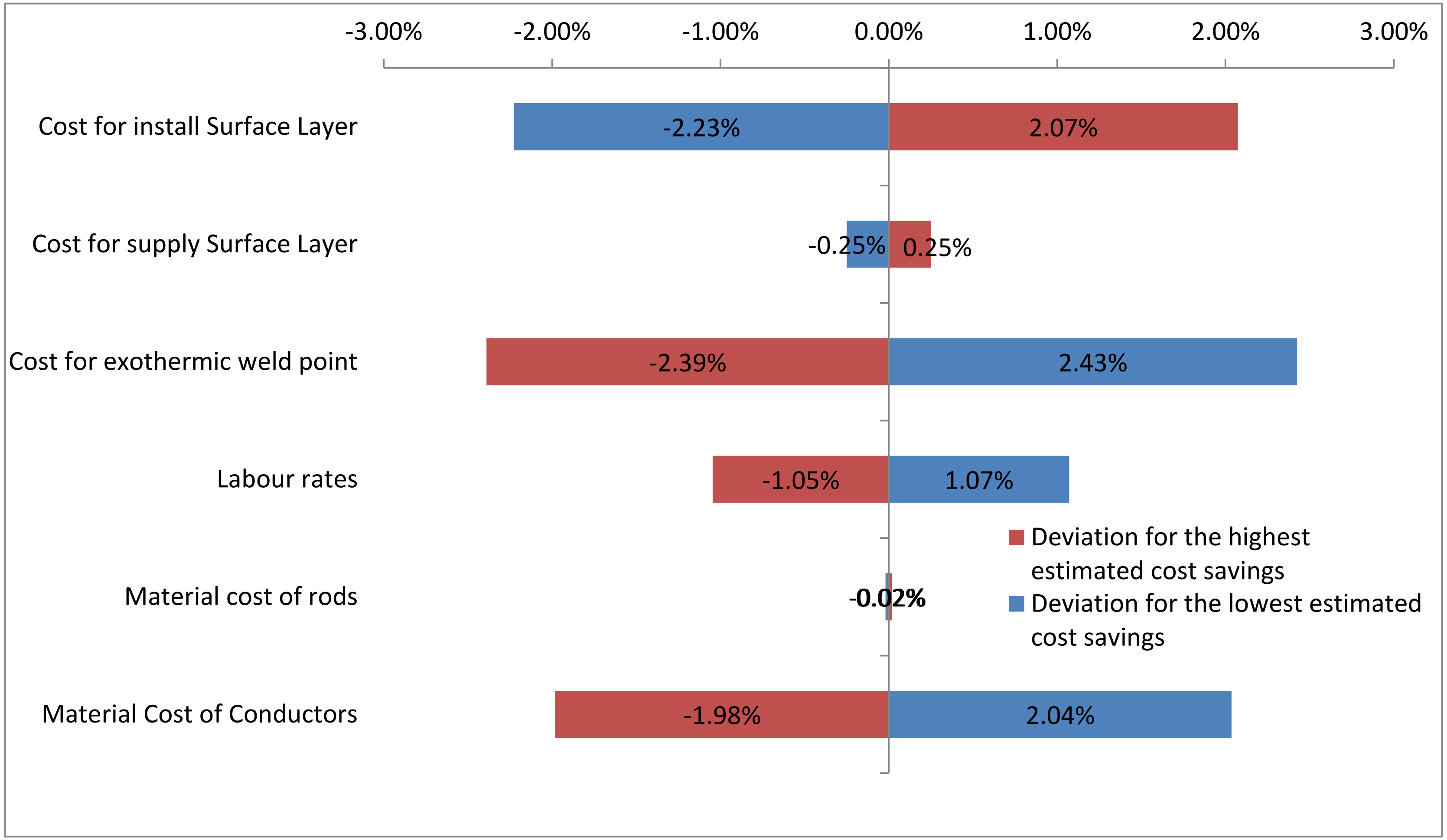


Figure 7.1: Cost Sensitivity Analysis of Cost Saving from the Proposed Cost Optimization Methodology

7.4 Simulation Results for More Cases

In order to generalize and verify the simulation results and achieveable cost saving from the proposed optimization methodology, design calculations and optimization have been performed for few other cases and results obtained can be seen inthe following graphs.

Table 7.5 Grid Design Parameters

Properties	**Unit**	**Case 3**	**Case 4**	**Case 5**	**Case 6**	**Case 7**	**Case 8**	**Case 9**	**Case 10**
Soil Resistivity	**Ωm**	60	150	350	400	250	120	150	200
Surface Layer resistivity	**Ωm**	5000	5000	5000	5000	5000	5000	5000	5000
Fault duration	**s**	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Maximum Grid Current	**kA**	28	23	8.5	8.5	11	16	12	8.5
Grid Size	**m^2**	24*48	60*80	60*60	40*56	40*80	40*40	32*48	45*60

Earthing grid design was carried out in accordance with the IEEE 80 standard general procedure and newly proposed cost optimization methodology, for all of the above different sample cases. The results obtained were included in the table below . In each case, the values for the earth grid design parameters obtained in accordance with the IEEE common practice and the proposed cost optimization methodology were given respectively. (For each case, the values obtained for the IEEE general design procedure are mentioned in the first row and in the second row, the values obtained for those parameters with proposed cost optimization methodology were mentioned.)

Table 7.6 Comparison between Original Design and Optimized Design Parameters

Case	d (No's)	Nr (No's)	D (m)	h_s (m)	L_r (m)	Cost (Rs.)	GPR (V)	E_s (V)	E_m (V)	R_g (Ω)
3	3	20	1.5	1	12	6,706,334.00	21864.99	1380.78	1762.02	0.78
	12	40	1	0.2	12	4,531,450.00	22567.50	495.34	1677.89	0.81
4	4	50	1.5	1.2	12	24,640,608.00	22385.43	1163.74	1803.48	0.97
	3.2	35	1.2	0.43	12	17,155,523.00	22438.26	1542.42	1710.92	0.98
5	3	80	1.5	1	6	20,071,238.00	22051.08	1375.05	1749.48	2.59
	3	70	0.4	0.12	9	9,186,208.00	22797.80	2751.61	1442.12	2.68
6	4	80	1.5	1.2	12	12,838,550.00	31695.34	1213.72	1778.75	3.73
	4	80	0.5	0.5	12	7,582,070.00	32964.79	2335.53	1759.81	3.88
7	4	40	1.5	1	12	15,049,738.00	21838.25	1116.31	1791.81	1.99
	4	40	0.6	0.5	12	9,326,578.00	22498.38	1897.71	1731.89	2.05
8	4	30	1.5	1	12	7,841,578.00	15922.73	1099.70	1756.36	1.00
	5	38	0.88	0.3	12	4,026,074.00	16317.93	1220.09	1647.74	1.02
9	4	60	1.5	1	6	7,799,766.00	20528.75	1037.02	1711.63	1.71
	8	40	0.6	0.12	12	2,702,448.40	21466.03	1004.65	1428.65	1.79
10	3	4	1.5	1	6	14,298,715.00	14676.10	1110.17	1556.72	1.73
	5	24	1.3	0.15	12	5,388,562.00	15049.22	824.37	1493.62	1.77

Based on the results obtained, it can be seen that the cost savings that can be achieved by the proposed cost optimization of the earthing grid design methodology are approximately 50 per cent, respectively, for the common earthing grid design practice. However, this cost saving mostly depends on the experience of the designer and his ability to assign values for design parameters in cost effective manner. If the initial design is closer to the cost optimized design , the saving may decrease, while if the initial design is more deviating from the cost optimized design, the cost saving that can be achieved by cost optimization may be higher.

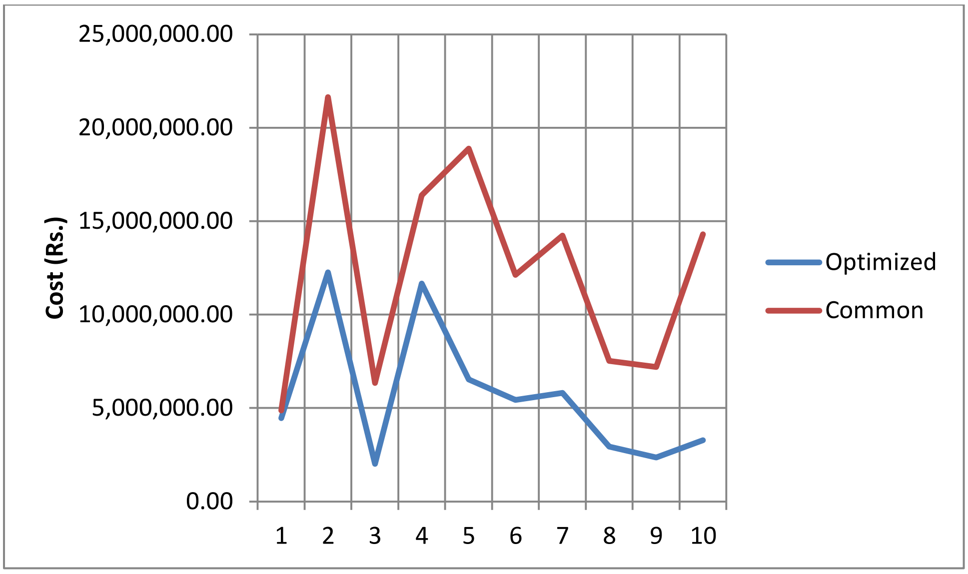


Figure 7.2 Total Construction Cost of Substation Earthing Grids For Considered Earth Grid Designs

When comparing the values obtained for the safety parameters (step voltage ,mesh voltage and earthing grid resistance) of the earthing grid design, most of the time, the values of safety parameters of cost optimized deisgns are always closer to the safety limits than those obatained for safety parameters in general practice. It is also notable that safety limits have also changed during this procedure, as the thickness of the surface layer has changed during cost optimization and it directly affects the safety criterian of step voltage and touch voltage of the earth grid.

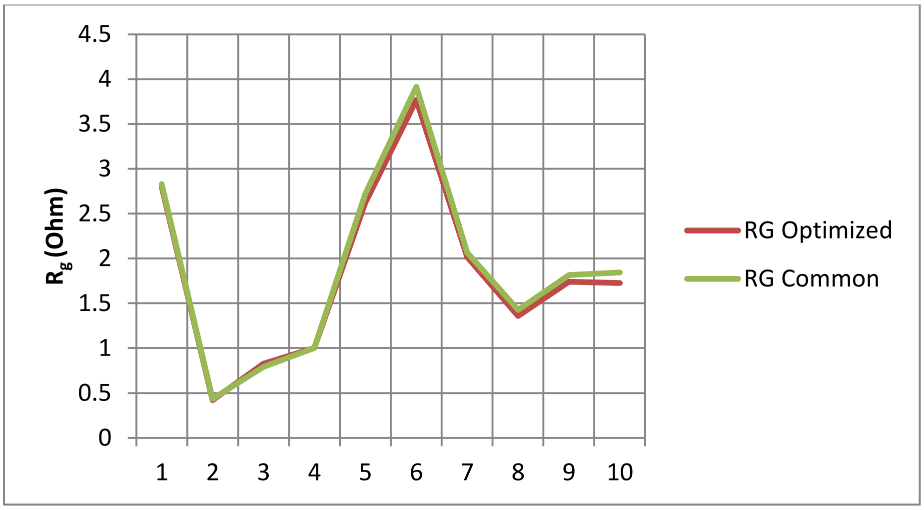


Figure 7.3 Earth Grid Resistance Values For Considered Earth Grid Designs

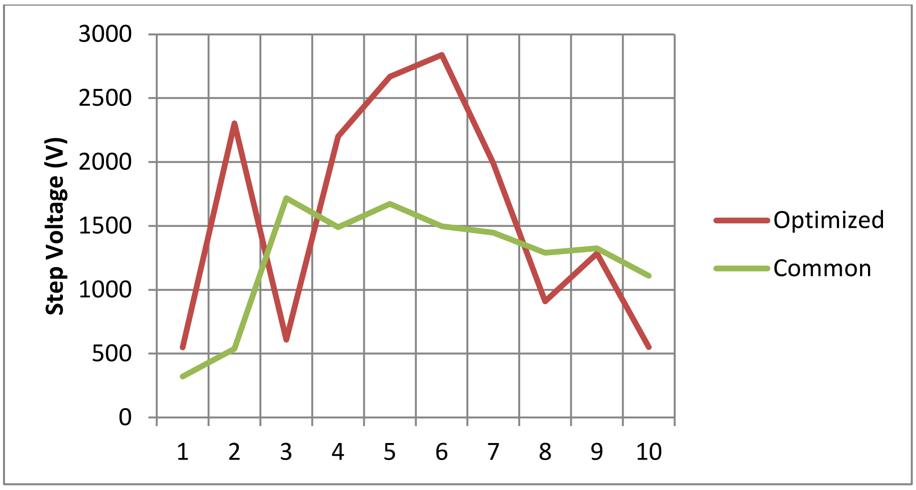


Figure 7.4 Step Voltage For Considered Earth Grid Designs

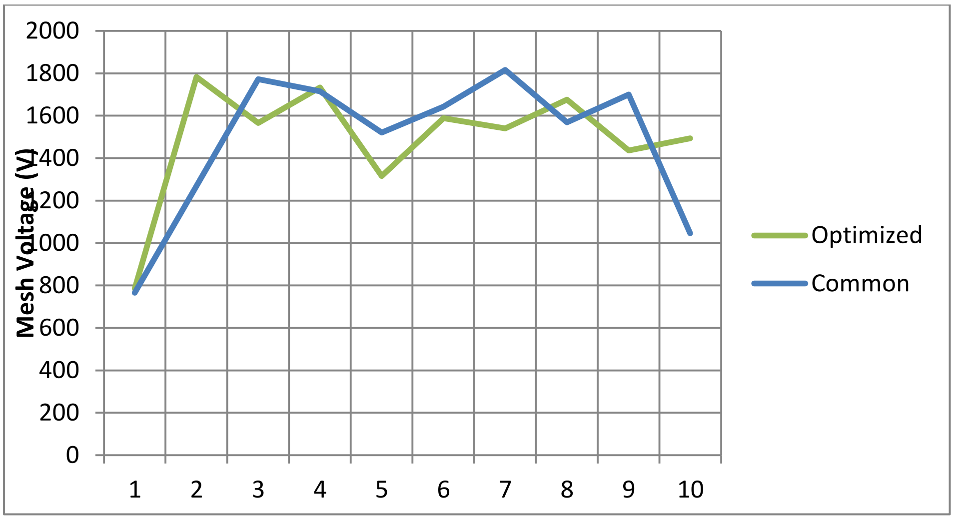


Figure 7.5 Mesh Voltages For Considered Earth Grid Designs

CHAPTER 8

8. CONCLUSION

This paper discusses the cost minimization problem, depending on a large number of parameters. The Genetic Algorithm was successfully used to create a safe and economical method of earthing design. The main objective is to reduce the overall cost of materials related to conductors, rods, surface layer, excavation and installation. In the introduced new cost function, includes length of conductors, number of rods, length of rods, number of exothermic welding connections and surface layer thickness.

The results show that the maximum grid resistance, step voltage and mesh voltage of the grid reach the safety limits in the optimized grid design without violating the criteria. The values for the earth grid design parameters (d, L_r, N_r, h_s, D) are also modified to achieve optimum earth grid design cost during the optimization process.

It can be seen from the above calculations that the cost optimization methodology implemented in this work can be used to minimize the cost of common earth grid design by approximately 25% .This cost saving is ensured by doing cost-sensitivity analysis for fluctuations in labour rates and material prices. The Cost Sensitivity Analysis indicates that labour and material price fluctuations of + or – 5% to 10% can only impact the average cost-saving deviation by 2.5%.

Although the sample calculations are made for square shaped earth grids, this methodology also applicable to any other shape that IEEE method applies. This is because the design calculations are independent from the optimization procedure.

Considering the reduction of only the total length of the earthing conductor (by taking decision variables for the optimization problem as the number of meshes along length and width of the grid , the length of the earthing rods and the number of earthing rods), the cost saving of 29% has been achieved compared to the common un-optimized grounding grid.[28].Therefore, it is also evident that the increase in the number of decision variables considered for optimization has improved the cost saving in this work. Therefore, this developed methodology greatly improves the process of earthing grid design in terms of time saving, reliability and preciseness.

However, this work only took into account equal mesh sizes and uniform soil conditions. By using variable mesh sizes, taking into account the distribution of voltage within the earth grid, the design can be further optimized in terms of cost. The unequally spaced grid saves about 34% of grounding grid material. The installation of the grid also costs less.[30]

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