MODELING OF TRANSMISSION TOWER GROUNDING SYSTEM

Patabendi Mudiyanselage Anusha Udayangani Karunapala

(109223H)

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Department of Electrical Engineering

University of Moratuwa

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DECLARATION OF THE CANDIDATE AND SUPERVISORS

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November, 2015

The above candidate has carried out research for the Masters dissertation under my supervision.

Dr. Asanka Rodrigo

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ABSTRACT

Performance of power transmission lines has a great impact on reliability aspects of a particular power supply system of a country. Unreliable power transmission lines can even leads to total power failures resulting with great financial losses. In order to improve the withstand level of transmission lines, to reduce line lightning trip-out rate and the accident rate grounding resistance in grounding grid of transmission line tower should be effectively ameliorated.

This thesis is a study of a 132 kV transmission line tower grounding system. Several standards are developed for designing a grounding system for AC substations and building installation but it is harder to find references for transmission line tower grounding specially when the soil condition is poor. The transmission line is routed over a high resistive soil, where the requirements from the design standard can not be fulfilled.

During normal conditions, each tower can be properly grounded to earth with ground electrodes, but for high soil resistivity conditions there should be a properly designed earthing arrangement for transmission towers. By studying different practical earthing method being using all over the world for high voltage transmission towers, a suitable solution can be found. A Practical earthing design for different soil types was proposed for the modeling and simulation to find a suitable eathing design for Ceylon Electricity Board transmission lines specification.

This thesis will discuss the Finite Element Method (FEM) developed for grounding analysis. Computer software analysis packages can be used to assist in earthing design by modeling and simulation of different earthing configurations. FEM method of ETAP's Ground Grid Design Assessment software is used for modeling the new tower earthing design for different soil types based on soil resistivity values.

For the each earthing design type theoretical verification of the earth resistance values was done using Thapar-Gerez equation which is developed for the calculation of earth resistance values.

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Chapter 1

Introduction

1.1 Background

Access to electric energy is fundamental in most part of the world today. Except for a reliable and effective production, it is also of great importance to have a reliable and safe distribution of the electric energy from the producer to the consumer. All involved components in an electrical system have to be safe for both humans and equipment. A safe grounding of an electrical system is for this reason essential.

The object of grounding electrical systems is primarily for safety reasons, and secondarily for reliability reasons. Improper grounding can cause electrical shocks and even lead to mortal electrocution, a reason why grounding is of great importance in all electrical facilities [1]. Also, extensive equipment damage and improper operation might occur if the grounding system is inferior. The aim of grounding different parts in a system is generally to lead the fault currents away in a safe and controlled way. The technologies used are different depending on what the grounding object is and what it is supposed to protect. Generating stations are grounded in a different way than single equipment or buildings. Commonly the connection to ground is done to minimize the voltage difference between conducting metal objects and ground. Ground connection is also a way to detect ground faults.

The earth is not uniform and the soil properties might differ between locations and even have several layers on the same spot with variable resistivity. The soil will not act like a sponge with the ability to absorb and dissipate electrons unconditionally [1] This is why a soil investigation is important for each location of a grounding area.

1.2 Problem Identification

1.2.1 Specification on Transmission Tower Earthing in Sri Lanka

Quoted from Technical Specification on Transmission Lines [2]

"Prices shall be entered against the appropriate item in Schedules for the supply and installation of counterpoise earth systems including compression lugs and normally comprising one 60m lengths of 7/4.00mm stranded galvanized conductor per set, and connected to individual leg members in an approved manner. The earth counterpoise shall be buried not less than 600mm in the ground. Normally two counterpoise sets will be installed per tower connecting to individual leg members in an approved manner and shall run an opposite direction each other underneath the lines where possible.

Stranded counterpoise shall be electro galvanized to a minimum mass of coating comply with BS EN 10244. As an alternative to stranded counterpoise throughout the line, rates shall also be entered for supplying and installing galvanized steel earthing rods 25mm diameter in convenient section lengths to a depth of say 9m including 7/4.00mm stranded galvanized conductor connection and inter connection to all legs of the tower, together with a variation rate for varying the length of rod. Where earthing rods are used, they will normally be employed at the rate of one per tower, installed at the center of each tower base area.

Wherever possible individual tower footing resistance shall be reduced to a value not exceeding 10Ω (ohms) or as agreed by the Engineer following resistance measurements".

Measured transmission tower footing resistance values of some of the 132kV transmission lines in Ceylon Electricity Board (CEB) network has been reviewed in next section.

Case 1- Biyagama – Kothmale 220kV transmission line

Figure 1.1 shows the variation of earthing resistances of selected two line sections having tower numbers 31-52 and 83-97 starting from Kotmale end.

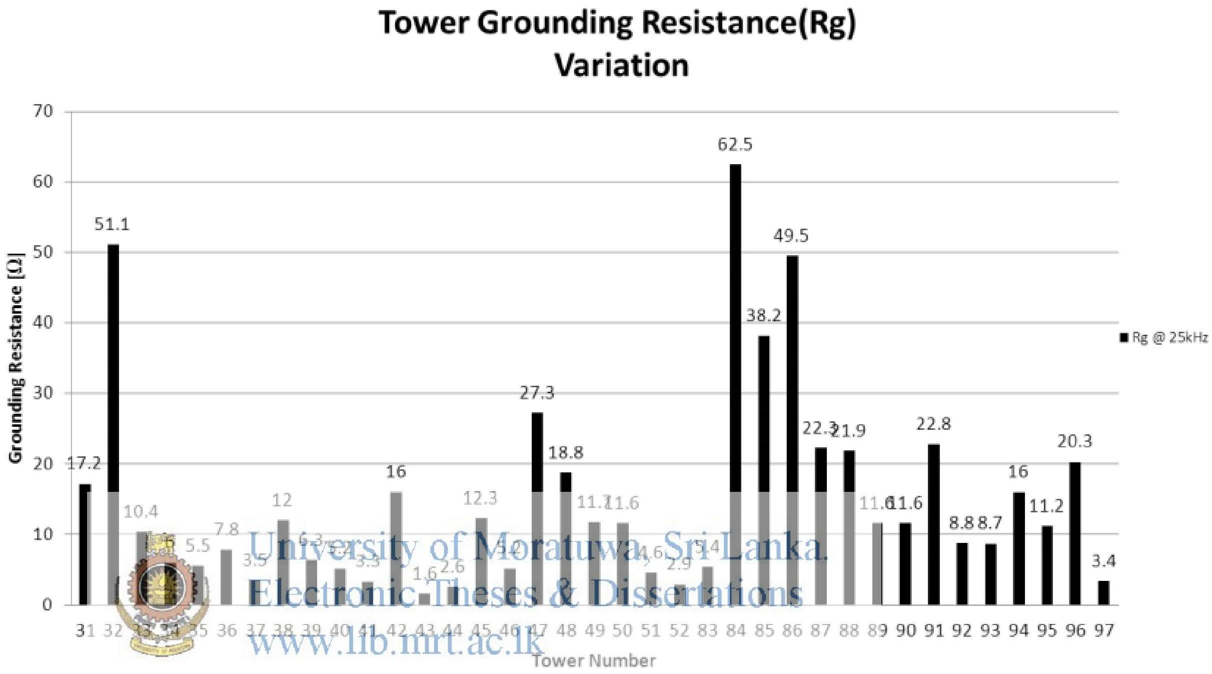


Figure 1.1 Grounding resistance variations of towers 31-52 and 83-97 starting from Kotmale end

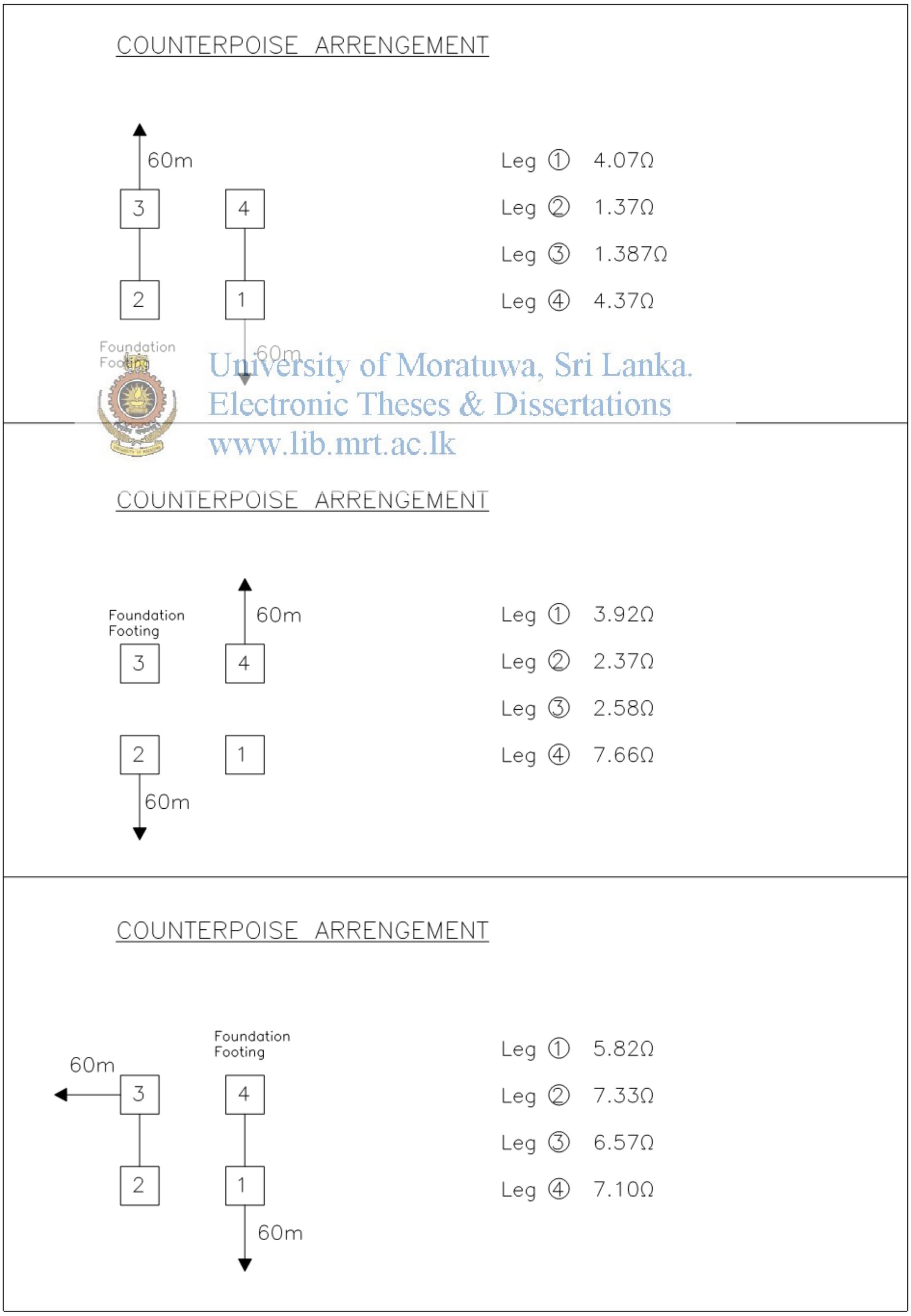
39% of towers are having earth resistance values more than 10 Ω and need to further improve grounding resistance.

Case 2- Randenigala – Mahiyanganaya 132kV transmission line

67 numbers of towers are in Randenigala – Mahiyanganaya 132kV transmission line. Ground resistance values are varying between 0.83 Ω – 141.47 Ω and 12% of towers are needed to have a proper earthing arrangement.

Case 3 – Ukuwela – Pallekele 132kV transmission line

Figure 1.2 shows the earthing arrangements proposed based on measured earth resistance values for some of the tower locations. These arrangements have been proposed according to the available specification on tower earthing. Here we can see that the earthing arrangements have been proposed on trial and error method without having proper design.



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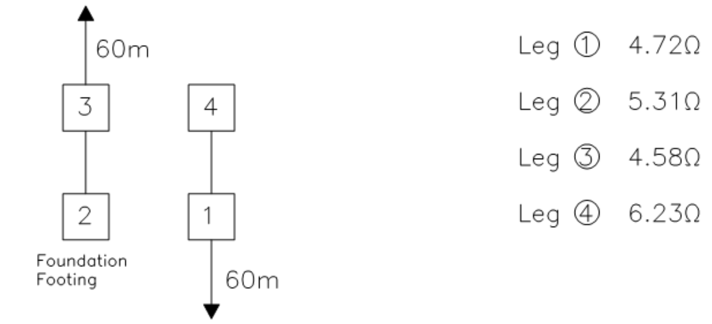

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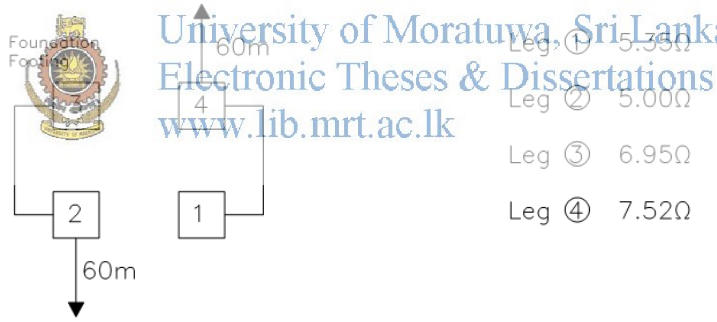

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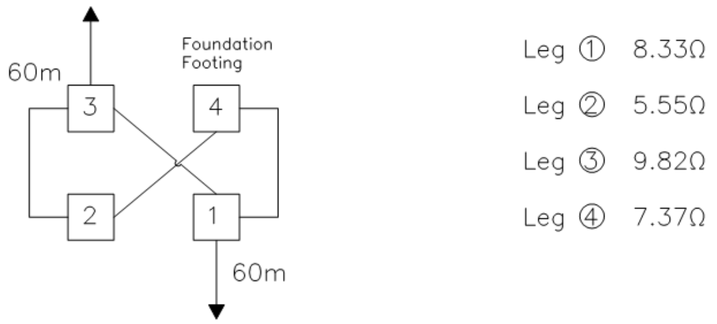


1.2.2 Drawbacks Identified in Transmission Tower Earthing Specification

1. From the sample calculation on counterpoise earthing arrangements using standard formulas, have been identified that for high soil resistivity areas it is very difficult to reduce earth resistance by using counterpoise wires only.

2. There are more efficient and more reliable earthing designs for transmission line towers in other countries with their own specified resistance values.

3. Using only counterpoise with maximum of 60 m lengths and two counterpoise sets achieving of specified 10Ω earthing resistance is of great difficulty in the areas where the towers are located in rocky lands or gravel soil conditions. In such situations contractors are laying 02 counterpoises in 60m length and do not giving effort to reduce resistance value to the acceptable limit and abandon the site as it is. On other hand lying of 60m length copper conductors is not practical in rocky areas.

4. Without considering fault current of the system, use of 7/4.00mm stranded galvanized conductor for every tower is not provided a safe grounding and selection of the size of the conductor should be done in according to an approved manner.

5. Analysis of the soil structure is not mentioned in this specification.

6. Here only mentioned a general value of earhing resistance and it has been proven by other researchers that achieving of earth resistance of 10Ω using any of the earthing method is not possible in high soil resistivity areas. Because of this reason most of the new tower earthing designs which are based on soil resistivity values have specified different earth resistance values based on the soil type of the tower location.

Because of the above reasons timely been necessary to introduce well explained, more effective earthing design for the transmission line tower earthing specification

1.3 The Aim and Scope of the Thesis

A large percentage of transmission line outages in Sri Lanka are due to lightning activity with backflashover being the main cause. Previous investigations have indicated that tower footing resistance is one of the main factors in reducing the occurrence of back flashovers. This study reviews some of the tower earthing options other than the currently being used in Sri Lanka. From this standard designs are proposed together with a tower footing earthing model of optimizing the design based on soil resistivity data. The process is presented via a procedure which includes the main measurement and modeling steps. This allows different standard designs to be selected to suit the type of soil structure at the site of the proposed transmission tower.

Selected earthing design is a practical earthing design and power frequency earth resistance value has been defined on practical experience. Initially performance of the design under fault condition is not known. There was a requirement of verification of the proposed values before practically use it and introduce to a new specification. Final aim of this research was the analysis of the performance of this new earthing design using a tower earthing model such that, in case of high fault current, tower footing resistance is within the acceptable limits. And also for the accessible tower locations step and touch potentials and ground potential rise are reviewed during this research. For this purpose I have used analytical modeling software.

Ultimate objective of this research is to propose a better tower earthing design for transmission line towers to overcome the drawbacks of the existing design.

Chapter 01 is for the introduction and problem identification of the research. Then I have explained the objectives of the research and structure of this thesis.

Chapter 02 and Chapter 03 are for the literature review of the research. In chapter 02 theoretical background on grounding of power systems and Chapter 03 specially for the transmission line tower earthing and identify the effect of tower footing resistance for the performance of the transmission line. In the latter part of the chapter present the available tower earthing systems which are using in other countries and identify the most suitable earthing design for the modeling and analysis of the earth resistance for different soil structures. Here also present some formulas that have been developed to calculate the effective ground resistance, and discussed on Finite Element Method (FEM) for calculating the ground resistance and Ground Potential Rise (GPR) is introduced.

Where acceptable grounding designs have to be designed under different conditions, the methods given in chapter 03 may not be sufficient. From the modeling of grounding design using analytical modeling software, can show that the proposed earthing method is more effective than the currently using earthing arrangement for transmission line towers. Modeling of the earthing design is presented in detailed in chapter 04. Results and analysis of the earthing model is illustrated in Chapter 05.

Finally, Chapter 06 and 07 are for the discussion on concluding remarks and the future work that needs to be done.

1.4 Relevant Standards on Earthing

Standards applicable to earthing systems have been examined for earthing requirements under transmission tower structure earthing and their recommendations are presented.

BS EN 62305-3:2011 Code of Practice for Protection of Structures against Lightning [3] recommends that the designing of earthing system intended to protect against lightning strikes should have an earthing resistance not exceeding 10Ω. This seems to be the only transient earthing system design limit specified and has been adopted by most of electricity companies in the UK. Although the standard recognises the importance of the inductive effects, the design limit appears to be based on resistance. The standard also recommends that the down conductor should be directly routed to the earth electrode.

IEEE Std. 80-2000, the IEEE Guide for Safety in AC Substation Grounding [4], does not give direct guidance on the design of earthing for systems likely to be subjected to lightning strikes but, in common with other relevant standards, it does recommend that surge arresters should „*always be provided with a reliable low resistance ground connection*" and have as „*short and direct a path to the grounding system as practical'*. It also suggests the design of grounding systems be carried out according to the principles used in the design of power frequency systems which, it considers, will „*provide a high degree of protection against steep wave front surges*". The standard recognises the capacity of the human body to withstand high magnitude transient currents for very short periods.

DIN VDE 0100 Part 540 is for Installation of power systems with normal voltages to 1000V; selection and installation of electrical equipment, earthing; protective conductors; equipotential bonding conductors.

DIN VDE 0151 introduce that the material and minimum dimensions on earth electrodes with reference to corrosion.

Chapter 2

Literature Review: Theory behind Electrical Grounding

This chapter presents the theoretical background to grounding and different grounding techniques. A brief introduction on tower earthing and the effects of earthing resistance is also discussed.

Although grounding is used for a long time by field engineers, there is a common misunderstanding on the meaning of grounding. Grounding or earthing is normally understood to be the connection of various exposed conductive parts (that are not current carrying under normal circumstances) of equipment together and to a common terminal (main grounding terminal) which is in turn connected by the earthing conductor to an earth electrode. There are two misconceptions in this statement. First, grounding is not only limited to equipment but also involves the electrical power system, the two being related and may refer to the same physical installation in some cases. Second, the term grounding, which is used interchangeably with earthing, is not the same thing. Grounding should be called earthing, only if it involves the physical earth and in case of a mal-functioning of some part of the system, some of the current returns back to the source through the earth. Therefore, the admitted definition of grounding according to [5] is the conducting connection whether intentional or accidental between an electrical circuit or conductive equipment part and a common terminal which is in turn connected by a conductor to an earth electrode or to some conducting body of relatively large extent that serves in place of the earth.

2.1 Description of the electrical system

The electrical system can be seen with the generating part as a source with a neutral point connected to ground as the reference of the system. The current is distributed between several loads and then lead back to the source through the neutral. A fault in an electrical system will create a fault current. The fault current will close a circuit by finding a return path to the grounded neutral of the system. This is described in figure 2.1.

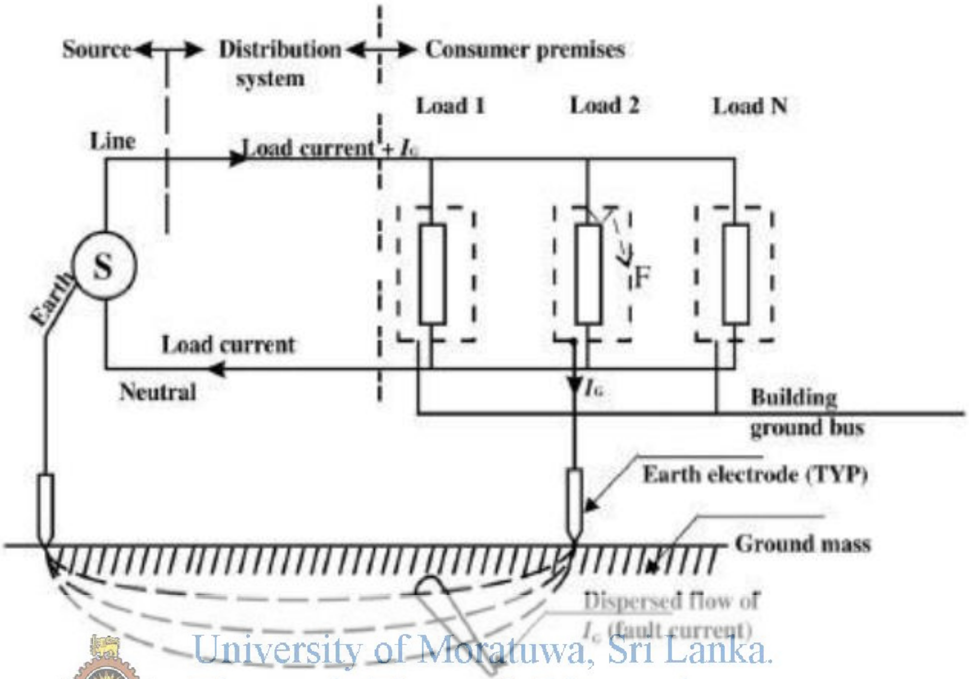


Figure 2.1 Fault current path in an electrical system [6]

When a fault current hits the ground through the ground electrode, the potential will rise at the ground plate compared to remote earth. The ground potential in the area will then decrease according to distance and depth. The potential decrease can be described according to the Figure 2.2 below. If the grounding resistance is higher, the cone will be wider due to Ohm´s law.

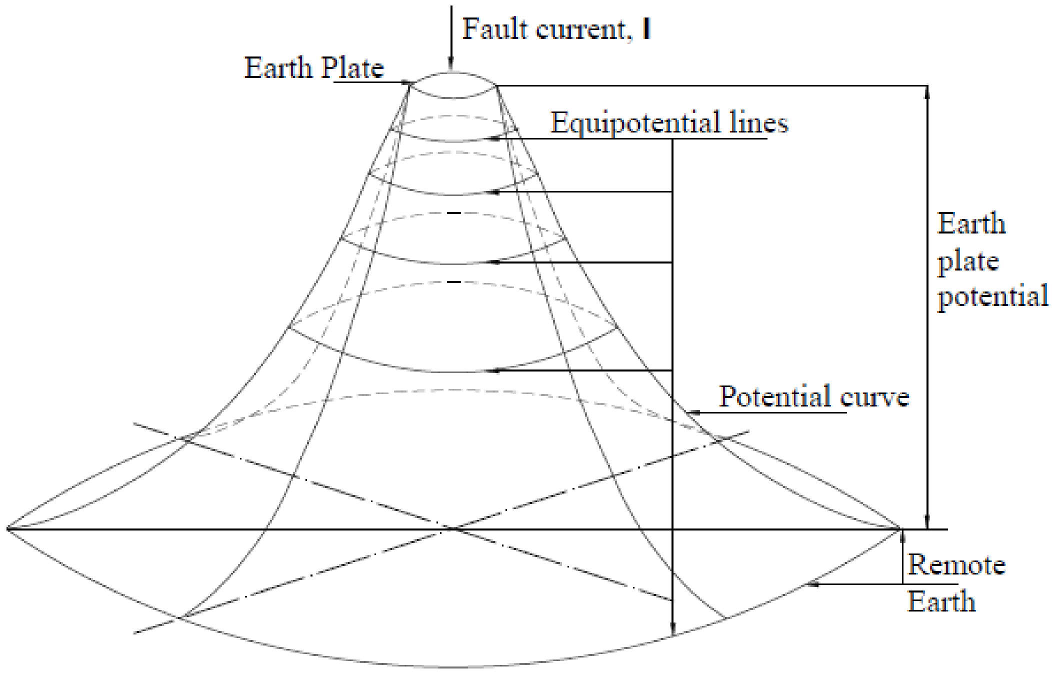


Figure 2.2 The potential field when a fault current hit the ground [7]

2.2 Effect of a fault

The effects of a fault current in a power system are not only located at the fault point, but also at connected loads, the generating plant and other connected facilities. The main effects are disturbances of the connected load which can be destroyed or cause reduced function and overheating at the fault location and in associated plants.

The incidence of faults depends on the climate conditions and the installation of the system. Faults on overhead lines are most common with approximately 60 % of all fault incidents. This is usually a result of lightning or climate conditions as wind, fog or ice. Faults might also affect cables, transformers or switchgear [8].

When a fault occurs in a circuit, it includes all interference with the normal current flow. The fault can be instant as during a lightning strike or when a short circuit occurs. The fault can also be permanent when lines are lying on the ground, when insulator strings are broken or during surge arrester failures. The current flowing immediately after a failure is determined by the impedances of the components in the network and the synchronous machines. A failure on a transmission line will create a current path from the conductor to the ground through the supporting tower [9].

Between 70 and 80 % of the faults on a transmission line are single line-to-ground faults where the fault occurs between one line and the ground. Other faults on a transmission line are line-to-line faults between lines which do not involve ground and double line-to-ground faults. When one or two conductors are open or a circuit breaker does not open the three phases simultaneously, an unbalanced current will flow in the system All these faults will cause an unbalance between the phases and are for this reason called unsymmetrical faults. A three-phase fault will still keep balance between the phases, also called a symmetrical fault, which occurs in roughly 5 % of the fault statistics [9].

Since unsymmetrical faults are the most common faults in a power system, this thesis will focus on those fault conditions [9].

2.3 The purpose of grounding

A proper grounding of an electrical system is fundamental for both safety and reliability of the system. The most important part of grounding is to protect people from high currents and voltage differences. Furthermore, grounding is done to protect structures and equipment since damage can cause outage or malfunction and result in economic losses of great values. Therefore, the grounding installation must ensure a safe and controlled flow of electric energy with minimum voltage drop to earth in all cases. A proper grounding installation will facilitate the protective device operation, preventing uncontrolled fault currents to flow to the earth until the protecting device operates. Grounding of a system will also limit the voltage stress on cables and equipment and extend the lifetime of the installations [10].

Grounding can be divided into three different types according to the purpose.

1. The neutral ground is intended to establish the ground reference of an electrical system. The neutral ground connection is usually connected to the

neutral point of the generator or transformer, and is grounded as far as the galvanic connection is reached.

2. The safety ground connection is done as protection for personnel and property within an electrical facility. The safety ground is done for an exposed part of a plant, which is not energized during normal conditions, but might be at live potential.
3. The equipment ground ensures a low impedance return path for the ground current if a fault occurs between live conductors and the equipment enclosure. In this case a circuit protection can break the faulted circuit in a short time [11].

The different types of grounding are described in the Figure 2.3 below.

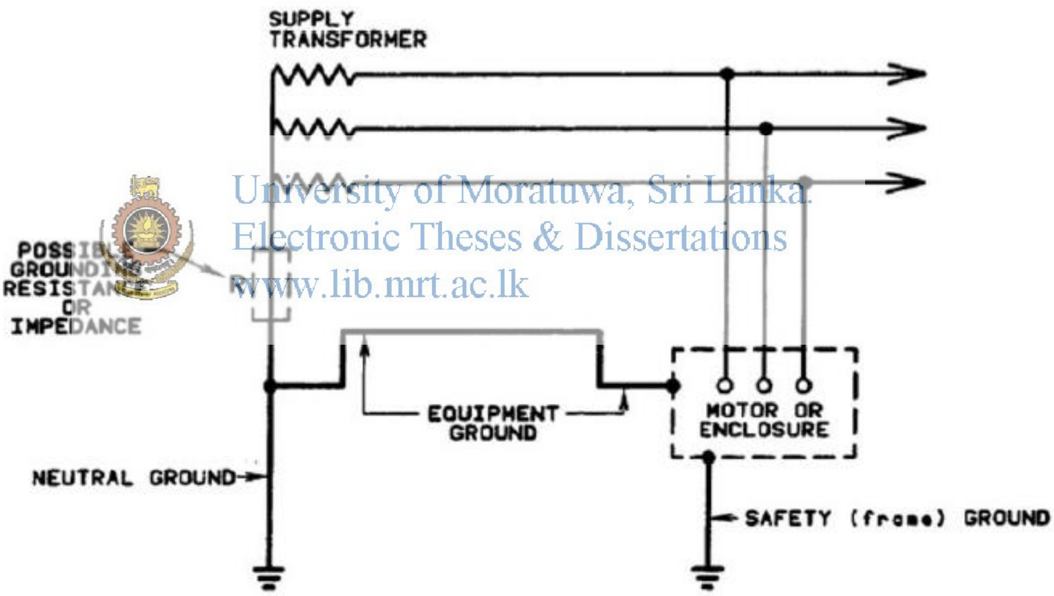


Figure 2.3 Definitions of neutral ground, safety ground and equipment ground. [11]

2.4 Design Criteria for a grounding system

When the decision to ground an electrical system is made, several considerations have to be done when designing the system. A long performance life has to be guaranteed, both from a mechanical and electrical perspective. It is also important to meet the requirements for safety and ability of serving the load. The grounding system will carry little or no current at all for long periods of time until a fault occurs or a lightning strike or other transient requires dissipation. At that point, the grounding system components will be expected to perform as they were new while conducting large amounts of currents [12].

Public access is important to investigate for reaching a suitable level of safety in the design. A study of the hazardous touch and step voltage levels has to be done for all sections that are accessible for humans which might come into contact with live parts. Ground Potential Rise, GPR, is a main design parameter for personnel safety. GPR is defined as the maximum potential of a grounding electrode during a fault relative to a distant point considered to be remote earth. [10].

The next thing to investigate is the components and equipment required for serving the system, and the costs that are included for material, construction and maintenance. This also includes a study of the continuity of service and level of maintenance needed in the future. Most of the grounding system components are buried below ground level, making inspection difficult or impossible. Since the underground environment is challenging for the material, the initial selection of the components used in the grounding system is of critical importance to its long-term effectiveness [12].

The costs and time spent on a proper investigation are in most cases a good investment. It is difficult to change a grounding installation after the facility is built when most of the grounding installation is buried below ground level and inaccessible after installation. Future expansions with additional buildings, more generating units or interaction with adjacent systems have to be considered and sufficient bonding points installed will reduce future costs and save time [13].

2.5 Safety in Transmission Line Grounding

Earthing systems for high voltage transmission lines are important for the security of the power system and safety of personal around the structures associated with the transmission lines. In this section safety limits are reviewed under typical electrocution scenarios.

Safety of a power system mainly concerns exposure to currents. The effect depends on both the current amplitude and the duration of the exposure. A safe grounding system has two primary objectives which is essential for all kind of grounding design.

1. A safe design has to provide the conduction for transporting electrical currents into the earth during normal and fault conditions without exceeding the limits for safety levels or affecting the continuity of service.

2. A safe design also has to guarantee that a person in contact with the grounded object or objects is not exposed to danger of electrical shock.

To fulfill these objectives it is important to understand the interaction between the intentional ground and the accidental ground and how to control them. The intentional ground consists of grounding rods pulled into ground. The accidental ground is harder to foresee and is created when a person is exposed to a potential gradient inside or close to a facility. Humans and livestock outside a facility may also be exposed to potential differences around facilities, transmission towers or by induced voltage. To prevent accidents, it is important to have reliable fences and other obstructions around high voltage equipment, and ensure a reliable grounding path which controls the fault currents. [10] Most of the accidents from earth faults are when the fault current energizes equipment, which people come into contact with [14].

2.5.1 Safety Voltages

The earth surface potential is defined as the potential attained by the earth as the current is dissipated into the earth via an earth electrode, e.g. a tower foundation. It is measured in relation to a remote earth point which is assumed to have a potential of 0V.

The earth potential rise for steel transmission towers and substation earthed metal work is defined as the voltage that the metal wall may attain with respect the potential of a remote earth. This earth potential rise is proportional to the magnitude of the fault or lightning current which flows via the earthing system to the earth and the magnitude of the earthing system impedance.

2.5.2 Touch Voltage

The touch voltage is regarded as the difference between the earth potential rise and the earth surface potential at the point where the person stands 1m from the earthed structure and at same time touches that structure. The route of the current due to the touch voltage circuit is passing from the hands to the feet (in parallel and in contact with soil).

Guidance on the requirements for the earthing systems for overhead lines exceeding 45 kV is provided in BS EN 50341-1 [15]. In this standard, there is a requirement to ensure safety for persons coming into contact with earthed metal work of lines under earth fault conditions. The procedure for establishing safety is based on tolerable body current values given in Figure 2.4 (Curve C2) reproduced from standard IEC60479-1. Parameters of the electrocution circuit, made up of human body resistance and additional resistances such as footwear, are suggested for different scenarios. Importantly, consideration of the touch voltage scenario is restricted to towers which are freely accessible and defined as frequently occupied. The permissible voltage against fault duration for an electrocution current with assumed typical resistances is based on hand to feet or hand to hand contact (without taking into consideration footwear or shallow material of high resistivity).

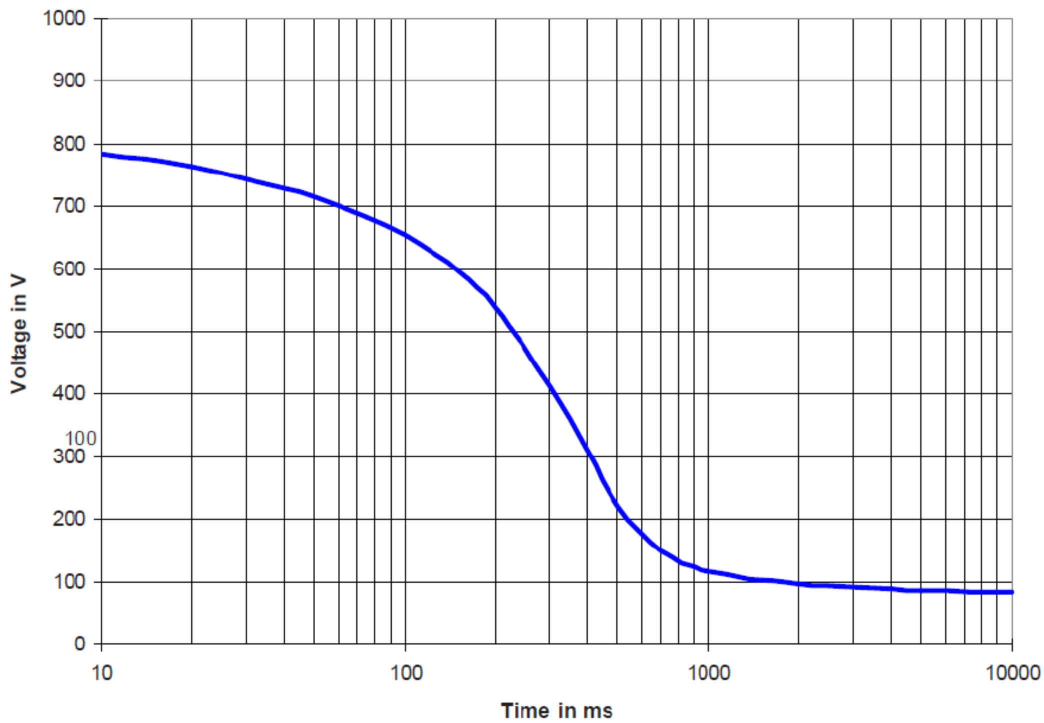


Figure 2.4 Tolerable touch voltage [Reproduced from [15]

2.5.3 Step Voltage

According to IEEE Std. 80 [16], the step voltage is the difference in earth surface potential experienced by a person bridging a distance of 1m with his/her feet without contacting any other grounded structure. In such circumstances, the current enters the body through one foot and leaves from the other. The body resistance when the current passes between extremities is conservatively considered to be 1000 Ω [16].

Step voltages are usually considered less hazardous than touch voltages. This is because the human body can tolerate higher currents for a path from foot to foot than current from hand to feet which passes through the chest, as described in IEC 479-1 [17]. Given the step voltage is lower than the touch voltage, if a system is safe for touch scenarios, it should also be considered safe for step scenarios.

2.6 Grounding resistance

As mentioned in previous chapters, connections to ground are done for minimizing the voltage difference between the conducting metallic object and ground. Different methods are used for connection to ground depending on the facility and its function, but all connections are called ground electrodes. The resistance of a ground electrode depends on the resistance of the electrode material, the contact resistance of the electrode to the soil and the resistivity of the soil itself.

Identifying the resistance to ground is a major point and it is mostly dependant on soil resistivity of the area to be grounded. There are multiple alternative methods for the designer to reduce grounding resistance. These alternatives are given next and are listed from simplest to complex. In each alternative either used equipment is considered in equations or soil models are determined for grounding resistance determination.

2.7 Grounding Methods

Alternative grounding methods can be classified into two groups as conventional methods and finite element methods. In the following sections, these methods are introduced.

<u>Conventional method</u>

a- One rod grounding design methods

If there is an electrode in the ground, the resistance to ground depends on the soil resistivity. Assume, one use a rod as an electrode located in the ground with a certain soil type. Many researchers studied on one rod grounding and they found different empirical equations to calculate ground resistance. Three of these methods are taken from references in the order of [18], [19] and [20].

Method 1

$$R = \frac{\rho}{2\pi C} \qquad \text{Equation (2-1)}$$

where R is resistance in Ω, ρ is soil resistivity in Ωcm, C is electrostatic capacitance (computed by Eq. (2-2)) of one rod in Farads. Electrostatic capacitance of one rod is given by the following formula.

$$C = \frac{13.25 L_r}{1.55 + \log(\frac{L_r}{d})} \qquad \text{Equation (2-2)}$$

where Lr is rod length in feet, d is rod diameter in inches.

By putting the computed electrostatic capacitance into Eq. (2-1), one can obtain resistance to ground value of a one rod grounding by knowing soil resistivity, rod length and rod diameter. For more detailed information refer to [18].

Method 2

Ground resistance of one rod or pipe grounding can be computed by Eq. (2-3).

$$R = \frac{100\rho}{2\pi L_r} \times \left(\ln \frac{8L_r}{d} - 1 \right) \qquad \text{Equation (2-3)}$$

where ρ is soil resistivity in Ω·m, Lr is rod length in cm, d is rod diameter in cm.

In this method, the diameter of copper rods recommended between 13mm and 19mm. Also length of copper rods recommended between 1,22m and 2,44m.

Method 3

This method is the most commonly used equation (given in Eq. (2-4)) for single rod grounding, which is developed by Prof. H. R. Dwight and called as Dwight method.

$$R = \frac{\rho}{2\pi L} \times \frac{\{(\ln 4L_r) - 1\}}{r} \qquad \text{Equation (2-4)}$$

where ρ is soil resistivity in Ω·m, Lr is rod length in cm, r is rod radius in cm.

b- Two rods system grounding method

If there are two electrodes in the ground, which are separated with a distance S, electrostatic capacitance given in Eq. (2-5) is valid.

$$C = \frac{61L_r}{3.56 + 2.31\log(\frac{L_r}{d}) + \frac{L_r}{S} + \frac{1}{3}(\frac{L_r}{S})^3 + \frac{2}{5}(\frac{L_r}{S})^5} \qquad \text{Equation (2-5)}$$

By computing the capacitance of two rods from Eq. (2-5) and putting it in Eq. (2-1), one can obtain resistance to ground value of two rods grounding by knowing soil resistivity, rod length and rod diameter [18].

c- Multi-rods system grounding

There is no specialized method to compute grounding resistance of a multi-rods system. In this kind of systems, only computation way to measure grounding resistance is using finite element analysis.

d- System grounding with grids in uniform soil conditions

Grounding grid is an intermeshed network of conductors which are located under the area which requires control of potential caused by a fault current. Resistance to ground calculation method for a uniform soil covered by a grounding grid region used to be studied by many researchers. IEEE 80-2000 [21] includes and defines some methods. Commonly used methods are Laurent-Niemann Method, Sverak Method, Schwarz Method and Thapar-Gerez Method.

I. Laurent-Niemann Method

The ground resistance is a function of the area covered by the substation and the soil resistivity in the substation region. The soil resistivity has a non-uniform nature. It is a well-known fact that soil resistivity may vary both vertically and horizontally in an earth region. Varying soil resistivity causes varying resistance from the direct relation between soil resistivity and resistance. So the designer try to estimate the minimum value of ground resistance at a certain depth h from the ground surface. Laurent-Niemann Method expressed Eq. (2-6) to estimate the ground resistance.

$$R = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} + \frac{\rho}{L_T} \qquad \text{Equation (2-6)}$$

where A is area covered by the substation in m^2, L_T is total buried length of conductors.

L_T formulation is taken from IEEE 80-2000 [21] and given in Eq. (2-7).

$$L_T = L_t + n_R \cdot h \qquad \text{Equation (2-7)}$$

where L_t is total length of conductors in grid in m, n_R is number of grounding rods used in grid in m, h is the depth of the grid in m.

From the examination of Eq. (2-6), left side of the summation is for calculating ground resistance at the surface of the soil and right side of the summation is for calculating ground resistance of the total buried length of the conductors. Summation leads the formulation to ground resistance R in Ω.

II. Sverak Method

This method can be called as the integrated form of Laurent-Niemann Method. Ground resistance at the surface of the soil is modified in order to improve the accuracy of the ground resistance calculated. Researchers observed significant effect of the grid depth on ground resistance and decided that this effect is large enough to be included it to the equation. Therefore, Eq. (2-6) is rearranged and the resultant Eq. (2-8) is obtained.

$$R = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] \qquad \text{Equation (2-8)}$$

Examining Laurent-Niemann and Sverak Equations, it can be easily understood that the resistance is directly proportional to resistivity and inversely proportional to total buried length of conductors. Resistance is also inversely proportional to square root of area. Therefore, the following observations can be derived. First such observation is that increasing area of grounding grid decreases the resistivity in the order of square-root. Sometimes this is possible in real life. If the land is not costly for grounding grid design region, increasing area will lead to a feasible solution. However, in residential areas, land is expensive and limited. Second observation is that ground resistance decreases while using more conductors in grid designs. Although, increasing the total buried length of conductors seems to be leading a desired ground resistance in grounding grid designs, desired solution won't be feasible enough because such conductor material, copper is very expensive. Reference [22] has derivation of Eq. (2-8) and further information about Sverak Method.

III. Schwarz Method

Schwarz developed following set of equations in order to determine the grounding resistance in uniform soil conditions. Schwarz equations are composed of three equations and one equation for merging the three.

Main equation merging the other three equations is given in Eq. (2-9).

$$R = \frac{R_1 R_2 - R_m^2}{R_1 + R_2 - 2R_m} \qquad \text{Equation (2-9)}$$

where, R1, R2, Rm are determined by three different equations. R1 is determining the ground resistance of a grid formed by straight horizontal wires and represented in Eq. (2-10).

$$R_1 = \frac{\rho}{\pi L_t}\left[\ln\left(\frac{2L_t}{a'}\right) + \frac{k_1 L_t}{\sqrt{A}} - k_2\right] \qquad \text{Equation (2-10)}$$

where ρ is the soil resistivity in Ωm, Lt is the total length of all connected grid conductors in m, 2a is the diameter of conductor in m, a' is $(a \cdot 2h)^{1/2}$ for conductors buried at depth h, or a' is a on earth surface, A is the area covered by conductors in m2, k1 and k2 are the coefficients found by the following equations according to the value of grid depth (h).

The values of k1 and k2 in Eq. (2-10) are given in Table 1 for different values of the grid depth. In the formulations x is given as the length to width ratio of grid.

h	k_1	k_2
0	-0.04x+1.41	0.15x+5.50
$1/(10A^{1/2})$	-0.05x+1.20	0.10x+4.6
$1/(6A^{1/2})$	-0.05x+1.13	-0.05x+4.40

Table 1 Values of k1 and k2

In Eq. (2-11), R2 determines the ground resistance of a rod bed.

$$R_2 = \frac{\rho}{2\pi n_R L_r}\left[\ln\left(\frac{4L_r}{b}\right) - 1 + \frac{2k_1 L_r}{\sqrt{A}}\left(\sqrt{n_R} - 1\right)^2\right] \qquad \text{Equation (2-11)}$$

where Lr is the length of each rod in m, 2b is the diameter of rod in m, nR number of rods placed in area A.

The third variable in Schwarz Equation is given in Eq. (2-12). Rm is the combined ground resistance of the grid and the rod bed.

$$R_m = \frac{\rho}{\pi L_t}\left[\ln\left(\frac{2L_t}{L_r}\right) + \frac{k_1 L_t}{\sqrt{A}} + 1 - k_2\right] \qquad \text{Equation (2-12)}$$

One can obtain the grounding grid resistance by computing k1, k2, R1, R2, Rm in the given order and putting the calculated values in Eq. (2-9). Reference [23] has the necessary derivations to obtain Schwarz equations.

IV. Thapar-Gerez Method

Thapar and Gerez worked on a complex computer program, which is based on finite element analysis in order to determine resistance of a grounding system made of straight linear conductors laid in three mutually perpendicular directions. Thapar and Gerez determined ground resistances of more than 100 grids which have different shapes, configurations and sizes by using their program. They developed an empirical equation which is valid for their predetermined grid shapes and configurations for varying sizes.

In Eq. (2-13), Thapar-Gerez formula is given and this formula is the integrated version of Eq. (2.7-8). In detail, an extra multiplication part is added to include the effect of grounding region shapes on calculated resistance.

$$R = \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] * 1.52\left[2\ln\left(L_P\sqrt{2/A}\right) - 1\right]\frac{\sqrt{A}}{L_P}$$

Equation (2-13)

where LP is the peripheral length of grid.

Thapar-Gerez equation is dimensionless and does not change according to the shape of the grid. Also it is based on the factor. This factor comes from the known fact that ground resistance of a conductor of given surface area decreases as the length over which the area spreads is increased.

All of these four methods assume solutions in uniform soil models. Also all four methods are inversely proportional to primary parameters such as length of total conductors (LT) used in grid and area covered by the grid (A). Differences of these methods are the secondary parameters used such as depth of grid (h), diameter of conductor (2a), rod diameter (2b), and rod length (Lr).

e- Two layer or multilayer system grounding

Highly non-uniform soil characteristics may be encountered from Wenner Test results of the grounding design region. In such soil conditions, both two layer and multilayer soil models can be used. Multilayer soil models can be used if and only if there does not exist a feasible two-layer equivalent design according to [21]. A multilayer soil model includes several horizontal soil layers. Techniques to interpret highly non-uniform soil resistivity require the use of computer programs or graphical methods developed by the researchers. As it is given in [21], that in most cases, the grounding regions can be modeled, based on an equivalent two-layer model that is sufficient for designing a safe grounding system.

For further information on details of multilayer model calculations, [21] gives adequate information. Multilayer model is not discussed in this study whereas details of two-layer soil model calculations are given next.

Two layer soil models can be designed in three different ways:

1. Determination of an earth model by minimizing error function
2. Determination of an earth model by graphical data
3. Determination of an earth model by finite element model

Most commonly use type of soil modeling is done by graphical data. Therefore here presented only the graphical method for soil model in next section.

Determination of an earth model by graphical data

One can obtain the soil characteristics of a region in two layer soil model by using graphical methods. Many researchers study on these methods to investigate an easy way for soil resistivity determination whereas usage of these methods require accurate and close enough Wenner-four-pin test results to apply, that is not possible in most cases. Sunde graphical method is introduced next. [21] Includes necessary information in order to find studies of other researchers on this subject.

Sunde method composed of several steps as follows:

- Wenner four pin method tests are applied to the area to be grounded.
- Plot a graph from the test data such as given in Figure 2.5. Vertical axis of graph is resistivity ρ in $\Omega \cdot m$ and horizontal axis of graph is probe spacing a in m.
- Estimate $\rho 1$, $\rho 2$ from the plotted graph in step above. Upper limit of the graph is estimated as $\rho 2$ and lower limit of the graph is estimated as $\rho 1$.
- Calculate $\rho 2 / \rho 1$ and use this value in Sunde graph (given in Figure 2.6) as selecting the matched plot or drawing a matching plot on the same graph.
- Select the value $\rho a / \rho 1$ on y-axis within the sloped region of the appropriate $\rho 2 / \rho 1$ curve in Figure 2.6.
- Read the corresponding value in x-axis for a / h ratio. - Compute ρa from $\rho a / \rho 1$ value.
- Read the probe spacing a (illustrated in Figure 2.5) by using computed ρa.
- By using a, find h from a / h ratio found.

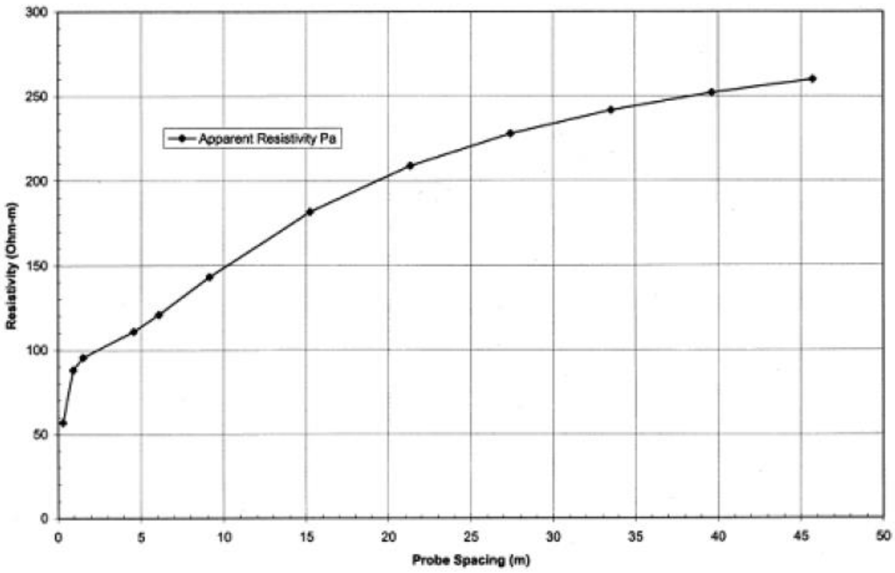


Figure 2.5 Example Wenner data graph [21]

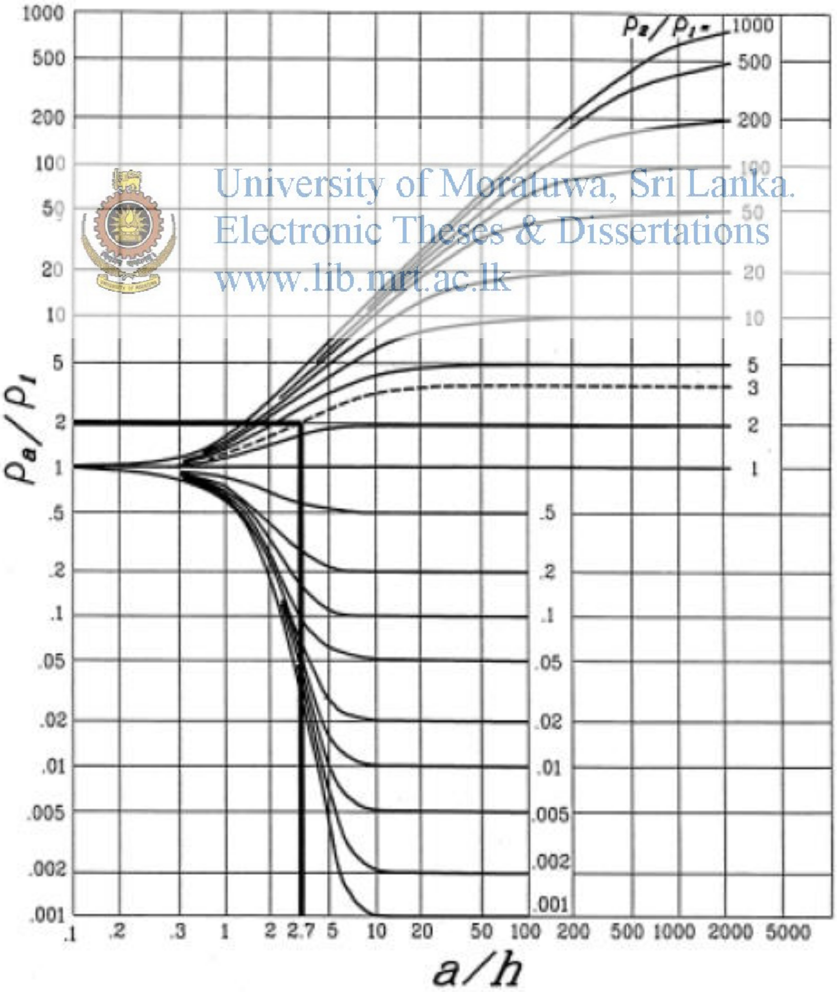


Figure 2.6 Sunde graph [21]

Determination of earth model by Finite Element Model

Finite element analysis, which is used in determination of ground resistance, is capable of both one or multi rod grounding and uniform or non-uniform soil models grounding computations. In non-uniform resistivity soil conditions, using tow layer soil model or multilayer soil model is essential.

Most recent studies about grounding analysis are based on Finite Element Methods (FEM). FEM used to determine grounding resistance of a design or a grounded region. They give more accurate results compared to conventional grounding methods discussed in above section under Conventional Grounding Methods.

Old FEM methods are composed of current flow analysis by using grid potential set. After the current is computed, ground resistance can be found by dividing voltage by current. In this method, main disadvantage is selecting the size of the model such as earth distance to be considered is starting from the grounding grid. Since analysis of each potential in the soil for a selected point is considered from grounding grid to the point.

New FEM methods are developed by researchers such as main disadvantage of old FEM method is overcome. They model the problem from the beginning. In the first step, they assume that grounding resistance is such a parameter that does not depend on potential or current in the grid except frequency cases other than power frequencies (50Hz or 60Hz). Second assumption is that the region is an infinite flat surface. ([24] gives sample results and derivations). Model structure for this solution is given in Figure 2.7.

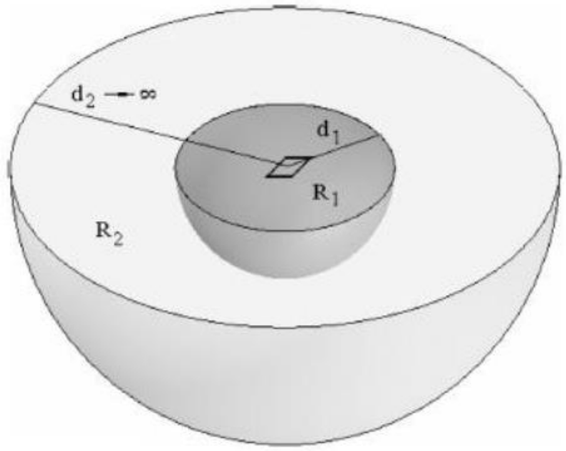


Figure 2.7 New Finite Element model of soil [24]

R1, R2, d1 and d2 are the variables for the model where d1 is the distance from grid to the points where semi-spherical model of equipotent surface disturbs, d2 is the distance from grid to the points where electrical potential goes to zero. Technically, this point is at infinity. R1 is the resistance inside the semi-spherical surface and R2 is the resistance outside the semi-spherical surface.

2.8 Soil Resistivity

Soil resistivity is defined as the resistivity of a 1 m^3 sized cube between the two opposite sides, and is measured in ohmmeter or ohmcentimetres. Soils have generally been deposited in layers, which can have different values of soil resistivity.

By measuring the resistivity of the soil at varying depths, it is possible do develop a profile which can be used to identify the most appropriate ground electrode design [25]. The soil immediately adjacent to the electrode is most important for the conductivity and the resistivity in the layers depends on several factors such as:

- Moisture content
- Temperature of the soil
- Material content
- Presence and concentration of conducting chemicals
- Level of compaction

A wet soil has low resistivity and the ability to keep a high moisture level depends on factors as the content of organic material and grain size. A ground electrode should be located at a depth where the moisture content is less fluctuating during the season, for a more constant soil resistivity. The temperature will affect the moisture content near the surface where the moisture can dissipate, but also close to freezing point since the resistivity sharply goes up below 0°C. The compaction of soil will affect the resistivity since a loose soil is less conductive compared to compacted soil with the same content [25]. Rock is very high resistive. Except for being conductive salts, the presence of chemicals, is also important from a corrosive point of view, since the chemicals might increase the corrosion of the metallic electrode.

The guidance values in table 2 (acc. DIN VDE 0101) apply for the specific resistance of various soil types. For further values refer table 3-9 of DIN VDE 0228.

Type of soil	Resistivity of the soil in Ωm
Boggy soil	5 to 40
Clay, loam, humus	20-200
Sand	200-2500
Gravel	2000-3000
Weathered rock	Generally below1000
Sandstone	2000-3000
Granite	To 50000
Ground moraine	To 30000

Table 2 Specific Resistivity Values of Different Soils

2.8.1 Soil resistivity measurement

Measuring the soil resistivity can be done with a method called the Wenner method, developed by Dr. Frank Wenner. The theory is to use four ground stakes positioned in the soil in a straight line. The distance between the stakes should be at least three times the stake depth. A known current is generated through the two outer stakes, and the drop in voltage potential is measured between the two inner stakes. The resistivity can then be measured by using Ohm´s law, U=IR.

Suitable equipment exists on the market that makes this type of measurement automatically, by generating the current and measuring the voltage differences. The resistivity is automatically calculated and showed on a display. The measurements are often distorted by underground metals like pipes or underground aquifers, which might be detected and avoided by turning the axis of the stakes 90° to the first measurement. By measuring several depths using different distances, a reliable profile of the areas resistivity can be made. When the resistance is given the following equation is used to get the soil resistivity [26]:

$$\rho = 2\pi AR \qquad \text{Equation 2.14}$$

ρ is the average soil resistivity.

R is the measured resistance value.

Soil resistivity tests are often corrupted by the existence of ground currents and their harmonics. Advanced equipment exists on the market, with a system which automatically selects the testing frequency with least amount of noise for a clear reading.

2.9 Types of earth Electrodes

Classification by Location [27]

a) Surface earth electrodes are earth electrodes that are generally positioned at shallow depths to about 1m. They can be of strip, bar or stranded wire and be laid out as radial, ring or meshed earth electrodes or as combination of these.

b) Deep earth electrodes are earth electrodes that are generally positioned vertically at greater depths. They can be of tubular, round or sectional material.

c) Foundation earths are conductors embedded in concrete that is in contact with the ground over a large area. Foundation earths may be treated as if the conductor were laid in the surrounding soil.

Classification by shape and cross section [27]

Strips, stranded wire and tube earth electrodes.

Natural earth electrodes are metal parts in contact with the ground or water, directly or via concrete, whose original purpose is not earthing but they act as an earth electrode. They include pipes, caisson walls, concrete pile reinforcement, and steel parts of buildings etc.

Cables with earthing effect are cables whose metal sheathing, shield or armouring provides a leakage to earth similar to that of strip earth electrodes.

Control earth electrodes are earth electrodes that by their shape and arrangement are more potential control than for retaining a specific earth-electrode resistance.

Rod electrodes of any significant length generally pass through soil horizons of varying conductivity. They are particularly useful where more conductive lower soil horizons are available and the rod earth electrodes can penetrate these horizons sufficiently (appr. 3m). To determine whether more conductive lower soil horizons are available, the specific resistance of the soil at the site is measured.

2.10 Earthing Material

The material in a ground electrode must be robust and sufficient for the environment, without corroding or bending with good conductivity. Earth electrodes (underground) and earthing conductors (above ground) must confirm to specific minimum dimensions regarding mechanical stability and possible corrosion resistance as listed in table below.

Material	Form	Minimum Dimensions			Remarks
		Diameter (mm)	Cross section (mm^2)	Thickness (mm)	
Copper, bare	Strip		50	2	For surface earths
	Round wire		25		
	Stranded wire	1.8	25		
	Tube	20		2	
Copper, tin-coated	Stranded wire	1.8	25		
Copper, zink-coated	Strip		50	2	
Copper, with lead-coated	Stranded wire	1.8	25		
	Round wire		25		
Steel, hot-dip Zink-coated	Strip		90	3	Edges rounded
	Sectional bar		90	3	
	Tube	25		2	
	Round bar	16			For deep earths
	Round wire	10			For surface earths
Steel, with lead coating	Round wire	8			For surface earths
Steel, with copper coating	Round bar	15			For deep earths
Steel, copper plated	Round bar	14.2			For deep earths

Table 3 Minimum dimensions for earth electrodes (according DIN VDE 0101)

For earthing conductors the following minimum cross section values are to be observed with respect to mechanical withstand against corrosion:

Copper : 16 mm^2

Aluminium : 35 mm^2

Steel : 50 mm^2

Copper is mostly used as ground electrodes but also copper clad steel because of the conductivity in the material. In some cases galvanized steel or stainless steel can be used.

Chapter 3

Transmission Line Tower Grounding

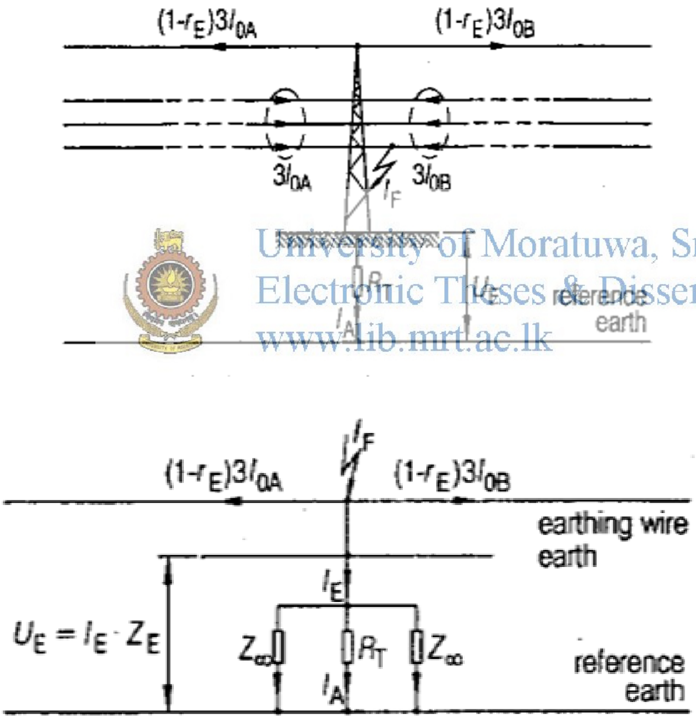
The content of this chapter is mainly focus on the review of transmission line tower grounding methods.

The networks for transmission might include both overhead wires and underground cables with different characters. Since the 132 kV transmission line in this study consists of overhead lines, this theory part will focus on grounding arrangement of overhead transmission lines. The grounding of a transmission line is a combination between the grounding of the individual towers, underground continuous counterpoise and shield wires. The purpose of the shield wires is to protect the conductors from a direct strike of lightning. One or two shield wires might be placed horizontally above the conductors and connected to earth at each tower [28]. OPGW is an optical shield wire, which combines the functions of grounding and communication. The optical fibres are surrounded by layers of steel and aluminium wires for conducting towers together and protect the conductors from lightning [29]. The shield wires act as protection for the conductors and lead the current through down conductors into the ground. The presence of shield wires can also have great influence on the induced overvoltage when it reduces the electric and magnetic fields that affect the voltage between phase conductors and ground. For an effective protection of the transmission line, the installation of a shield wire has to be combined with a proper insulation design and be grounded at every tower with low resistance grounding at the tower footing [30].

A continuous counterpoise is a wire buried underground along the line route. It is situated between the outer phase conductors and act as a return path for a fault current. It is connected to each pole and usually made of copper or copper clad steel with high conductivity. According to Swedish regulations, the minimum depth of the ground wire should be at least 0.6 meters below the earth surface. If solid rock or other factors prevent the required depth, a shallower depth might be accepted [28].

The connection between shield wires and ground electrodes at a tower footing is usually done by down-conductors for wooden and concrete structures and along the tower body for metallic towers. Each structure has an individual connection to earth often one for each foot if the tower has more than one foundation. The ground electrode can be a rod, radial wires, a ring shaped grounding electrode or a combination between the electrodes depending on the soil resistivity. Buried metallic components such as concrete-enchased reinforcement bars or tower grillages also works as an electrode, contributing to the dispersion of currents into soil [30].

From the below diagram we can clearly identify the behavior of fault currents, voltages and earth resistance in case of an earth fault at a transmission tower.



$I_F = 3.\ I_{OA} + 3.\ I_{OB}$

$Z_E = 1/(1/R_T + 2/Z_\infty)$

$I_E = r_E.\ I_F$

Figure 3.1 Earth fault current, voltage and resistance in case of an earth fault at a tower [31]

$3.\ I_{OA}$ – Total zero –sequence current from system part A

$3.\ I_{OB}$ – Total zero –sequence current from system part B

I_F – Earth fault current

I_E – Earth Current (not measurable)

I_A – Current flowing through the earth resistance of the tower having an earth fault

r_E – Reduction factor of the line

R_T – Tower resistance

Z_∞ – Impedance of the line

Z_E – Earthing impedance

U_E – Earthing voltage

3.1 Effects of Lightning on Overhead Transmission Lines

Lightning are causing several interruptions in power transmission and are one of the most frequent reasons for surges in electrical systems. A direct hit from lightning create extremely high voltage pulses at the strike point, which are propagated as travelling waves in both directions from the strike point. This will cause insulation flashovers when the voltage levels exceed the insulation levels. Another effect from lightning is the induced voltage from nearby strikes, when the lightning hit the ground in proximity of the line. Flashes might be collected by taller objects in the surrounding, and the induced voltage will create surges in the transmission lines and conduct these along the electrical system [30].

According to statistics, transmission lines short-circuit tripping accidents caused by lightning strikes accounted 60-80% among the entire accidents each year. Therefore, the lightning withstand level of transmission line plays a vital role on security and stability of transmission line [32].

According to the study [33] it has been found that there is a direct relationship the monthly Isokeraunic level (IKL) variation with the monthly average failures of transmission lines in Sri Lanka.

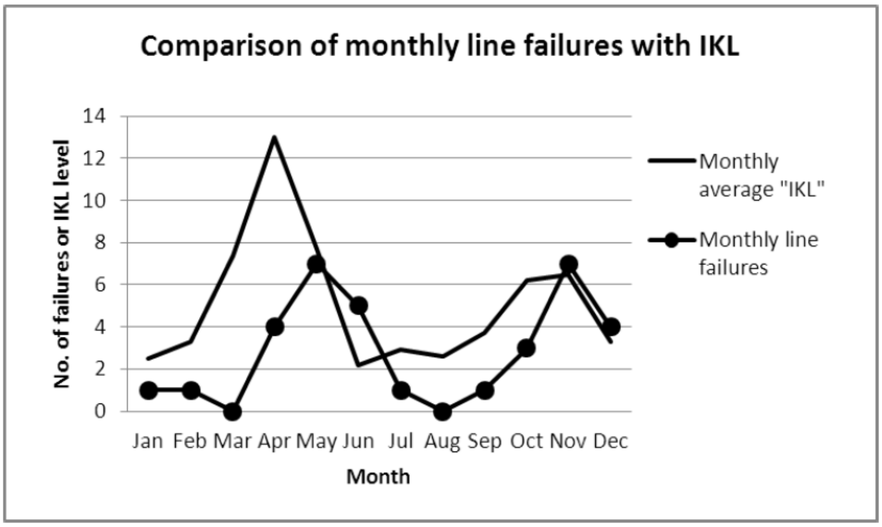


Figure 3.2 Comparison of monthly line failures with IKL [33]

The lightning withstand level is related to three major factors, 50% discharge voltage of line insulator, lightning current intensity and impulse grounding resistance of tower grounding devices [32].

In order to reduce the number of flashovers on the lines, there are different methods to improve the lightning performance of lines i.e improving critical flashover of insulators, reducing grounding impedance, installing shield wires for lines and installing lightning arresters. The tower footing resistance is one of factors effected the back flashover voltage across the insulator in transmission system.

The accumulation experience from many years of operating shows that the tower, which mostly has high measuring ground resistance, probably tends to be stricken by lightning. The size of grounding device resistance is critical to prevent lightning flashover.

Lightning flashover rate of the tower with greater than 20 Ω grounding resistance dozens times over lightning flashover rate of the tower with less than 10 Ω grounding resistance. Therefore, reducing tower grounding resistance under power frequency is effective measure to increase the line lightning withstand level, prevent lightning counter-attack, and reduce line lightning trip-out rate [32].

Tower footing resistance of the earthing system will depends on

- Type of electrode configuration
- Soil resistivity

3.2 Tower Footing Resistance Performance under Fault Conditions

If a transmission line tower is struck by lightning and the potential of the tower is raised above the voltage impulse strength of the insulator string, a flashover will occur from the tower to a phase conductor which may lead to serious outages of the system. This type of flashover is called back flashover. The electrical resistance of the tower footing is a significant parameter affecting back flashover voltage across the insulator(s) in transmission systems (IEEE Std. 1313.2-1999) [34]. According to IEEE Std. 1243-1997 [35], the individual performance of each tower is important in determining the lightning performance of the transmission line. „„*The overall performance of an entire transmission line is influenced by the individual performance of the towers rather than by the average performance of all the towers together''* [36].

To investigate the effect of the average tower footing resistance on the lightning outage rate, a study carried out by Whitehead [37] on a 500 kV transmission line showed that the outage rate was approximately proportional to the average tower footing resistance as can be seen in Figure 3.3. For an average tower footing resistance of 30 Ω, the lightning outage rate was 1.0 per 100 km per year. The findings confirmed results obtained by Chisholm and Chow [38]. The influence of the tower footing resistance on the lightning fault rate was also studied by Tomohiro et al. [39], as shown Figure 3.4, where it is shown that the lightning fault rate increased with the increase in tower footing resistance.

As a result of the important effect that the tower footing resistance has on the lightning performance of transmissions lines, a design standard for footing resistance against system voltage, isokeraunic level and importance of the line has been published by a Japanese power company [39], as shown in Table 4. In many other countries, the target level of tower footing resistance is taken as 10Ω or less to give protection from back flashover, and it is considered more economical than adding extra insulation to increase the capacity of the insulators to withstand lightning strikes [40]. However, the higher footing resistance, for example 50Ω, may cause outage rate of the shielded transmission line higher than that of the unshielded one [41].

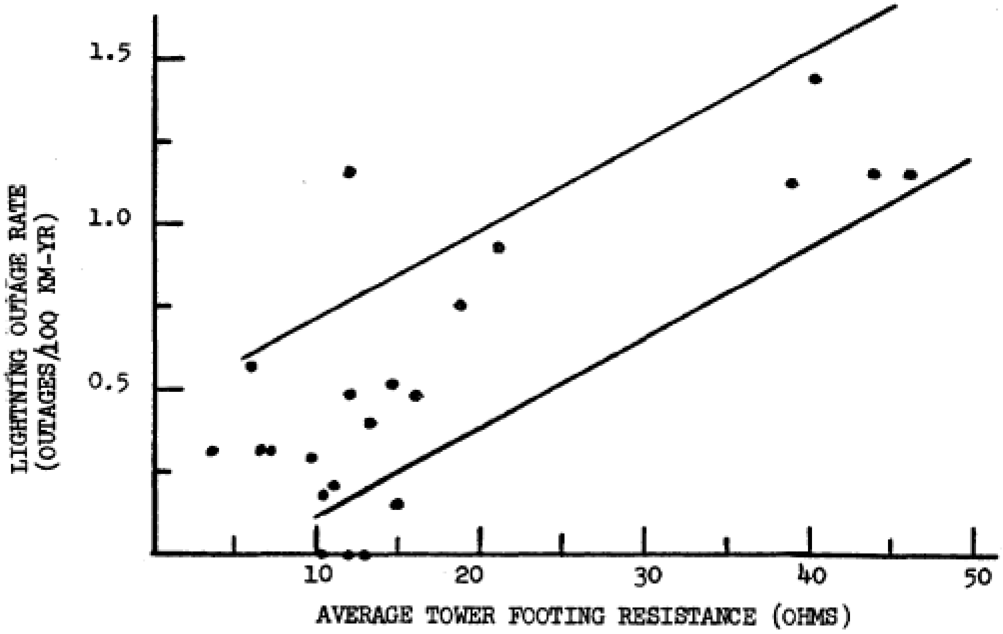


Figure 3.3 Lightning outage rate Vs. tower footing resistance for a 500 kV line [39]

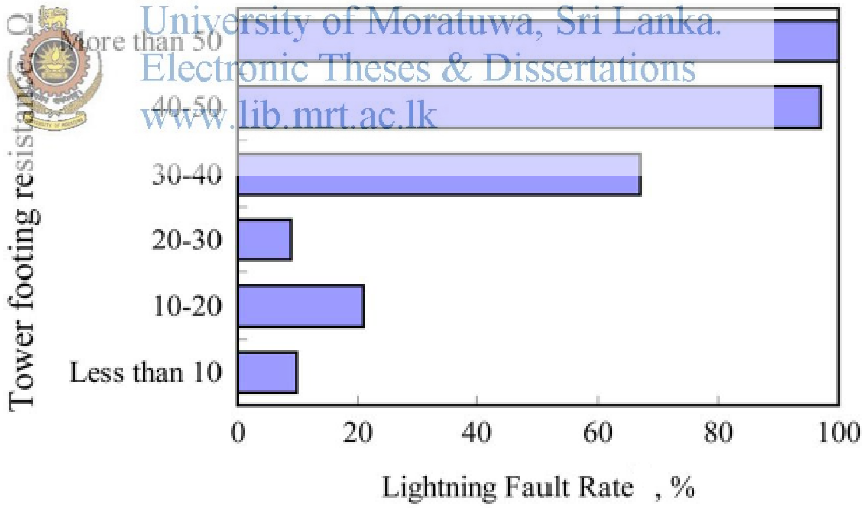


Figure 3.4 Tower footing resistance vs. lightning fault rate [39]

System voltage, kV	Design value of tower footing resistance, Ω		
	I	II	III
500	13		
275	13		
154	15		20
77	13		20
33	20		

IKL: Isokeraunic level, thunder storm days per year

I : IKL more than 30 and important lines.

II : IKL from 20 to 30.

III : IKL less than 20.

Table 4 Design standard for footing resistance against system voltage, isokeraunic level [39]

3.3 Reasons for High Transmission Line Grounding Resistance

Reasons for high transmission line grounding resistance is consisted of, both design and construction reasons, as well as operation and maintenance reasons, but also reasons for natural conditions, such as high soil resistivity, complex geological condition, inconvenient construction and others [32].

3.4 Common method for reducing tower footing resistance [32]

Improving tower earthing resistance is the key way of avoiding backflashovers. The tower footing resistance can be reduced by adopting the following techniques.

- Horizontal extension grounding

This method can be used when there is relatively good horizontal laying position and soil conditions near the tower. Horizontal laying mode has low cost, can not only reduce the power frequency grounding resistance, but also effectively reduce impulse grounding resistance while the extension is not very far.

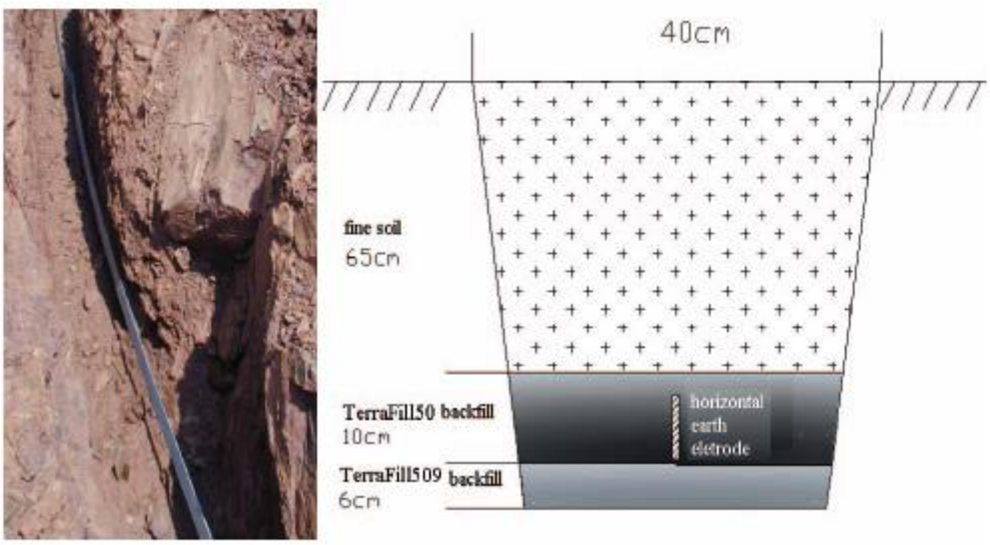


Figure 3.5 Horizontal ground body [32]

- Deeply buried type grounding

Deeply buried type or shaft type grounding can be used when deeper underground soil resistivity is lower [32]. Take advantage of nearby natural grounding, or choose a place where groundwater is rich and groundwater level is high.

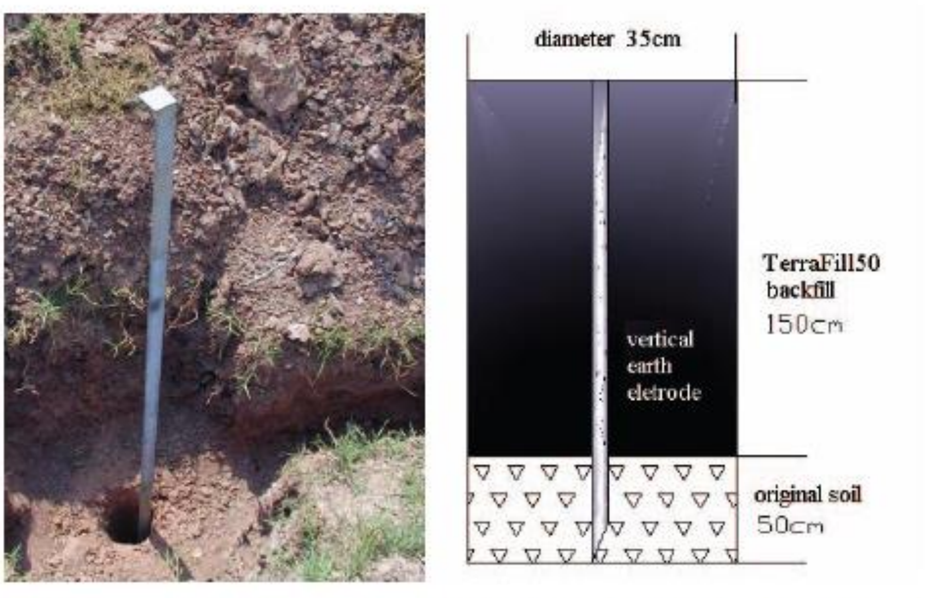


Figure 3.6 Vertical ground body [32]

- Methods of using special resistance reducing material

1) Backfill

As China's Yunnan plateau has dry climate, thin soil, and weak capacity in maintaining moisture, so backfill technique is used appropriately in the renovation of part of the tower grounding grid. TerraFill of the U.S. ALLTEC Company is common backfill, with a good match with a variety of polar material (flat iron, angle steel, electrolytic grounding electrode, open spandrel grounding electrode), that can be fully applied to the entire grounding system with lifespan of 30 years.

Figure 3.7 shows how backfill technology is used in actual construction. The technology can effectively solve high tower grounding resistance problemcaused by dry soil, rocky areas and other geological factors.

Figure 3.7 TerraFill backfill [32]

2) Electrolytic grounding electrode

TG-EX10S electrolytic grounding electrode of the U.S. ALLTEC Company is for the purpose of diffusing flow, which is a multi-purpose electrolytic ions grounding system. It is primarily designed for diffusing lightning current efficiently and quickly through the system to the soil in different types of soil environment. This system can achieve the desired effect even in poor soil conditions, and greatly reduce soil resistivity, with lifespan of 20 years.

Figure 3.8 Electrolytic grounding electrode [32]

3) WJ-type open spandrel grounding device

This device is possessed of the possibility of water injection single time or several times, which is designed for high soil resistivity areas, mountains, hills, and arid regions. This device can maintain long-term wet state, which help improving diffusion flow effect of grounding body; it also has good anticorrosion capacity, long lifespan of about 15 to 20 years without replacement.

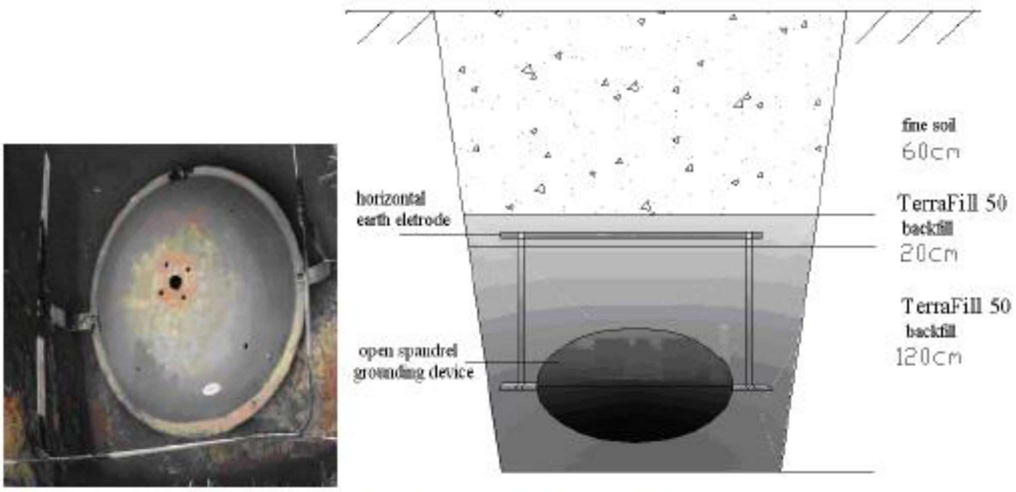


Figure 3.9 Open spandrel grounding device [32]

4) Domestic DVD-F01 low resistance grounding module

DVD series of potent anti-corrosion low resistance grounding body is made of non-metallic and minerals that have stable conductive, anti-corrosion, pollution-free characteristics. It can be used in environment for different climate, soil, gravel, rocks and other situations, with lifespan of 30 years.

Figure 3.10 Grounding module [32]

5) Reliable welding of metal in remote field

Sometimes there is inconvenient to carry power supply to some remote places of the construction of the tower grounding grid, and the use of fire welding technology can make metal welded together conveniently and reliably, even for different metal including copper and iron.

3.5 Transmission Line Structure Earthing Systems

The earthing systems of transmission line structures fall into two categories; The tower footing which includes the metallic part of the tower surrounded by its concrete foundation in soil, and Supplementary earthing electrodes such as vertical rods, etc. which are selected depending on the conditions and nature of the earth around each individual transmission tower.

Tower earthing designs have been categorized in to three groups.

1. Spur design – composed of horizontal earth electrodes, or counterpoise. This is the design presently used in Sri Lanka for transmission line towers.
2. Concentrated design – Mesh design around tower base augmented with driven rods.
3. Combination of spur and concentrated design.

For the high soil resistivity areas, combination of spur and concentrated design is the most suitable one.

3.6 Preliminary Studies on Transmission Tower earthing

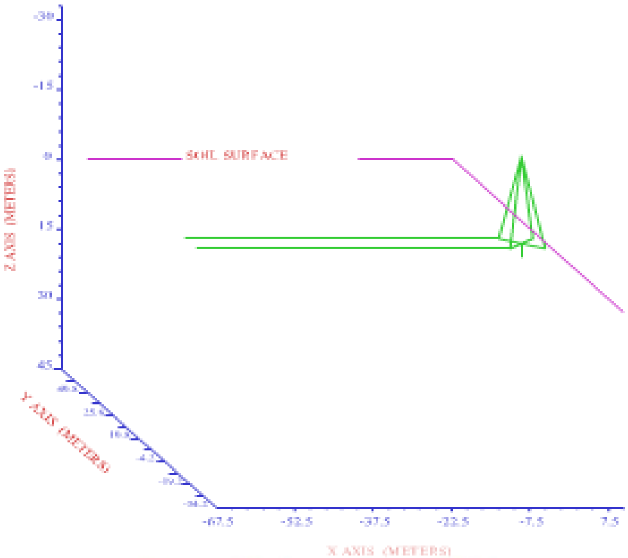
An earthing system refers to metallic wire(s) of various geometrical shapes and sizes acting as electrodes and buried in the soil. The commonly used earthing electrodes are the vertical rod, horizontal electrode, ring electrode and earthing grid. The vertical rod is the simplest and most economical form of earth electrode. It is highly effective for small installations especially when the bottom layer of soil penetrated has a lower resistivity than that of the upper strata [42]. However, in general, the resistance of a single rod is not sufficiently low, and it is necessary to use a number of rods connected in parallel. For large electrical installations, however, the horizontal earth is mainly used and is normally buried at a shallow or moderate depth where there is no significant effect of the depth on the earth resistance if the electrode length is more than about 10m and 50m in the case of transient and steady state conditions respectively [43]. The ring electrode is a type of horizontal earthing grid and is sometimes used as peripheral earth conductors around structures e.g. wind turbines. To obtain even lower earth resistance, the horizontal earth grid can be augmented with vertical rods which are normally inserted at the periphery of the earthing grid.

In the literature, very few experimental field studies are reported on tower earthing systems.

Study 01

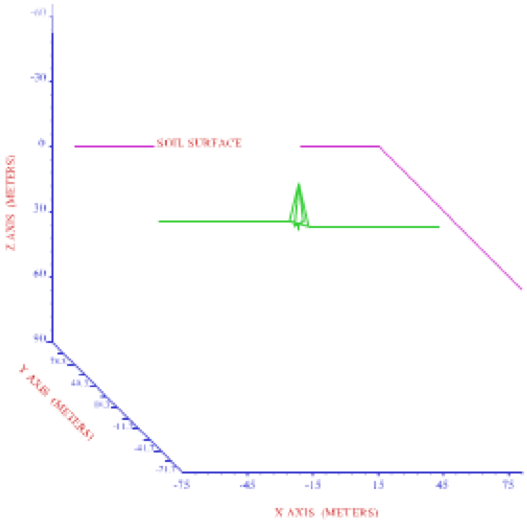
According to the study [44], there are six main tower earthing arrangements which are using in power system in Malaysia.

<u>Arrangement 01</u>



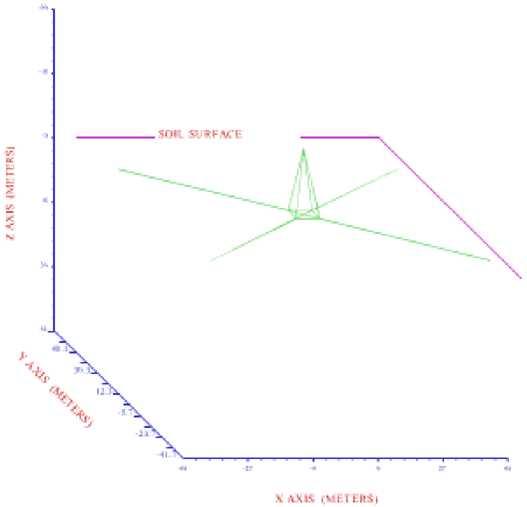
2x60 m of counterpoises in one direction & a single rod of 3.6 m length

<u>Arrangement 02</u>



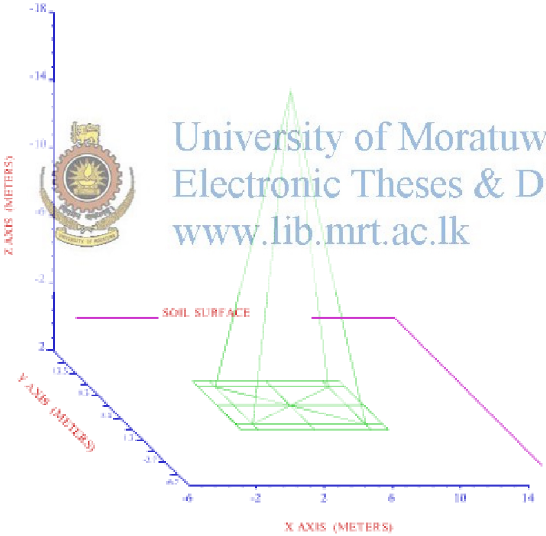
2x60 m of counterpoises in opposite directions & a single rod of 3.6 m length

Arrangement 03



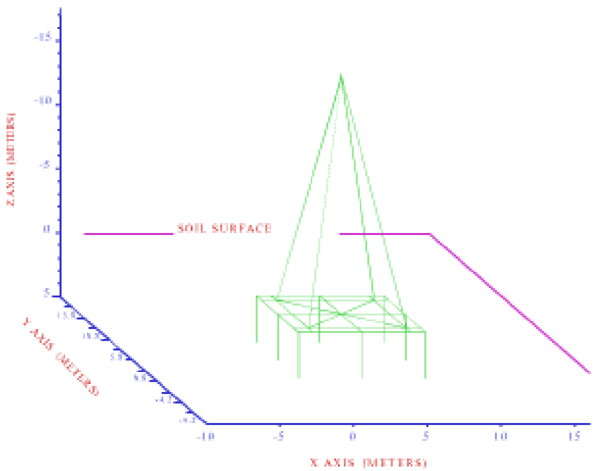
Radial spurs from each tower leg (50 m length)

Arrangement 04



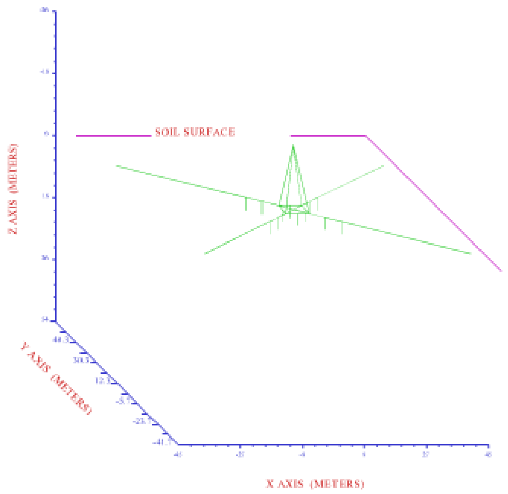
Mesh around tower base

Arrangement 05



Mesh around tower base with 8 vertical earth rods (3.6 m)

Arrangement 06



Radial spurs from each tower leg plus 12 vertical earth rods of 3.6 m length

From this study they have concluded that in a uniform soil, electrodes occupying a large area with additional electrodes near to the injection point are the best, but most expensive to install (Arrangement 1& 2).

In a two layer high-low soil structure, a concentrated electrode including rods penetrating the low resistivity bottom layer is the most effective. Extended counterpoises are not effective (Arrangement 4).

In a two layer low-high soil structure, extended counterpoises are effective and rods are ineffective apart from those very close to the tower and not beyond the top layer boundary (Arrangement 5 & 6).

Study 02

Because of the importance of consideration of soil structure for a proper grounding design, Power Industry Standard in China, DL/T 5092 -1999 Technical Code for Designing 110-500kV Overhead Transmission Line have mentioned that the Power frequency resistance for tower with earth wire unconnected should not exceed the values listed in the table.

Resistivity of Soil ρ(Ωm)	Type	a(m)	Number of ray	Length of ray (m)	Earth rods	PFR (Ω)
ρ≤100	C1	12	0	0	0	10
100<ρ≤300	C2	12	4	8	0	15
300<ρ≤500	C3	12	4	20	0	15
500<ρ≤1000	C4	12	4	15	12	20
1000<ρ≤2000	C5	12	4	30	20	30
2000<ρ≤3000	C6	12	8	20	32	30
3000<ρ≤4000	C7	12	8	25	40	30

Table 6 Earthing design types

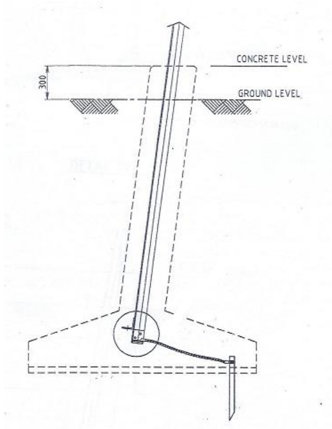
Counterpoise should be connected to all the tower's four footings. The value of 'a' should be enlarged when the distance of tower footings is large; when the distance is smaller, the value of 'a' should be reduced and the ray should be enlarged.

Depth of Counterpoise 't' is 0.8m for form land and for other arrears 0.6m.

3.7 Sample Calculations on Different Earthing Arrangements

Sample calculation of some of the conventional earthing arrangements has been carried out to find the effective lengths of the earthing conductor or rod when the soil resistivity is varying. Effective length has been calculated to maintain the earth resistance value bellow 10 Ω. From the results obtained, we can see that these conventional earthing methods are not suitable for medium and high soil resistivity areas.

1. Rods driven vertically in to the ground



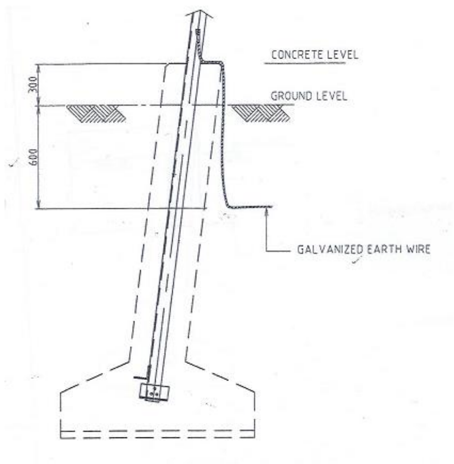
$$R_g = \frac{\rho}{2\pi L}\left[\ln\left(\frac{8L}{d}\right) - 1\right]$$

where:

ρ	*Soil Resistivity in Ωm*
L	*Buried Length of the electrode in m*
d	*Diameter of the electrode in m*

L (m)	ρ(Ωm)	d (m)	R (Ω)
3.2	30	0.012	9.944066
5.8	50	0.012	9.959816
12.75	100	0.012	10.04458
28	200	0.012	10.04194
78	500	0.012	10.05708
168	1000	0.012	10.06549

2. Horizontal Electrodes buried under the surface



INSTALLATION METHOD OF COUNTERPOISE CONDUCTOR

$$R_g = \frac{\rho}{\pi L}\left[\ln\left(\frac{4L}{(dh)^{\frac{1}{2}}}\right) - 1\right]$$

where:

ρ	*Soil Resistivity in Ω-m*
L	*Buried Length of the electrode in m*
d	*Diameter of the electrode in m*
h	*Buried depth of the electrode in m*

L (m)	ρ (Ωm)	d (m)	h (m)	R (Ω)
4	30	0.012	0.6	10.11957
7.7	50	0.012	0.6	10.11506
18	100	0.012	0.6	10.15543
42	200	0.012	0.6	9.988786
67	300	0.012	0.6	10.05799

3. Radial conductors

$$R_g = \frac{\rho}{n\pi L}\left[\ln\left(\frac{4L}{(dh)^{\frac{1}{2}}}\right) - 1 + N(n)\right]$$

$$N(n) = \sum_{m=1}^{m=n-1} \ln\frac{1+\sin \pi m/n}{\sin \pi m/n}$$

where:

ρ	*Soil Resistivity in Ω-m*
L	*Length of each radial in m*
d	*Diameter of each radial in m*
h	*Buried depth of the radials in m*
n	*Number of radials*

L(m)	ρ(Ωm)	d(m)	h(m)	n	N(n)	R(Ω)
5	30	0.01	0.6	2	0.7	5.016292
5	50	0.01	0.6	2	0.7	8.360487
5	100	0.01	0.6	6	4.42	9.520189
10	200	0.01	0.6	8	6.5	9.346656
15	300	0.01	0.6	8	6.5	9.669273
25	500	0.01	0.6	12	11	9.104163

Chapter 4

Modeling of the Grounding Design

4.1 Methodology and Procedure

1st Step

The first step was the selection of the earthing design which is suitable for transmission tower earthing. From the literature survey found some transmission tower earthing designs using in other countries and they have their own specifications on the earth resistance values. Out of those earthing designs as explained in chapter 03, selected one of the earthing design which is suitable for all soil types with optimizing the design based on soil resistivity measurement data. This design can be used in high soil resistivity areas like 4000 Ωm resistive soils.

One of the main difficulty in doing the tower earthing in high soil resistivity areas as well as rocky and mountain areas with long counterpoise length and deep buried length can be overcome with this earth design. Buried length of the earthing system is around 0.6m. With from land in rocky areas and mountain areas we can install one of the selected designs with maximum buried length of 0.8m easily. On the other hand this is more compact design and maximum ray length of the earth design is 25m from tower footing in 4000 Ωm resistive soils.

Because of the above features selected the earthing design reviewed in study 03 in Chapter 03 for the modeling and analyzing the earth resistance for different soil structures. Done some modifications to the selected design to match with existing specification and easy of the modeling.

Selected soil categories for the modeling are as follows;

Soil Type	Resistivity Value (Ωm)	Selected Resistivity Range ρ(Ωm)
Moist humus soil, moor soil, swamp	30	$\rho \leq 100$
Farming soil, loamy and clay soil	100	
Sandy clay soil	150	$100 < \rho \leq 300$
Moisty sand soil	300	
Moist gravel	500	$300 < \rho \leq 500$
Dry sand soil, dry gravel	1000	$500 < \rho \leq 1000$
Weathering rock	2000	$1000 < \rho \leq 2000$
Lime rock, quarts rock	3000	$2000 < \rho \leq 3000$
Lime rock, quarts rock	4000	$3000 < \rho \leq 4000$

Table 7: Soil categories for the modeling

Technical details of the earthing design, such as earthing material, tower footing details have been selected based on the preliminary studies and data founded during the literature survey which have been done for this study and mentioned in the Chapter 02 and Chapter 03 in this thesis.

Earthing conductors - Stranded copper conductors of $50mm^2$

Earthing rod - Copper clad steel rods of 25mm Diameter

Distance of tower footing - 12m

2^{nd} Step

Before doing the modeling and verification of the earth resistance values from the simulation of the earthing design model, I did a theoretical verification of the design using Thapar-Gerez equation which has been explained in details in Chapter 02. This equation is dimensionless and does not change according to shape of the grid, also it is based on the factor $\sqrt{A}/Lp$. This factor comes from the known fact that ground resistance of a conductor of given surface area decreases as the length over which the area spread is increased.

Type	ρ(Ωm)	A(m^2)	L_T	L_P	h(m)	Calculated Earth Resistance (Ω)
C1	100	144	48	48	0.6	5.12
C2	300	336	80	80	0.6	9.74
C3	500	624	128	128	0.6	10.9
C4	1000	504	122.4	108	0.6	24.2
C5	2000	864	192	168	0.6	33.54
C6	3000	2704	246.4	208	0.6	35

Table 8 Calculated values of earth resistance

3^{rd} Step

The effectiveness of the design discussed in above in handling of fault current was previously not known. The aim of this study is mainly focus on the modeling of the earthing design and for the analysis of earthing design model finding the most suitable eathing design type for different soil type mentioned above.

Computer software packages can be used to assist in earthing design by modeling and simulation of different earthing configurations. The tools either come as standalone packages or plug-in modules to power systems analysis software such as ETAP's Ground Grid Design Assessment.

What is ETAP

ETAP is the most comprehensive enterprise solution for design, simulation, operation, control, optimization, and automation of generation, transmission, distribution, and industrial power systems.

Ground Grid Systems module of ETAP enables engineers to quickly and accurately design and analyze a safe and cost-effective ground protection. The Ground Grid System program utilizes the following four methods of computation:

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

Using Ground Grid System (GGS) program we can calculates the followings:

- The maximum allowable current for specified conductors. Warnings are issued if the specified conductor is rated lower than the fault current level.
- The Step and Touch potential for any rectangular/triangular/L-shaped/T-shaped configuration of a ground grid, with or without ground rods (IEE Std 80 and IEEE Std 665).
- The tolerable Step and Mesh potential and compares them with actual, calculated Step and Mesh potentials (IEE Std 80 and IEEE Std 665).
- Graphic profiles for the absolute Step and Touch voltages, as well as the tables of voltages at various locations (Finite Element Method).
- The optimum number of parallel ground conductors and rods for a rectangular/triangular/L-shaped/T-shaped ground grid. The cost of conductors/rods and the safety of personnel in the vicinity of station during a ground fault are both considered. Design optimizations are performed using a relative cost effectiveness method (based on the IEE Std 80 and IEEE Std 665).

- The Ground Resistance and Ground Potential Rise (GPR).

Ground Grid System 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 grounding system. The Soil View is used to edit soil properties of the surface, top and lower layer of soil. The 3D View is used for three dimensional display of the grounding system. The 3D View also allows the display of the grounding system to rotate, offering views from various angles. The GGS presentation allows for graphical arrangement of the conductors and rods that represent the grounding system, and to provide a physical environment to conduct grounding system design studies.

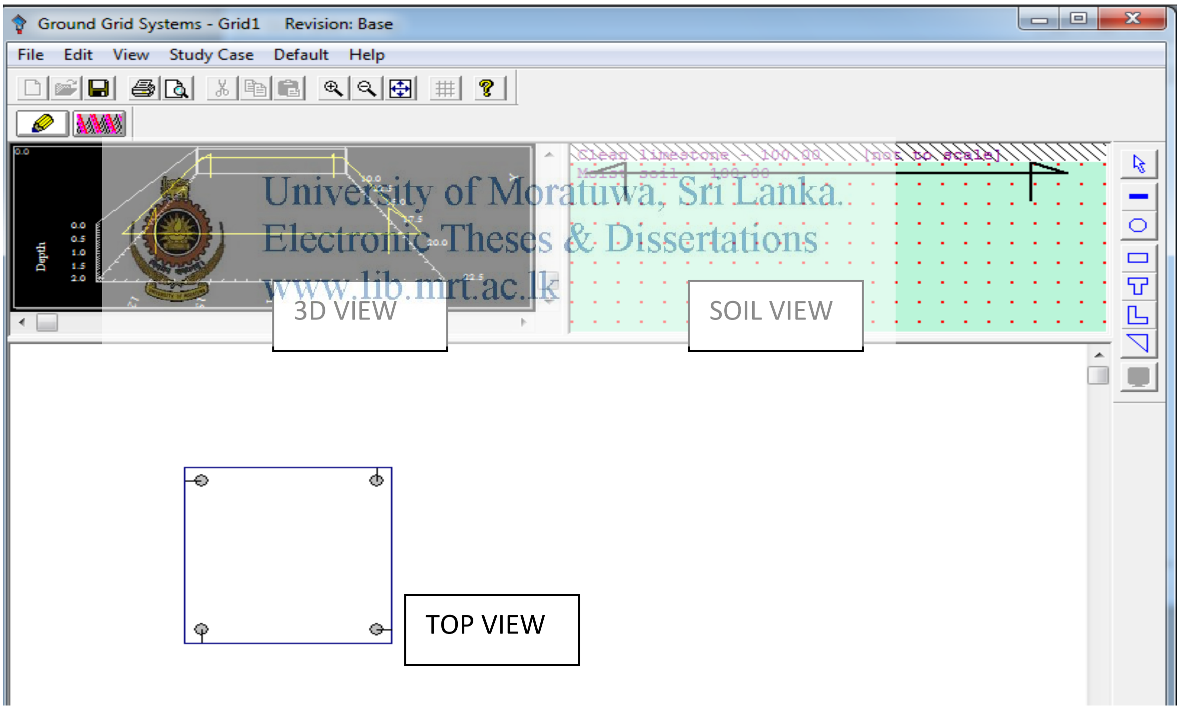


Figure 4.1 Ground Grid System graphical user interface window

- Handle irregular configurations of any shape
- Check the allowable current for grid conductors
- Compare allowable currents against fault currents
- Compare potentials to tolerable limits
- Automatically use short circuit results
- Two-layer soil configuration plus surface material

- Table of potentials at the earth surface
- External boundary extensions
- Variable weight & temperature options
- User-expandable conductor library
- Ground grid configurations showing conductor & rod plots
- Reflection factor (K)
- Decrement factor (Df)
- Ground potential rise (GPR)
- Ground system resistance (Rg)
- Surface layer derating factor (Cs)
- Step, touch, & absolute potentials inside & outside grid
- Application of the field resistivity measurement

4th Step

Input Data for the Modeling

To run a Ground Grid System study, the following related data is necessary: Soil Parameters, Ground Design Data and System Data.

System Data

System Frequency	= 50 Hz
Average Weight of Worker	= 70 kg
Ambient Temperature	= 30 ^{0}C
Short Circuit Current	= 4 kA (Single phase)
Duration of Fault	= 0.5 s

Soil Parameters

Surface Material Resistivity	= N/A
Surface Material Depth	= N/A
Upper Layer Soil Resistivity	= 100 Ωm, 300 Ωm, 500 Ωm, 1000 Ωm etc….
Upper Layer Soil Depth	= 10m
Lower Layer Soil Resistivity	= N/A

Ground Conductor Library

- Material Conductivity
- Thermal Coefficient of Resistivity
- K_0 Factor
- Fusing Temperature
- Ground Conductor Resistivity
- Thermal Capacity Factor

Conductor/Rod Data

- Material Type
- Insulation
- Cross Section
- X. Y and Z Coordinates of One End of Conductor
- X. Y and Z Coordinates of Other End of Conductor
- Cost

5th Step

Using ETAP ground grid system package and selecting FEM method modeled earthing designs types with the optimum earthing conductor arrangement to maintain the earth resistance value bellow 10 Ω. With the change of earthing material and shapes of the earthing conductors I have simulated each design to find most suitable material which can be used for this design. On other hand I have done a comparison on the cost of each design to find the most cost effective conductor size for each design type.

Finally it was obtained the earth resistance values and plot the Ground Potential Rise, Touch and Step voltage distributions etc. for all design types.

Earth Design Model 1

This design is suitable for the soil type which has soil resistivity bellow 100 Ωm.

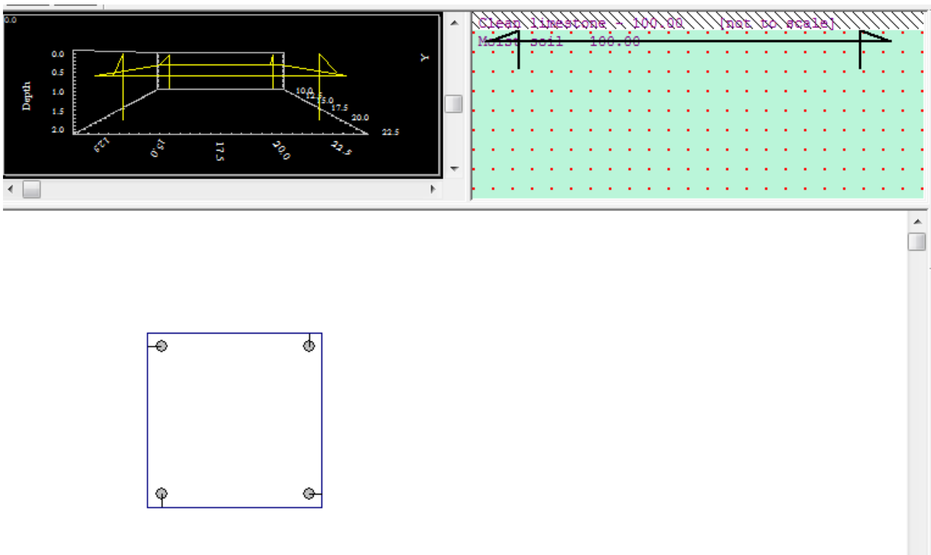


Figure 4.2 Earth Design Model 01

Earth Design Model 02

Earthing design for the soil resistivity range between 100 Ωm to 300 Ωm.

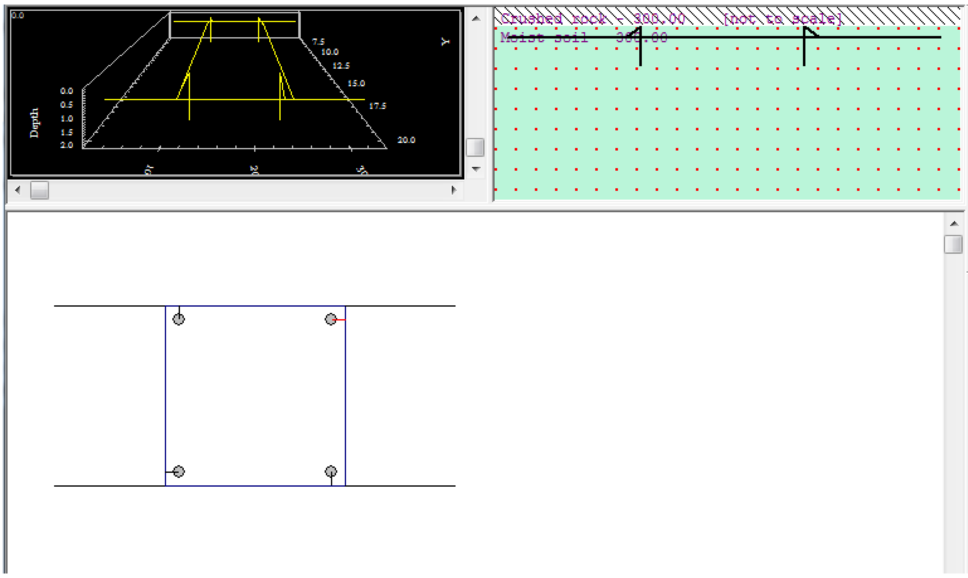


Figure 4.3 Earth Design Model 02

Earth Design Model C3

Earthing design type C3 is for the soil resistivity range between 300 Ωm to 500 Ωm.

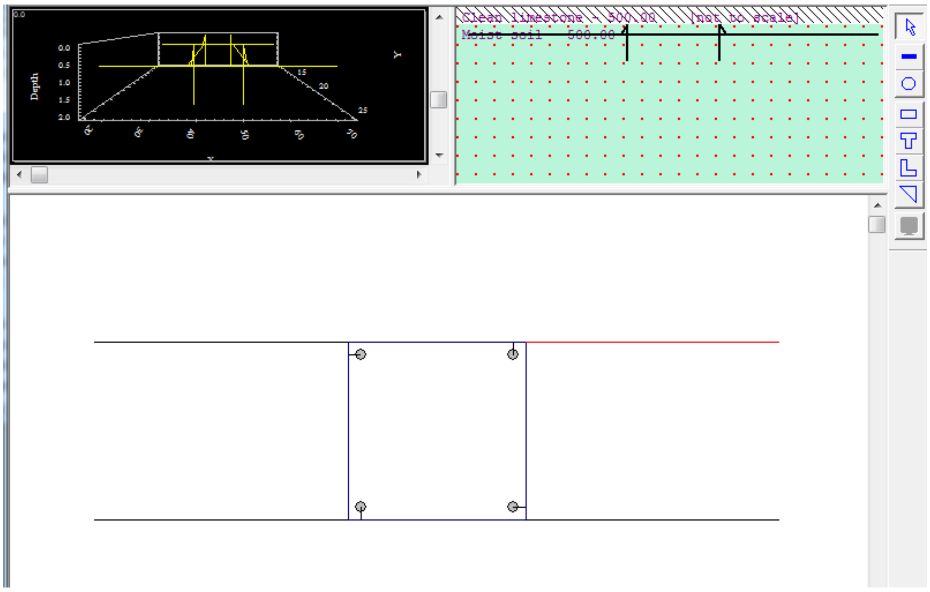


Figure 4.4 Earth Design Model 03

Earth Design Model C4

Earthing design which is suitable for soil type of having soil resistivity between 500 Ωm to 1000 Ωm.

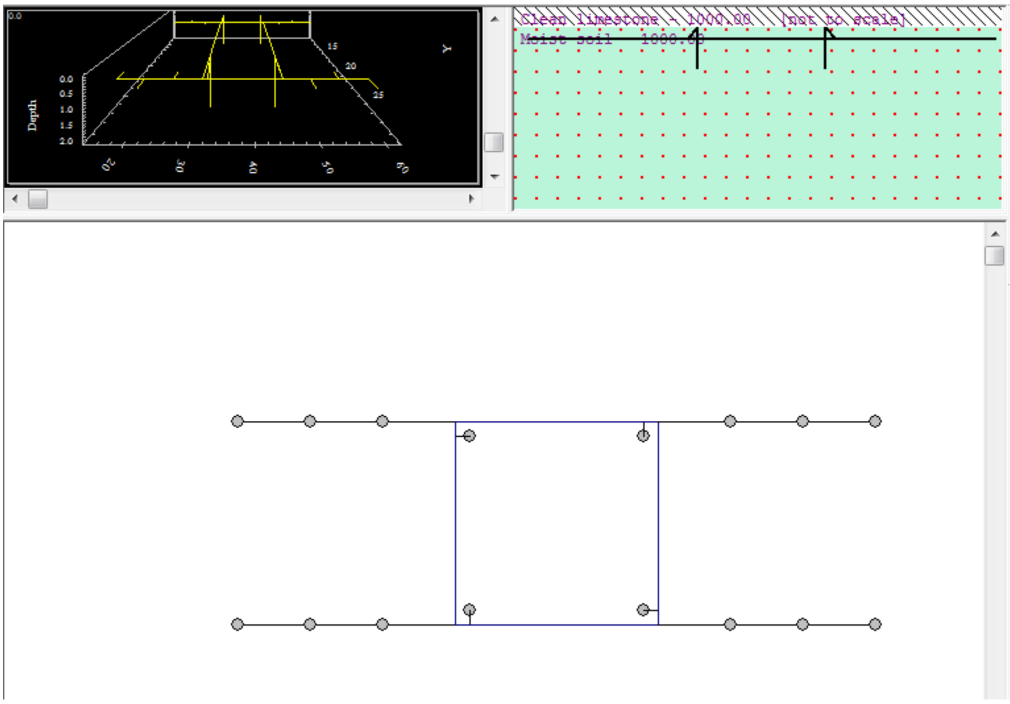


Figure 4.5 Earth Design Model 04

Earth Design Model C5

Eathing design type 5 is for the soil type of having resistivity between 1000 Ωm to 2000 Ωm.

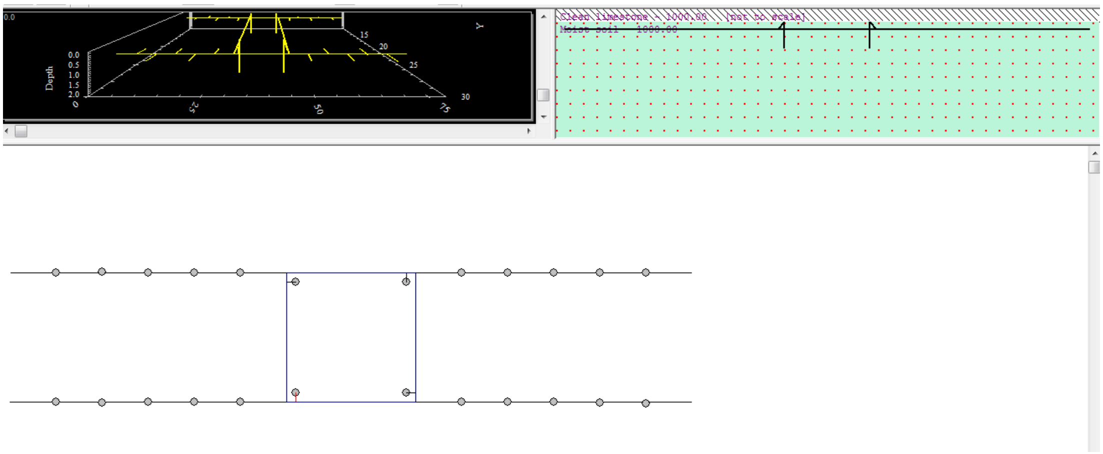


Figure 4.6 Earth Design Model 05

Earth Design Model C6

This is the suitable earthing design for soil type of having soil resistivity of 2000 Ωm to 3000 Ωm.

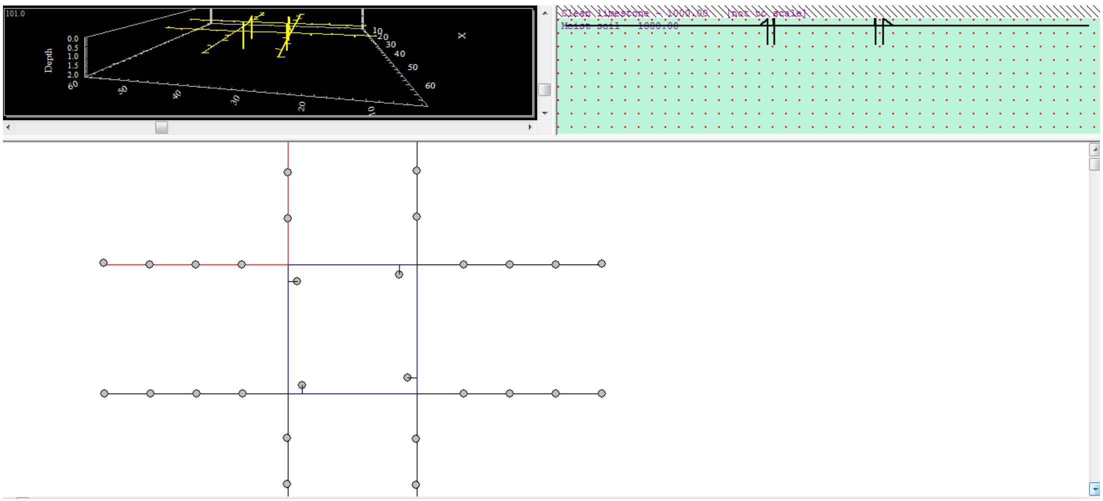


Figure 4.7 Earth Design Model 06

6th Step

6th step was the modeling of earth designs for two layer soil types. The two-layer soil models were categorized as either a high soil resistivity top layer with a lower soil resistivity bottom layer, referred to as 'Hi-Lo' soil model, or a low resistivity top layer with a high resistivity bottom layer, referred to as a 'Lo-Hi' soil model. These models are illustrated in Figure 4.8.

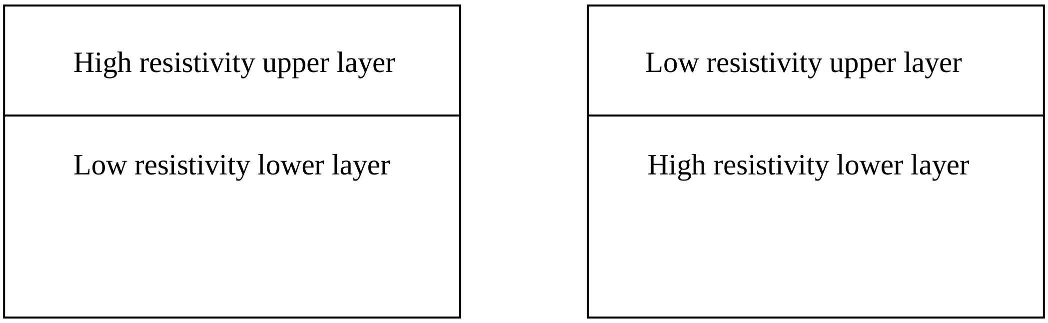


Figure 4.8 Two Layer soil models Hi-Lo Soil Model and Lo-Hi Soil Model respectively

These classifications were intended to provide a balance between technical accuracy and practical application of the design optimisation process. Soils with greater number of layers would need to be approximated to the most suitable two-layer model, depending on the relative layer thickness and resistivities.

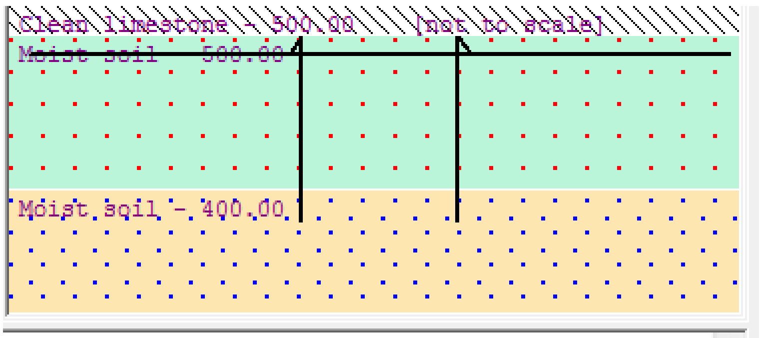


Figure 4.9 Graphical view of two layer soil model

Soil Model	Upper layer soil resistivity (Ωm)	Lower layer soil resistivity (Ωm)
Hi-Lo Soil Model	500	100
Lo-Hi Soil Model	100	500

Table 9 Selected values for two layer soil models

Under above soil categories analysis was done for earth design type C1, C2 and C3. Because other design types are considered for the soil resistivity values above 500 Ωm and ultimate aim was to find the optimum design for the above soil categories from those 3 types.

<u>7th Step</u>

As the final step I prepared a user interface for the selection of appropriate earthing design based on the soil resistivity value of the tower location. All the details tabulated in the following table entered into the Microsoft Excel sheet and then prepared the user interface using VLOOKUP functions.

Resistivity of Soil ρ(Ωm)	Type	A(m^2)	L_T	L_P	h(m)	a(m)	Numb er of ray	Length of ray (m)	Earth rods
$\rho \leq 100$	C1	144	48	48	0.6	12	0	0	0
$100<\rho \leq 300$	C2	336	80	80	0.6	12	4	8	0
$300<\rho \leq 500$	C3	624	128	128	0.6	12	4	20	0
$500<\rho \leq 1000$	C4	504	122.4	108	0.6	12	4	15	12
$1000<\rho \leq 2000$	C5	864	192	168	0.6	12	4	30	20
$2000<\rho \leq 3000$	C6	2704	246.4	208	0.6	12	8	20	32

Table 10 Details for the User Interface

When we obtained the soil resistivity value from site measurements we can entered that resistivity value to the yellow coulor cell and then the program shows that the earthing design type according to the entered soil resistivity value and display the details of the particular earthing design type (A, LT, LP and h). Then calculate the actual earthing resistance value for the selected earthing design type using Thapar-

Gerez equation. Finally display the earthing arrangement details of the selected earthing design type.

Enter Resistivity Value (Ωm)	50

Type	C1
A(m2)	144
L_T	48
L_P	48
h(m)	0.6

Resistance(Ω)	2.562447

a(m)	12
Number of ray	0
Length of ray (m)	0
Earth rods	0

Table 11 User Interface for calculation of earth resistance value

Chapter 5

Results and Analysis

Results obtained from the simulation of earth designs will be discussed in this chapter and further analysis of the thesis. With the completion of earth design modeling it was done simulation and results were recorded in different way for the analysis.

As the first simulation, it was simulated 06 types of earthing designs explained in table 06 of chapter 03 for the total range of soil resistivity values and recorded the earth resistance values with respect to the soil resistivity.

5.1 Simulated values of earth resistance for the selected earth design types

Earthing design types explained in table 06 of chapter 03 were simulated for total range of the soil resistivity values and results obtained for earth resistance values in Ω are tabulated below. Simulation was done for the copper, annealed soft drawn conductor of $50mm^2$. Only considered soil resistivity range from 50 Ωm to 3000 Ωm for the simulation.

Results obtained from simulations are compared with the design values and theoretically calculated values of earth resistance. Theoretical values have been calculated for the highest resistivity value of the particular design type. Therefore comparison was done for only the highest resistivity value of the particular design type.

Earthing Design type	Soil Resistivity ρ(Ωm)																
	50	100	150	200	250	300	400	500	600	700	800	900	1000	1500	2000	2500	3000
C1	2.09	4.18	6.27	8.36	10.45	12.54											
C2	1.54	3.08	4.61	6.15	7.69	9.23	12.31	15.38									
C3	1.06	2.12	3.18	4.25	5.31	6.37	8.49	10.61	12.74	14.86							
C4	1.12	2.24	3.52	4.48	5.63	6.71	8.95	11.19	13.43	15.66	17.90	20.14	22.38				
C5	1.03	1.6	2.82	3.19	3.74	4.79	6.37	7.89	9.12	10.83	12.76	14.36	15.95	23.93	31.9	39.88	47.23
C6	0.92	1.48	2.17	2.96	3.15	4.43	5.68	7.39	8.73	10.06	11.82	13.24	14.78	22.16	29.55	36.94	44.33

Table 12 Simulated results of earth resistance values

Earth Design Type	Soil Resistivity ρ(Ωm)	Power Frequency Resistance (Ω)		
		Design Value	Theoretically Calculated value	Values obtained from the simulation
C1	ρ≤100	10	5.12	4.18
C2	100<ρ≤300	15	9.74	9.23
C3	300<ρ≤500	15	10.9	10.61
C4	500<ρ≤1000	25	24.2	22.38
C5	1000<ρ≤2000	30	27.8	31.9
C6	2000<ρ≤3000	30	29.2	44.33

Table 13 Comparison on design values, simulated values and theoretically calculated values

Results obtained from the simulation of earth model is acceptable for design type C1, C2, C3 and C4 which are having soil resistivity below 1000 Ωm. For the design type C5 and C6 simulated earth resistance values are higher than the designed and the theoretical value.

5.3 Earth Resistance value with respect to the size of the earth conductor

Here the simulations were done for 6 types of earthing designs to see the variation of earth resistance value with respect to the size of the earth grid conductor. Selected conductor is copper, annealed soft drawn conductor and earth rod is 25mm diameter, copper clad steel rod.

	Earth resistance value (Ω)			
Size of the earth conductor (mm^2)	35	50	70	95
Earth design type C1	4.22	4.18	4.14	4.1
Earth design type C2	9.31	9.22	9.13	9.05
Earth design type C3	10.42	10.32	10.23	10.14
Earth design type C4	22.98	22.79	22.6	22.44
Earth design type C5	32.67	32.45	32.31	31.98
Earth design type C6	44.96	44.77	44.47	44.21

Table 14 Earth resistance values vs. size of the earth conductor

It was able to identify that there is no significant change of earth resistance values with respect to size of the earth conductor.

Next simulation was to find the most cost optimum conductor size for each earth design type. It was presented the earth resistance value and cost of the design with respect to the size of the conductor. In this situation it was considered only the cost of the conductor for particular earth design type, because there is no change in size of the earth rod in all earthing design types.

Conductor prices are different from suppler to suppler. It was check the bare copper conductor prices for each size from different suppliers and calculated the average cost of the conductor per meter. Then cost calculation of each design was done on the total conductor length required for the particular design.

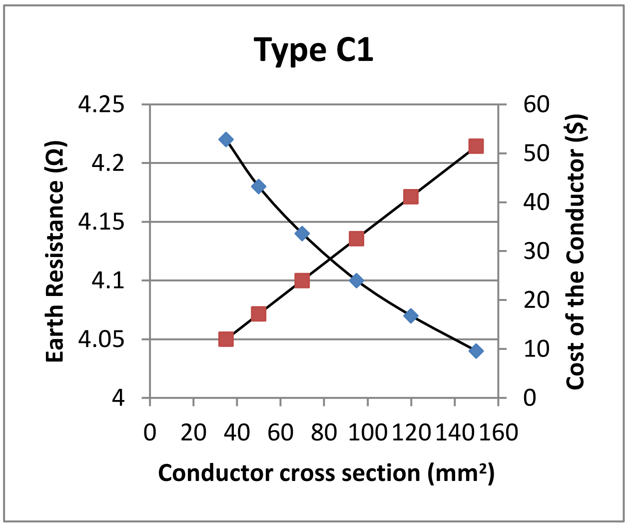
Earth design type	Total length of the conductors (m)	Total length of the earth rods (m)
C1	57	8
C2	89	8
C3	141	8
C4	121	22
C5	181	32
C6	221	47

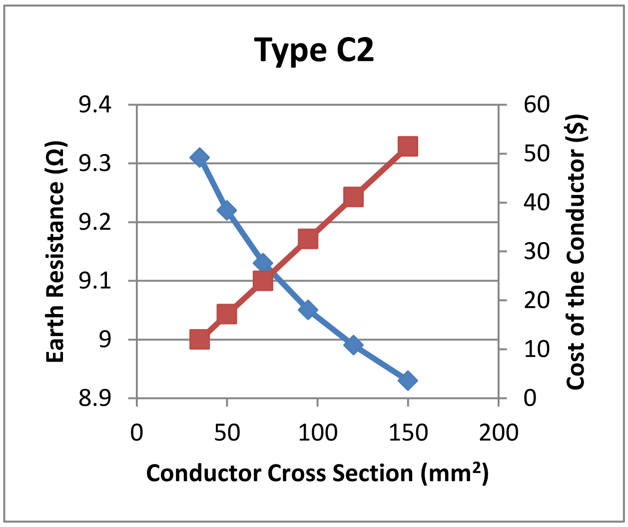
Table 15 Earth grid conductor lengths

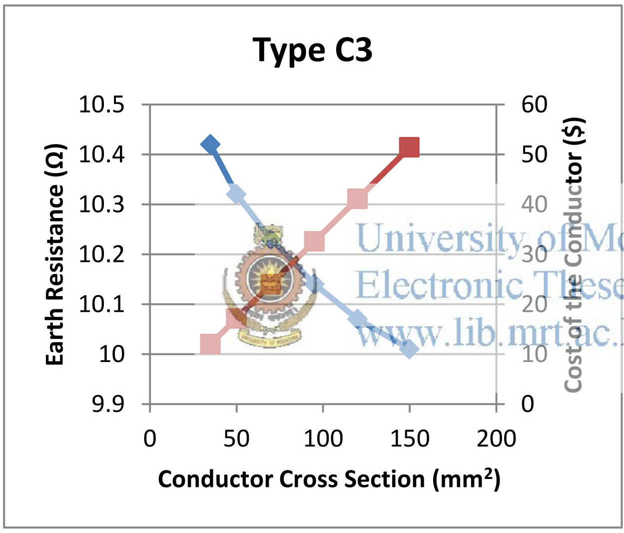
Average cost of the copper, annealed soft drawn conductor is as follows

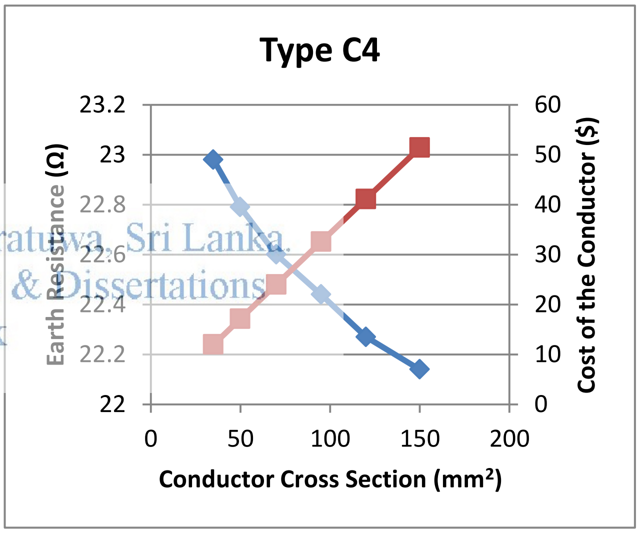
Conductor cross section (mm^2)	Cost per unit length ($)
35	12
50	17.16
70	24
95	32.57
120	41.14
150	51.43

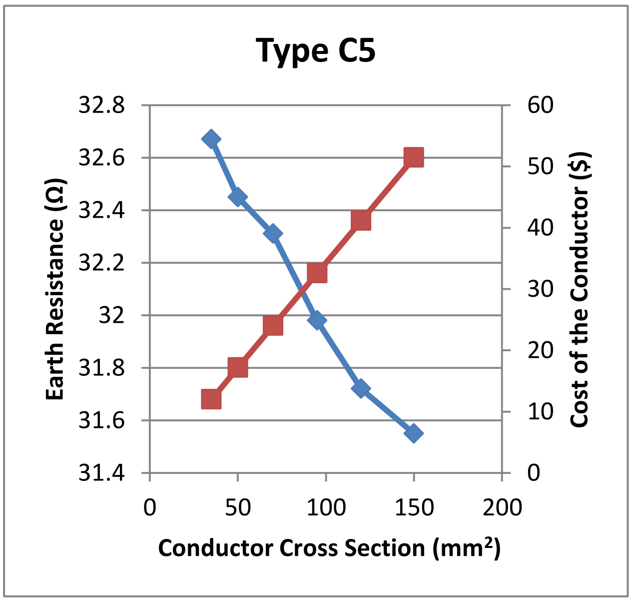
Table 16 Average cost of the copper, annealed soft drawn conductor

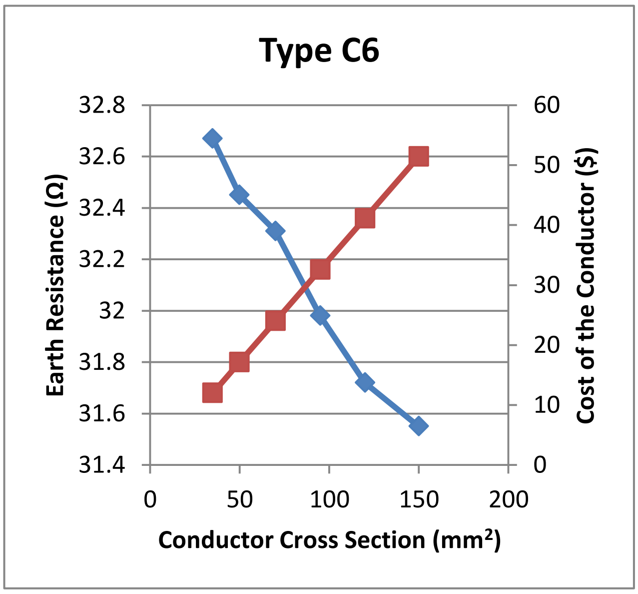












■ Lines are the cost of the conductors required for the particular earthing design and ■ lines are the Earth Resistance values.

Optimum conductor sizes for each design were identified from the above graphs and tabulated in below table for the analysis.

Earthing design type	Optimum Cross section (mm^2) of the earth conductor
C1	80
C2	80
C3	85
C4	85
C5	90
C6	75

Table 17 Optimum Cross section (mm2) of the earth conductor for each design type

5.4 Earth Resistance values with respect to the material of the earth conductor

For the analysis for the change of earth resistance values with the change of earth conductor material, it was simulated each earthing design type using four types of earth conductor materials. Size of the earth conductor is 50 mm^2 for each earthing material.

	Earth resistance value (Ω)			
Earth conductor type	Copper-clad steel wire (40 Sm^{-1})	Copper, annealed soft drawn (100 Sm^{-1})	Copper, commercial hard drawn (97 Sm^{-1})	Alluminium -clad steel wire (20 Sm^{-1})
Earth design type C1	4.18	4.18	4.18	4.18
Earth design type C2	9.23	9.23	9.23	9.23
Earth design type C3	10.61	10.61	10.61	10.61
Earth design type C4	22.38	22.38	22.38	22.38
Earth design type C5	31.9	31.9	31.9	31.9
Earth design type C6	44.33	44.33	44.33	44.33

Table 18 Earth Resistance values vs. Earth conductor type

5.5 Earth Resistance value with respect to the shape of the earth conductor

Two shapes of conductors were selected for this simulation; copper-clad steel wire and copper-clad steel rod with same diameter of 50 mm^2.

	Earth resistance value (Ω)	
Shape of the earth conductor (50 mm^2)	Steel wire	Steel rod
Earth design type C1	4.18	4.18
Earth design type C2	9.23	9.23
Earth design type C3	10.61	10.61
Earth design type C4	22.38	22.38
Earth design type C5	31.9	31.9
Earth design type C6	44.33	44.33

Table 19 Earth resistance values with respect to the shape of earth conductor

Here it is clearly identified again that there is no change of earth grid resistance value with respect to the shape of the earth conductor whether it is wire or rod of the same material.

5.6 Earth resistance value and the cost for each earthing design

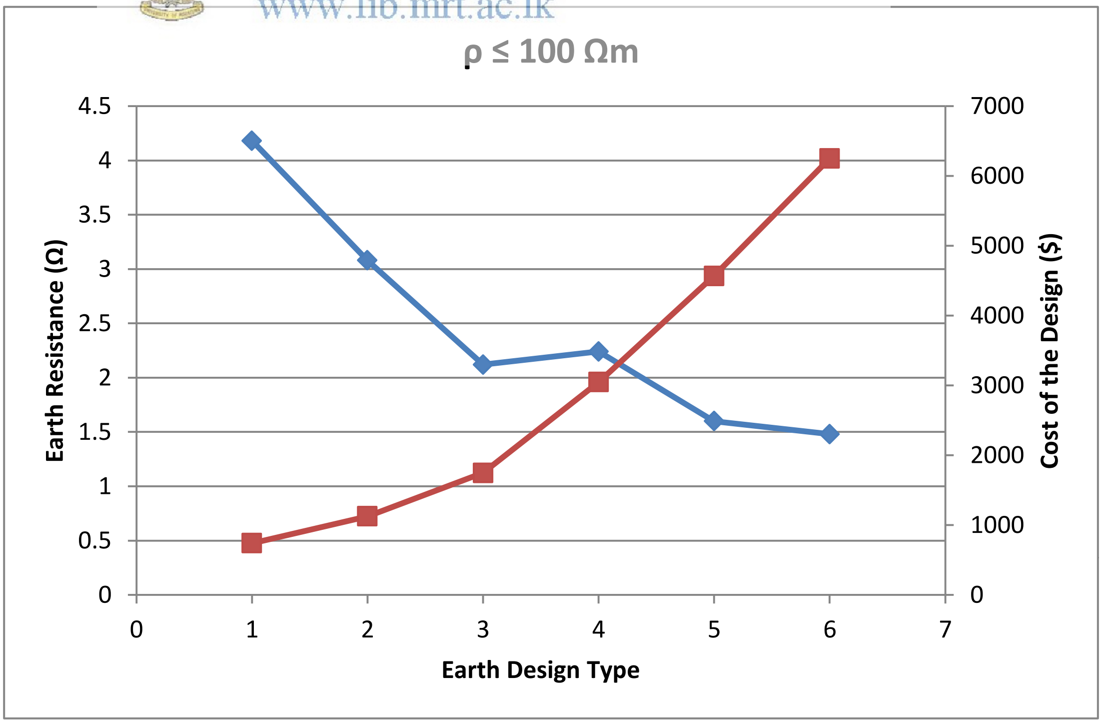
It was listed the earth resistance values according to the soil resistivity values and cost of each design to find the most cost effective earthing design for a selected soil category as mentioned in the above table 10.

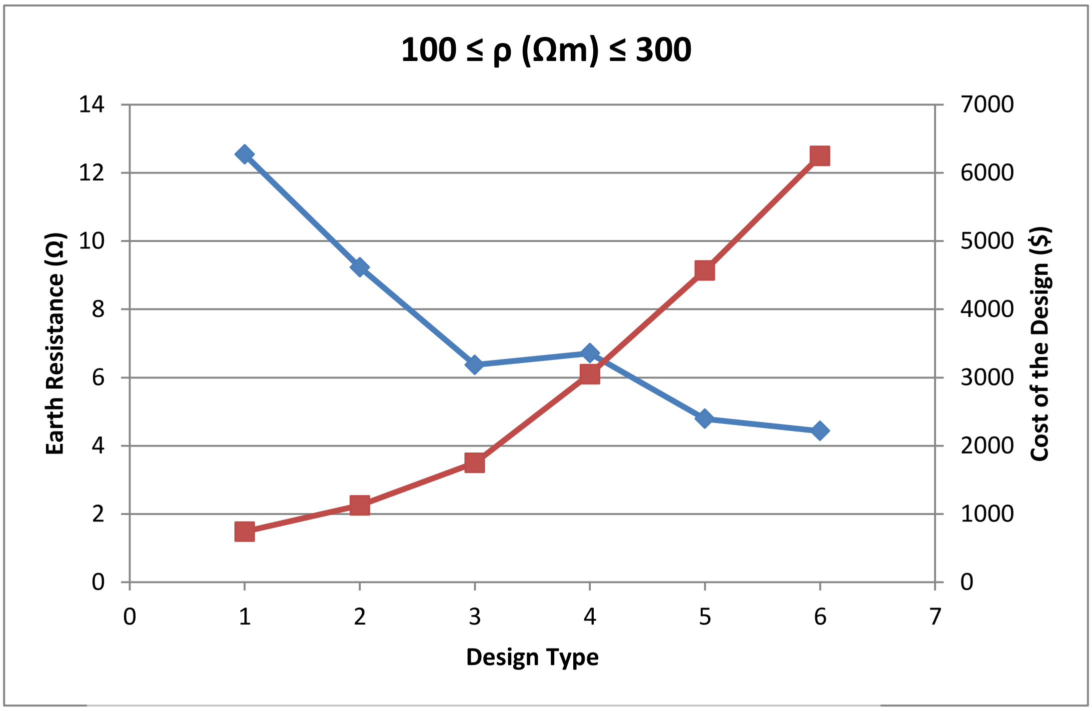
Earth design type	Soil Resistivity values (Ωm)					Cost of the design ($)
	100	300	500	1000	2000	
C1	4.18	12.54	15.38			740
C2	3.08	9.23	10.61			1125
C3	2.12	6.37	11.19	20.02		1748
C4	2.24	6.71	7.89	22.38	44.28	3048
C5	1.6	4.79	7.39	15.95	31.9	4568
C6	1.48	4.43	15.38	14.78	29.55	6248

Table 20 Earth resistance values and cost of each design with respect to soil resistivity values

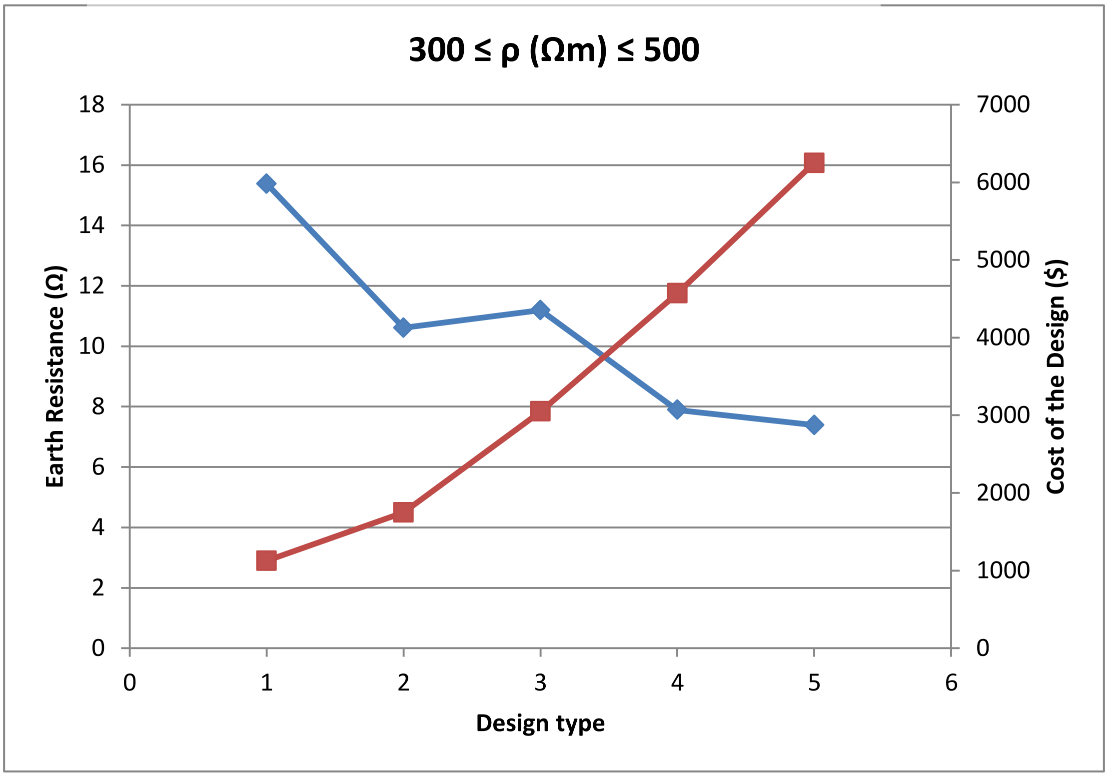
For the analysis of cost optimum earth design for particular soil category, it was presented above data as follows;

Lines are the cost of the earthing design and lines are the Earth Resistance values.

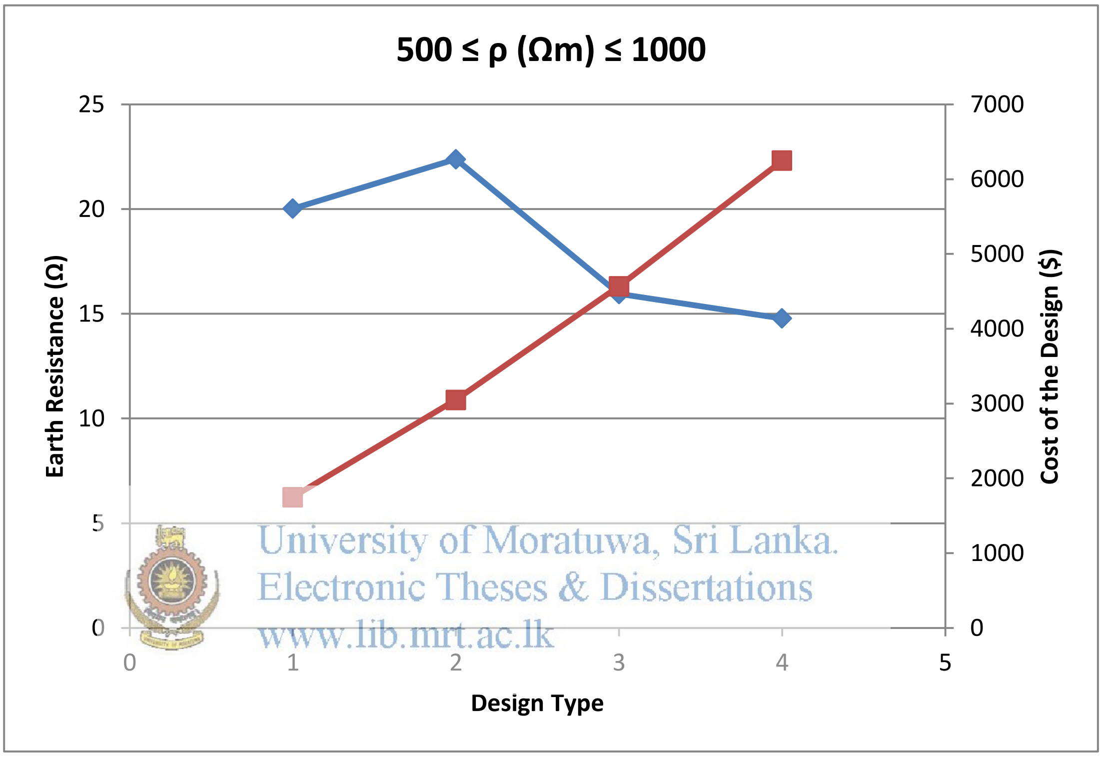




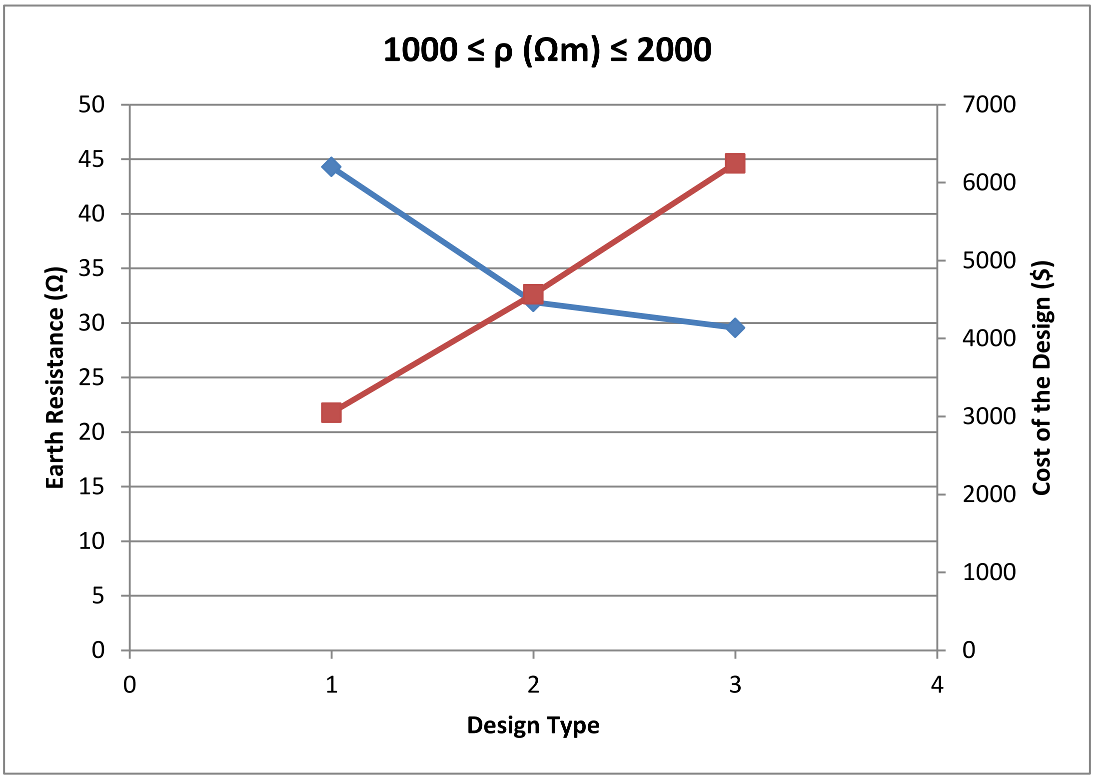
Above graph shows that the cost optimum design for soil resistivity range of 100 Ωm to 300 Ωm is also earthing design type C4.



Above graph shows only design type C2, C3, C4, C5 and C6 for the selected soil category. Under the design type 1,2,3,4 and 5 shows the actual design type C2, C3, C4, C5 and C6 respectively. Here also earthing design type C4 is the cost optimum design for 300 Ωm to 500 Ωm soil category.



Design type 1, 2, 3 and 4 are for the actual design type C3, C4, C5 and C6 respectively. This graph shows that the design type C5 is the cost optimum design for soil resistivity range of 500 Ωm to 1000 Ωm.



For the soil resistivity range of 1000 Ωm to 2000 Ωm considered only design type C4, C5 and C6 for this analysis as shown on the above graph as design type 1, 2 and 3 respectively. Here also we can identify that the design type C5 is the cost optimum design for the soil resistivity range of 1000 Ωm to 2000 Ωm.

5.7 Comparison of the existing tower earthing methods and new earthing design

A comparison was done for currently being used transmission tower earthing methods and newly proposed earthing design from the economical perspective and installation perspectives. Following assumptions were made for the analysis.

1. The selections were done only for soil resistivity range up to 1000 Ωm; because the use of existing tower earthing methods are practically impossible above the soil types having more than 500 Ωm.

2. Cost has been calculated based on the total length of the earthing conductors and earth rods required for the particular earthing method. Earth conductor is copper, annealed soft drawn conductor of $95mm^2$ and earth rod is copper clad steel rod of 25mm diameter.

3. Average cost of the 95mm2 Copper, annealed soft drawn conductor is 32.57 $/m and 25mm diameter, Copper clad steel rod is 13.25 $/m.

4. Here it is considered minimum length required to maintain the earth resistance bellow 10 Ω.

Soil Resistivity category (Ωm)	Single rods driven vertically in to the soil		Horizontal electrodes buried with the surface		Radial Electrodes		New earthing Design	
	Length of the earth rod (m)	**Cost for the earthing ($)**	**Length of the earth conductor (m)**	**Cost for the earthing ($)**	**Length of the earth conductor (m)**	**Cost for the earthing ($)**	**Length of the earth conductor and earth rods (m)**	**Cost for the earthing ($)**
ρ≤100	12.75	169	18	586	30 (6m x5)	977	57, 8	1962
100<ρ≤300	28	371	67	2182	120 (15m x 8)	3098	89,8	3005
300<ρ≤500	78	1034	123	4006	300 (25m x 12)	9771	141,8	4698
500<ρ≤1000	168	2226	265	8631	1000 (50m x 20)	32570	121,22	4232

Table 21 Cost comparison of the conventional earthing arrangements and newly proposed design

1. For the soil type of resistivity below 100 Ωm, single rod driven vertically in to the soil is the most economical method for the tower earthing. But practically it is very difficult to drive a 12m rode in to the soil. In the new design the buried length of the conductor is only 600 mm and just around the tower footing. Therefore there is no difficulty in installation of the conductor. On other hand it is possible to obtain low tower footing resistance value from this new design than the other methds mentioned above.

2. Only considering the cost value of the earthing method, single driven rod is the economical method for soil resistivity range of $100\ \Omega m < \rho \leq 300\ \Omega m$. But as mentioned in the above more compact and the easy installation is the newly introduced method.

3. The new design is more practical, economical and a compact design for soil type which is having $300\ \Omega m < \rho \leq 500\ \Omega m$ soil resistivity.

4. The new design is also more economical and a compact design for soil type which is having soil resistivity from 500 Ωm to 1000 Ωm.

5.8 Touch and step voltages and GPR values

Touch and step voltage values obtained from the simulation are tabulated in the table below. The calculated values of the maximum touch and step voltages are much higher than the tolerable limits.

Design type	Maximum Touch Voltage (V)		Maximum Step Voltage (V)		GPR (V)	Distance to the safe point
	Tolerable	Actual value	Tolerable	Actual value		
Earth design type C1	255.3	7866.4	355.3	6495.9	16452.2	22 m away from the center of the tower
Earth design type C2	321.9	21389.4	621.7	11753.2	36329.9	60 m away from the center of the tower
Earth design type C3	287.1	24514.2	656.2	11241.3	40685.1	70 m away from the center of the tower
Earth design type C4	555.1	52692.6	1554.2	27126.0	89834.6	60 m away from the center of the tower
Earth design type C5	888.1	74900.3	2886.4	34487.5	128014.6	100 m away from the center of the tower
Earth design type C6	1221.2	93123.7	4218.6	38602.5	177894.7	120 m away from the center of the tower

Table 22 Touch and Step Voltages and GPR

Touch and step profiles and the ground potential rise profile of the each type of the design are attached in Annex 01 with the complete report on simulation results.

5.9 Earth resistance values on two layer soil model

As per the soil categories explained in the previous chapter, earth resistance values were obtained for earth design type C1, C2 and C3. Results are shown in the table below.

Earth Design type	Earth Grid Resistance (Ω)	
	Lo-Hi Soil Model	Hi-Lo Soil Model
C1	7	15.45
C2	5.68	10.72
C3	4.21	6.74

Table 23 Earth resistance values for two layer soil models

When considering the Lo-Hi soil model; all the three types of earthing designs are acceptable because of the earth resistance values are below 10 Ω. This is, because the earth grid is laid in the top layer of the soil. For the Hi-Lo soil model, only the earthing design type C3 is acceptable since it is already designed for the uniform soil of having 500 Ωm resistivity.

The next attempt was to reduce the earth grid resistance value of type C1 and C2 further in Hi-Lo soil model by changing the length of the vertical earth rod. Variation of earth resistance with respect to the earth rod length is illustrated here.

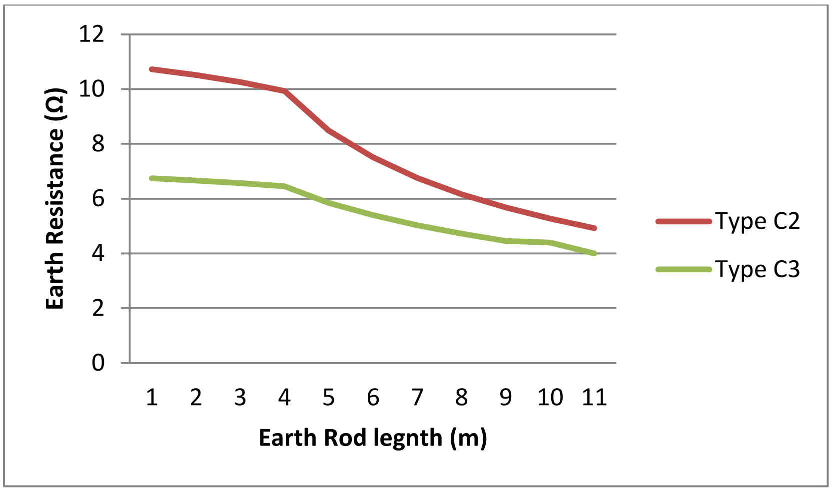


Figure 5.1 Earth Resistance value Vs. earth rod length for two layer soil models

For Hi-Lo soil model type, C2 is giving the low resistance value than type C1. For both types, effective length of the earth rod is more than 4 m. In the next step it was selected type C3 for further analysis of this Hi-Lo soil model for the upper layer soil resistivity value above 500 Ωm. Selected earth rod length is 6m.

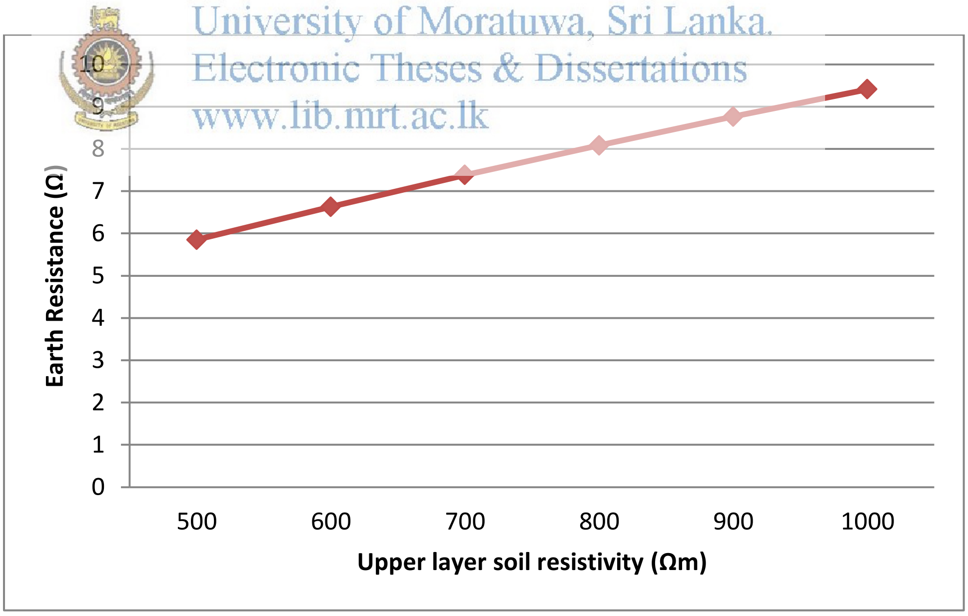


Figure 5.2 Earth Resistance value Vs. upper layer soil resistivity for two layer soil models

Form the values obtained, it is possible to identify that the earth design type C3 can be used for Hi-Lo soil model which is having upper layer soil resistivity up to 1000

Ωm and we can see that the earth resistance will reduce further with the increase of the length of earth rod.

It is also noted that the lower layer soil resistivity can be increased up to 400 Ωm in Hi-Lo soil model for earth design type C3. The values obtained are summarized in following table.

Hi-Lo Soil resistivity (Ωm)	Earth resistance value obtained (Ω)
500 - 100	5.85
500 - 200	7.09
500 - 300	8.17
500 - 400	9.12

Table 24 Earth resistance values for Hi-Lo soil models for design type C3

Chapter 6

Discussion

This chapter is for the discussion on results and analysis of the thesis. The studies carried out to investigate suitable transmission tower earth designs in different soil conditions have been reviewed in this chapter. One of the tower earth designs developed on practical experience has been used for the modeling using ETAP's Ground Grid Design Assessment software. The modeling and analysis of the proposed earthing design was done based on the following assumptions;

1. In the first part of the modeling the soil modeling is done for a uniform soil type and the soil depth is selected as 10m.

2. In the actual scenario, the down riser conductor of the earthing arrangement was connected to the tower stub. But in this software package, it is impossible to model the conductors above the ground level. Therefore down riser conductor has been ended up at the top layer of the surface soil.

3. Connection of earth conductors to earth rods was done using a suitable connector. But in the model it is assumed that the earth rods were directly connected to the earth conductor ray without having such connector as shown in the design illustrated in chapter 03. Here it is assumed that the effect of this connector to the earth resistance is negligible.

4. Short circuit fault level of the transmission line is not a fixed value for every line and it is varying between 3 kA to 25 kA. It was selected an average fault level of 15 kA and the calculated single phase short circuit current is 4 kA.

5. From the simulation it was able to obtain only the power frequency earth resistance value of the earthing design.

Selection of the most suitable software for the modeling was a challenging task. From the literature survey it was found similar kind of researches done previously using different softwares such as PS CAD, Safe Grid, ANSYS Maxwell, ETAP and CDEGS. Unfortunately it was not possible to find a working version of above mentioned software other than PS CAD, ANSYS Maxwell and ETAP. Representation of soil structures is extremely difficult in PS CAD and it is not worth doing this model in PS CAD. Then it was tried with ANSYS Maxwell and it was able to complete the modeling of the design. But the issue was the finding of earth resistance of the model. It was very difficult to find a solution for this problem. Finally earth design modeling and analysis was done using ETAP software.

From the analysis done for each earthing type for soil resistivity range of 0 – 3000 Ωm, it was found that type C1 is giving bellow 10 Ω earth resistance for soil resistivity up to 200 Ωm. Earth design type C2 is acceptable for soil resistivity up to 300 Ωm and for soil type of having 0 to 300 Ωm, design type C2 is better than C1. Earth resistance values are within 10 Ω resistance range up to 500 Ωm soil types. When the soil resistivity is more than 500 Ωm, 10 Ω earth resistance cannot achieved by any of the earth design type modeled in this design. But results obtained from simulation for type C4 and C5 are acceptable when comparing with the design values of 25 Ω and 30 Ω respectively. Earth resistance value obtained for type C6 is higher than the design value of 30 Ω.

Design values of each earthing arrangement are based on the practical experience and it is the maximum power frequency resistance value we can obtained from particular design. Theatrically calculated values are always below than the design values and difference of the design value and the theatrically calculated value is small for the soil types having resistivity above 500 Ωm.

From the results obtained for different conductor sizes we can identified that there is no significant change of the earth resistance value with respect to the size of the earth conductor. Because the conductor size depends on the magnitude of the fault current and the earth resistance value of the particular design type will depend on the conductor arrangement. The conductor size mostly use in Sri Lanka is 95 mm^2 copper stranded conductor for tower earthing. Although the 95 mm^2 copper stranded conductor is acceptable for this design it should be selected the conductor size which is suitable for handling the fault current of the respective transmission line according to the IEEE 80-2000 standard.

From the analysis done for the selection of the most cost optimum conductor size for each design it was found that the 80 mm^2 is the cost optimum conductor size for design type C1 and C2. For design type C3 and C4, 85 mm^2 and for type C5 and C6 size 90 mm^2 and 75 mm^2 are the cost optimum sizes of the earth conductor. But earth conductors are not available in above said sizes in the market. Therefore it is possible to recommend 70 mm^2 or 95 mm^2 conductor as appropriate for all the design types.

There is no change of earth grid resistance with respect to the material of the conductor. In theory it has been proven that the properties of earth conductor material were not considered for the calculation of earth resistance. And also, there is no effect of shape of the earth conductor for the earth resistance value for all earthing design types.

Results obtained from the analysis of cost optimum earth design for different soil categories, show that the earth design type C4 is the cost optimized design for soil resistivity range of 0 Ωm to 500 Ωm. Earth design type C5 is the cost optimum design for 500 Ωm $\leq \rho \leq$ 2000 Ωm soil resistivity range.

From the comparison done on currently being used methods and the newly proposed earthing method, it can be identified that the newly proposed design is more economical and a compact design for all soil categories.

According to comparison carried out on the calculated tolerable limits and the results obtained for touch and step voltages and the ground potential rise values of the earthing designs it can be identified that tower area is not in safe limits and the safe point is far away for the tower base area. Most of the time, transmission line routes are going through nonresidential areas and it is not worth to improve touch and step voltages and the ground potential rise values of the earthing designs.

For the Lo-Hi soil model, all the three types of earthing designs are acceptable since the earth resistance values are below 10 Ω. This is due to the earth grid is laid in the top layer of the soil. For the Hi-Lo soil model, only the earthing design type C3 is acceptable, because it is already designed for the uniform soil type of having 500Ωm resistivity. For Hi-Lo soil model type C2 is giving the low resistance value than the type C3. For both types, effective length of the earth rod is more than 4 m. It is recommended to have about 6m length earth rods for both designs in Hi-Lo soil model.

Design type C3 can be used for Hi-Lo soil model which is having upper layer soil resistivity up to 1000 Ωm and lower layer resistivity up to 400 Ωm. By increasing the earth rod length, the earth resistance will reduce further.

With the use of user interface we can select the earthing design type and the calculated earth resistance value based on the soil resistivity value of the particular tower location easily.

Chapter 7

Conclusion

The purpose of this thesis was to generally examine transmission line tower grounding and grounding techniques; and also how the inferior grounding is affecting to humans and equipment. The study is also included a model of a transmission tower earthing design and the analysis on how this model can be used to find a suitable earth design based on soil resistivity value of the tower location.

Tower earthing is a crucial part of transmission line design and installation. There are many steps in the process of designing a safe and effective tower earthing system. The manual calculation may be very tedious and difficult, thus it may lead to incorrect results. On the other hand, model a theoretical design and find out an equation for the calculation of tower earth resistance is not an easy task and it is more complex. Performing calculation and modification to the design can be a lengthy process. Now the computer programs have been developed to make the earthing design easier and more accurate.

From the results of this study, it can be concluded that grounding is essential for safety of electrical installations. The main objective of grounding is to facilitate to conduct fault currents to ground in a safe and controlled way to avoid risk for humans and equipment. The tower earthing resistance plays a major role in handling the transmission tower fault current under fault conditions as well as on lightning conditions. Improving tower earthing resistance is the key way of avoiding back flashovers in transmission lines. However it is not practical as well as not economical to use the currently used method in Sri Lanka when the towers are located at hilly areas where the soil resistivity is very high. From the proposed new earthing design it is possible to overcome these practical issues, since the design is based on soil structure which is possible to select the most suitable earth design according to the condition of the tower location.

According to the results obtained touch and step voltages and the ground potential rise values of the earthing designs are not in safe limits. High levels of step voltage and GPR depend on soil properties and can be limited by a proper design of grounding electrodes and the area of contact between electrode and soil. By improving the soil condition of the top layer by adding surface material such as crushed rock, gravel, crusher run granite and clean limestone etc. it is possible to reduce the touch voltage limit to the acceptable value. But most of the transmission line routes are running through forest and non-residential areas. Therefore it is not worth and economical to improve touch and step voltages and ground potential rise of the tower surrounding in each tower. When there is a tower located in residential area and it is necessary to maintain the safety limits to avoid risks for personnel and livestock which might come into contact with exposed parts of an electrical system. Therefore a proper grounding design is essential together with fences and other obstructions.

Earth resistance improvement of a transmission line or a tower location is importance in a bad soil conditions, but not economical for each and every case. Before doing a special earthing design to a particular transmission line or a tower location, it is better to have an analysis on the importance of the particular transmission line to the system. It is also necessary to have records on lightning level of that transmission line or line route. After that it is possible to take a decision on improving the tower earthing resistance using special techniques.

Finally, I would like to conclude that the introduction of new earthing system to the transmission line tower speciation is timely appropriate. Procedure for installation of proper tower footing earthing design can be introduced to the specification according to the following steps.

Step 1- Analysis of the fault current of the particular transmission line or obtained the fault level from Transmission Planning Brach.

Step 2 – Select the earth grid conductor size of stranded copper conductor from the calculation using IEEE Standrad 80 Equation 37.

Step 3 – Conduct a soil resistivity measurement of the tower location and model the soil structure using graphical method explained in Chapter 02. For the soil resistivity measurements, Driven Rod (3 Pin) method is more suitable for transmission line structure earthing or areas of difficult terrain.

Step 4 – Select the most suitable earthing design type based on the soil type of the site from the following earthing arrangements.

Resistivity of Soil ρ(Ωm)	Type	a(m)	Number of ray	Length of ray (m)	Earth rods	PFR (Ω)
ρ≤100	C1	12	0	0	0	10
100<ρ≤300	C2	12	4	8	0	15
300<ρ≤500	C3	12	4	20	0	15
500<ρ≤1000	C4	12	4	15	12	20
1000<ρ≤2000	C5	12	4	30	20	30
2000<ρ≤3000	C6	12	8	20	32	30
3000<ρ≤4000	C7	12	8	25	40	30

Table 25 Proposed Tower Earth Designs based on soil types

Counterpoise should be connected to all the tower's four footings. The value of parameter 'a' should be enlarged when the distance of tower footings is large; when the distance is smaller, the value of parameter 'a' should be reduced and the ray should be enlarged.

Depth of Counterpoise 't' is 0.8m for form land and for other arrears it is 0.6m.

Step 5 – Install the tower earthing design and measure the earth resistance value using proper test equipment like high frequency ground tester.

Step 6 – When the earth resistance value is not within acceptable limits, high grounding resistance can be effectively solved by using one of the technique explained under clause 3.4 in this thesis.

Step 7 – It is better to have an earth resistance measurement test of the grounding system after the completion of the total transmission line. Theoretically it has been proven that the surge impedance of the transmission line tower is always lower than the ground resistance value. Therefore if the power frequency earth resistance value is below 10 Ω, performance of the tower under the lightning condition is acceptable.

Other than the above mentioned design steps we can use prepared user interface for the selection of the earthing design type and the calculated earth resistance value based on the soil resistivity value of the particular tower location easily.

Future Works

Performance of this new earthing system has been accomplished by the analytical software model. As the future work of this study, it is required to analyse the performance of the earthing design in practical situations. For this purpose, installation of each earthing design in different soil structures and take the measurements at the site are a necessary requirement.

On the other hand, earth resistance value of the earthing design under fault conditions has been evaluated and it is good to do an analysis on performance of earthing design under lightning condition in future.

Reference

[1] Emma Grubbstrom, “Grounding of a 230kV Transmission Line over a limestone ridge”, A Case Study in Lao P.D.R, UPTEC ES11028, Examensarbete 30hp, 2011.

[2] Ceylon Electricity Board Technical Specification on Transmission Line.

[3] BS EN 62305-3:2011 „Protection against lightning part3: physical damage to structures and life hazard‟European Committee for Electrotechnical Standardization (CENELEC).

[4] IEEE Std. 80-2000 „Guide for Safety in Substation Grounding‟ The Institute of Electrical and Electronic Engineers, New York, 2000.

[5] The New IEEE Standard Dictionary of Electrical and Electronic Terms‖, IEEE Std. 100, USA, 1992.

[6] Vijayaraghavan et al, “Practical Grounding, Bonding, Shielding and Surge Protection”, Elsevier, Oxford, 2004.

[7] VAST, Vattenfalls jordningskomitté: “Jordning av stationer och ställverk-Konstruktionsanvisningar, Mätmetoder.”, Rapport, 1987.

[8] Laughton, M.A, “Electrical Engineer´s Reference Book, 16th Edition, Elsevier, 2003.

[9] Grainger, John J., Stevenson, W. Jr. “Power System Analysis”, McGraw-Hill Inc., Singapore, 1994.

[10] IEEE, “IEEE Guide for Safety in AC Substation Grounding”, IEEE Std. 80-2000, revision of IEEE Std. 80-1986, 2000.

[11] IEEE, “IEEE Guide for Generating Station Grounding”, IEEE Std. 665-1995, revision of IEEE Std. 665-1987, 1996.

[12] ERICO, “Facility Electrical Protection Catalogue”, Catalog E905C-EUEN.

[13] Zipse,”Grounding Methods- A Primer”, Industrial and Commercial Power Systems Technical Conference, IEEE, 2002.

[14] Guldbrand, A., ”Earth Faults in Extensive Cable Networks”, Licentiate Thesis, Department of Measurement Technology and Industrial Electrical Engineering, Lund University, 2009.

[15] Overhead Electrical Lines Exceeding AC 45kV- Part 1: General requirements – Common specifications, BS EN 50341-1:2001 British Standard, 2001.

[16] *IEEE Guide for Safety in AC Substation Grounding*, ANSI/IEEE Standard 80, 1986, 1986.

[17] *Effects of Current on Human Beings and Livestock-Part1:General Aspects*, IEC/TS 60479-1:2005, 2005.

[18] Raytheon Engineers & Constructors, Electric Distribution Systems Engineering Handbook, McGraw Hill, New York, 1994.

[19] K.C.Agrawal, Industrial Engineering and Applications Handbook, Newnes, Great Britain, 2001.

[20] Paul Gill, Electrical Power Equipment Maintenance and Testing, Marcel Dekker, New York, 1998.

[21] IEEE Guide for Safety in AC Substation Grounding‖, IEEE Std. 80, USA, 2000.

[22] J. G. Sverak, ―Simplified Analysis of Electrical Gradients above a Ground Grid; Part I – How good is the present IEEE method?‖ , IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, pp. 7-25, January 1984.

[23] S. J. Schwarz, ―Analytical Expressions for the Resistance of Grounding Systems‖, AIEE Transactions, Vol. 73 part III-B, pp.1011-1016, 1954.

[24] J.A. Güemes, F.E. Hernando, F. Rodrigez, J.M. Ruiz, ―A Practical Approach of Determining the Ground Resistance of Grounding Grids‖, IEEE Transactions on Power Delivery, Vol. 21 No.3, July 2006.

[25] IEEE, "IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems", IEEE Std. 142-2007, revision of IEEE Std. 142-1991, 2007.

[26] Beaty, H. Wayne, Fink, Donald G., "Standard Handbook for Electrical Engineers", 15th Edition, McGraw-Hill Inc., 2007.

[27] Elfving, "ABB Handbok Elkraft", Wallin och Dalholm Tryckeri AB, Lund, 1987.

[28] Svenska Kraftnät, "Technical Guidelines for 400 kV and 200 kV OH-Lines, SvK TR5-13", revision of TR5:113-2000, 2010.

[29] IEEE, "IEEE Standard for Testing and Performance for Optical Ground Wire for Use on Electrical power Lines", IEEE Std. 1138-2009, revision of Std. 1138-1994, 2009.

[30] Cooray, V., "Lightning Protection", Institution of Engineering and Technology, ISBN: 978-0-86341-744-3, 2010.

[31] Overhead Power Lines, Planning, Design, Construction by F. Kiessling, P. Nefzger, J.F Nolasco, U. Kaintzyk.

[32] Research on Reducing Ground resistance of transmission line tower grounding grid, Feng Zhenghua Lu Ling, Feng Junzhong, 2003.

[33] K.S.S. Kumara (year 2009) “Lightning Performance of Sri Lankan Transmission Lines: A Case Study”, MSc Thesis, University of Moratuwa, Sri Lanka.

[34] *IEEE Guide for the Application of Insulation Coordination*, IEEE Std 1313.2-1999, 1999.

[35] T*he Lightning Performance of Transmission Lines*, IEEE Std 1243-1997, 1997.

[36] Working Group on Estimating the Lightning Performance of Transmission Lines, „„IEEE Working group report estimating lightning performance of transmission lines II-updates to analytical models,“““ IEEE Transaction on Power Delivery, vol. 8, No. 3, pp. 1254 – 1267,1993.

[37] James T. Whitehead, „„Lightning performance of TV‟s 500-kV and 161-kV transmission lines,“““ IEEE Transaction on Power Apparatus and Systems, vol. PAS-102, No. 3, pp. 752-768, 1983.

[38] W. A. Chisholm, Y. L. Chow and K. D. Srivastava, „„Travel time of transmission Towers,“““ IEEE Transaction on Power Apparatus and Systems, vol. PAS-104, No. 10, pp. 2922-2928, 1985.

[39] Tomohiro Hayashi, Yukio Mizuno and Katsuhiko Naito, „„Study on transmission- line arresters for tower with high footing resistance,“““ IEEE Transaction on Power Delivery, vol. 23, No. 4, pp. 2456-2460, 2008.

[40] IEEE Guide for protective relay applications to transmission lines, IEEE Std C37.113, 1999.

[41] P. Chowdhuri, S. Li and P. Yan: „„Rigorous analysis of back-flashover outages caused by direct lightning strokes to overhead power lines,"" IEE Proceedings-Generation, Transmission and Distribution, vol. 149, No. 1, pp. 58-65, January 2002.

[42] Takehiko Takahashi and Taro Kawase, „„Calculation of earth resistance for a deep- driven rod in a multi-layer earth structure,"" IEEE Transactions on Power De1ivery, vol. 6, No. 2, pp. 608-614, 1991.

[43] Akihiro Ametani, Tomohiro Chikaraa, Hiroshi Morii and Takashi Kubo, „„Impedance characteristics of grounding electrodes on earth surface,"" Electric Power Systems Research, vol. 85, pp. 38-43, April 2012.

[44] N. A. Abdul Rahman, A. M. Ahmad Marican, A. M. Davies, "Tower earthing design to reduce faults in transmission lines due to lightning", *17th Conference of Electric Power Supply Industry (CEPSI 2008), October 2008, Macao.*