

**TECHNIQUES TO MINIMIZE TRANSFER POTENTIAL  
NEAR THE SUBSTATION BOUNDARIES**

Paragoda Liyanage Supun Bhasura

(168503N)

Thesis/Dissertation submitted in partial fulfilment of the requirements for the degree  
Master of Science in Electrical Engineering

Department of Electrical Engineering

University of Moratuwa

Sri Lanka

May 2021

## **DECLARATION OF THE CANDIDATE AND SUPERVISORS**

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature:

Date: 22/05/2021

P.L.S Bhasura

168503N

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

Signature of the supervisor:

Date: 23/05/2021

**Dr. Asanka S. Rodrigo**

## **ACKNOWLEDGEMENT**

First and foremost I offer my sincerest gratitude to my supervisor, Dr. Asanka Rodrigo, who has supported me throughout my thesis with his patience and knowledge whilst allowing me to work in my own way. His remarkable guidance helped me throughout the research.

Special thanks goes to all the lecturers engaged in the MSc course sessions and research sessions for making our vision broader, providing us with the opportunity to improve our knowledge in various fields and I specially thank Dr. (Mrs.) Rasara Samarasinghe for her guidance on ANSYS Maxwell Software which helped me to complete the modelling part of my research.

It is a great pleasure to remember the kind cooperation of all my superiors at my work place, my colleagues and my friends who have helped me throughout this Post Graduate programme.

Finally, I would like to thank my parents for supporting me throughout my life. Last but not least I would like to thank my wife for always motivating and supporting me throughout this research work.

## **ABSTRACT**

In Sri Lanka, the demand for electricity is growing at a rate of 5-6% each year. Transmission Infrastructure development is an essential task to cater this growing demand. Construction of grid substations and transmission lines are the major projects in transmission infrastructure development. It is very difficult and costly to find suitable lands for construction of grid substations in urban areas such as Colombo and Kandy. The designs of these grid substations are complex and congested, since they are confined to very small land extents.

It is vital to ensure electrical safety in a grid substation. Grid substation grounding system plays a major role in electrical safety. The grid substation grounding system carries the electric current to the earth at normal and faulty conditions. This flow of electric currents into the earth increases the ground potential not only in the premises of the grid substation, but also in the neighboring lands. Grid substation grounding system ensures the minimum grounding resistance, safe step potential and touch potential levels in the premises of the grid substation, but it does not cover the area beyond the boundary of the grid substation.

Soil structure of a land could be with a uniform soil resistivity or non-uniform and when it is non-uniform, it is considered as multiple layered with different soil resistivity in each layer. The flow of current in the earth depends on the resistivity of the soil layers. Accordingly current flow could be outwards from the land extent of the grid substation or to flow downwards from the surface. This behavior has been tested in this research with an artificially introduced vertical layer of Asphalt around the grid substation to reduce the flow of electric currents towards the adjacent lands from the land of the grid substation. The reduction of flow of electric currents in the upper soil layer of the adjacent lands, reduces the ground potential rise and the electric shock hazard beyond the boundary of the grid substation. The results show that with the increase of the depth and width of the vertical Asphalt layer, the ground potential rise of the adjacent land drops and hence the risk of electric shock reduces.

***Keywords:** Grounding, Potential Rise, Reflection Factor, Step Potential.*

# TABLE OF CONTENTS

<b>ACKNOWLEDGEMENT</b> .....	ii
<b>ABSTRACT</b> .....	iii
<b>TABLE OF CONTENTS</b> .....	iv
<b>TABLE OF FIGURES</b> .....	vii
<b>LIST OF TABLES</b> .....	ix
<b>LIST OF ABBREVIATIONS</b> .....	x
<b>CHAPTER 1</b> .....	1
<b>INTRODUCTION</b> .....	1
1.1 Background.....	1
1.2 Objective.....	2
1.3 Problem Statement .....	2
1.4 Motivation .....	2
1.5 Scope of Work .....	3
<b>CHAPTER 2</b> .....	4
<b>LITERATURE REVIEW</b> .....	4
2.1 Grid Substation Grounding.....	4
2.2 Soil Structure .....	5
2.3 Grounding System Design.....	7
2.3.1 Measurement of soil resistance and develop soil resistivity model .....	7
2.3.2 Selection of grounding conductor .....	9
2.3.3 Permissible voltages and body current .....	10
2.4 Ground Potential Rise in Adjacent Lands .....	13
2.5 Risk Minimization Techniques .....	15
2.5.1 Decrease ground resistance.....	15
2.5.2 Satellite grid.....	16
2.5.3 Chemical treatment of soil.....	17
2.6 Grid Substation Fence Grounding.....	17
2.7 Permissible Touch and Step Potential outside the Grid Substation .....	20

<b>CHAPTER 3.....</b>	<b>22</b>
<b>MODELLING CONCEPTUAL GROUNDING SYSTEM.....</b>	<b>22</b>
3.1 ANSYS Maxwell Model .....	22
3.1.1 Soil Model for Substation Grounding System .....	22
3.1.2 Model of Grounding System.....	24
3.1.3 Fault Current .....	25
3.1.4 Simulation Results .....	25
3.1.5 Effect of Different Soil Resistivity.....	27
3.1.6 Effect of Different Relative Permittivity of Soils .....	29
3.2 Presence of Ground Potential Rise beyond the Grounding System .....	32
<b>CHAPTER 4.....</b>	<b>33</b>
<b>GROUNDING SYSTEM OF AN ACTUAL SITE.....</b>	<b>33</b>
4.1 Collection of Site Data .....	33
4.2 ANSYS Maxwell Model for Actual Grid Substation Grounding System .....	35
4.3 Effect of High Resistive Surface Layer .....	38
4.4 Simulation of Actual Grounding System Model.....	39
4.5 Evaluate the Risk in the Area Outside the Grid Substation .....	40
<b>CHAPTER 5.....</b>	<b>43</b>
<b>PROPOSED RISK MINIMIZATION TECHNIQUE .....</b>	<b>43</b>
5.1 Application of the Effect of Reflection Factor for Vertical Layers.....	43
5.2 Simulation for the Different Depths of the Asphalt Layer .....	48
5.3 Simulation for the Different Widths of the Asphalt Layer .....	51
<b>CHAPTER 6.....</b>	<b>54</b>
<b>RESULTS.....</b>	<b>54</b>
6.1 Summary of Simulation Results for Different Depths of the Vertical Asphalt Layer..	54
6.1.1 Drop of Step Potential with the Increase of Depth of Asphalt Layer .....	55
6.2 Summary of Simulation Results for Different Widths of the Vertical Asphalt Layer..	57
<b>CHAPTER 7.....</b>	<b>61</b>
<b>DISCUSSION AND CONCLUSIONS.....</b>	<b>61</b>

5.1	Discussion.....	61
5.2	Conclusion.....	63
5.3	Recommendation .....	63
5.4	Limitations of the Study .....	63
	<b>REFERENCES.....</b>	<b>64</b>

## TABLE OF FIGURES

Figure 1: Basic Shock Situations in a Grid Substation [1] .....	4
Figure 2: Two-Layer Soil Model .....	6
Figure 3: Grounding System in Vertical Two Layer Soil Structure [9] .....	6
Figure 4: Wenner Arrangement for Soil Resistivity Measurement [3] .....	8
Figure 5: Schlumberger–Palmer Arrangement [3].....	9
Figure 6: Exposure to Touch Potential and Step Potential in a Grid Substation .....	11
Figure 7: $C_s$ vs $h_s$ Curve [1] .....	12
Figure 8: Potential Gradient around a Grid Substation [2].....	13
Figure 9: Distortion of Equipotential Lines over a Local Discontinuity of Top Soil Layer ...	14
Figure 10: 3-D Grounding System and Side View of It [10].....	16
Figure 11: Soil Model .....	23
Figure 12: Parameters of Soil Model .....	23
Figure 13: ANSYS Maxwell Test Model .....	24
Figure 14: Parameters of Copper Conductors.....	24
Figure 15: Injecting Test Fault Current .....	25
Figure 16: Voltage Profile of the Test Model.....	26
Figure 17: Hypothetical Lines over the Surface of the Ground Grid .....	26
Figure 18: Ground Potential Rise Plot .....	27
Figure 19: GPR for Soil Resistivity of 150 $\Omega$ -m .....	28
Figure 20: GPR for Soil Resistivity of 87 $\Omega$ -m .....	29
Figure 21: Parameters of Soil Model with Relative Permittivity of 5 .....	30
Figure 22: Voltage Profile of the Soil Model with Relative Permittivity of 5.....	31
Figure 23: GPR Profile along the Same Hypothetical Line (a) $\epsilon_r = 3$ (b) $\epsilon_r = 5$ .....	31
Figure 24: GPR Profile along the Hypothetical Line .....	32
Figure 25: Soil Resistivity Measured Routes of Colombo M Grid Substation.....	33
Figure 26: Graph of Soil Resistivity vs. Electrode Distance .....	34
Figure 27: Soil Model of Colombo M Grid Substation.....	35
Figure 28: Layout and Ground Mesh Plan of Colombo M Grid Substation.....	35
Figure 29: Earth Mesh Model of Colombo M Grid Substation .....	36
Figure 30: The Model of Actual Grounding System.....	37
Figure 31: Ground Potential Rise over the Grounding System .....	37
Figure 32: GPR Profile along a line parallel to X-Axis of the Grounding System Model .....	38
Figure 33: GPR Profile along a line parallel to Y-Axis of the Grounding System Model .....	38
Figure 34: ANSYS Maxwell Model of Grounding System with Surface Layer .....	39
Figure 35: Ground Potential Rise over the Grounding System with Surface Layer .....	39
Figure 36: GPR Profile along a Line Parallel to Y-Axis.....	40
Figure 37: GPR Profile along a Line Parallel to X-Axis.....	40
Figure 38: Potential Gradient beyond the Boundary of Grid Substation.....	41
Figure 39: Grounding System Model with Vertical Asphalt Layer around the Boundary .....	44
Figure 40: Section View of the Vertical Layers .....	44
Figure 41: GPR over the Grounding System with Vertical Asphalt Layer .....	45
Figure 42: GPR Profile along a line parallel to X-Axis with Vertical Asphalt Layer.....	45

Figure 43: Ground Potential Profile and Section of Grounding System .....46

Figure 44: Ground Potential Rise Profile along a Line Parallel to X-Axis .....46

Figure 45: Step Potential at the Boundary of the Grid Substation with Asphalt Layer Depth of 1.2 m .....47

Figure 46: Step Potential with Asphalt Layer Depth of 1.5m.....48

Figure 47: Step Potential with Asphalt Layer Depth of 1.8m.....49

Figure 48: Step Potential with Asphalt Layer Depth of 2.1 m.....49

Figure 49: Step Potential with Asphalt Layer Depth of 2.4m.....50

Figure 50: Step Potential with Asphalt Layer Depth of 2.7m.....50

Figure 51: Step Potential with Asphalt Layer Depth of 3.0m.....51

Figure 52: Ground Potential Profile with Asphalt Layer width of 0.7 m .....51

Figure 53: Ground Potential Profile with Asphalt Layer width of 0.8 m .....52

Figure 54: Ground Potential Profile with Asphalt Layer width of 0.9 m .....52

Figure 55: Ground Potential Profile with Asphalt Layer width of 1.0 m .....53

Figure 56: Step Potential vs. Depth of Asphalt Layer.....54

Figure 57: Percentage Change of Step Potential vs. Depth of Asphalt Layer .....56

Figure 58: Step Potential vs. Width of Asphalt Layer .....58

Figure 59: Percentage Change of Step Potential vs. Width of Asphalt Layer .....59

## LIST OF TABLES

Table 1: Permissible Potentials with and without High Resistive Surface Material .....	20
Table 2: Soil Resistance Measurement of Colombo M Grid Substation .....	34
Table 3: Parameters for Modelling Colombo M Grid Substation .....	36
Table 4: Parameters for Surface Layer .....	39
Table 5: Step Potential at the Boundary of the Grid Substation for Different Depths of Asphalt Layer .....	54
Table 6: The percentage change of step potential with the increase of the depth of Asphalt layer.....	56
Table 7: Step Potential at the Boundary of the Grid Substation for Different Widths of Asphalt Layer .....	57
Table 8: The Percentage Change of Step Potential with the Increase of the Width of the Asphalt Layer .....	58

## **LIST OF ABBREVIATIONS**

- AC : Alternating Current  
CEB : Ceylon Electricity Board  
GPR : Ground Potential Rise  
GSS : Grid Substation

### 1.1 Background

The Ceylon Electricity Board (CEB) is the national utility responsible for the generation, transmission and a major portion of distribution of electrical power in Sri Lanka. The growing demand for electricity in the Island is at a rate of about 5-6% per annum. Power generation and transmission capacity have to be re-enforced and strengthened to cater the growing electricity demand. The CEB carries out Long Term Transmission Development studies mainly, based on the National Load Forecast, Long Term Generation Expansion Plan and Medium Voltage Distribution Development Studies.

At present there are several infrastructure and economic development projects are being carried out and planned to be carried out in major cities in addition to the normal increase in demand for electricity. The utility infrastructure development is essential to cater the growing demand for electricity. Construction of grid substations is a major task in utility infrastructure development. Electrical safety is one of the major aspect which is considered by the grid substation design engineers. Grid substation grounding system ensures the safety of the equipment as well as the personnel working in the grid substation.

In the urban areas, the value of lands and scarcity of lands cause the designers to develop compact designs using Gas Insulated Switchgears. In such cases, the design of the grid substation grounding system is also a challenging task. However, though it is possible to ensure the safety of the premises of the grid substation, the adjacent lands of the grid substation could be vulnerable of a shock hazard.

## **1.2 Objective**

The objective of this research is to introduce a method to minimize the shock hazard to people in the vicinity of the grid substations in the urban areas, while ensuring the safety within the grid substation premises.

## **1.3 Problem Statement**

The grounding system of the grid substation provides protection from touch and step potential hazard to the personnel working in the grid substation. The adjacent outer perimeter of the fence of the grid substation is not safe due to high Ground Potential Rise (GPR) and a person touching the fence is vulnerable of touch potential hazard. In case, where sufficient land area is available for construction of grid substation, a restricted land strip is maintained along the perimeter of the grid substation. This area is covered with barbed wire fence and chain link fence. Also the grid substation grounding system can be extended out from the chain link fence which avoids touch potential hazard to the personnel enters into the restricted area for special requirements. But in the urban areas we cannot maintain such a restricted land around the grid substation due to scarcity of lands and the value of the lands. The higher fault levels of these grid substations cause the high ground potential rise. The fault current propagation could result in risk of step potential adjacent area around the outer perimeter of the grid substation.

There could be a lane, school, hospital or any other place with high presence of people next to the grid substation. Therefore we need to ensure the safety of the outer perimeter of these substation.

## **1.4 Motivation**

Grounding design of grid substations in urban areas is widely in discussion in the scope of grid substation construction projects. Installation of grounding system in a limited area and higher fault levels in these grid substations make the grounding design very complex and costly. In addition, it is necessary to ensure the safety of the lands in the vicinity of the grid substation. In recent projects of Ceylon Electricity Boards, various options were considered for this problem when arises. This situation highly motivated

me to initiate this research “Techniques to Minimize Transfer Potential near the Substation Boundaries”.

### **1.5 Scope of Work**

Scope of work is as follows.

- Studying the literatures on the same research area.
- Collecting site data of the soil condition and fault levels of grid substations.
- Analyzing the data to develop soil models.
- Developing the conceptual grounding design using ANSYS Maxwell software.
- Developing the actual grounding design using ANSYS Maxwell software.
- Evaluate the ground potential rise and the effect of high resistive surface layer with simulation results.
- Evaluate the risk on the adjacent lands of the grid substation using software model.
- Model the vertical high resistive (asphalt) layer around the grid substation boundary.
- Evaluate the ground potential rise with the vertical asphalt layer.
- Examine the effect of increase of depth and width of the vertical asphalt layer.

**2.1 Grid Substation Grounding**

The purpose of the grid substation grounding system is to provide safe grounding to the grid substation. The objectives of grid substation grounding are ensure safety of people in the grid substation by reducing the risk of exposing into the danger of critical electric shock and ensure the safety of equipment by carrying electric currents into the earth at normal and fault conditions without exceeding the equipment and operating limits and without severely interrupting continuity of electricity supply.

At a classic ground fault, the flow of fault current in to the earth will generate potential gradients in the grid substation premises and around it in the neighboring land. In Figure 1, the basic shock situations which can be occurred in and around a grid substation has been illustrated.

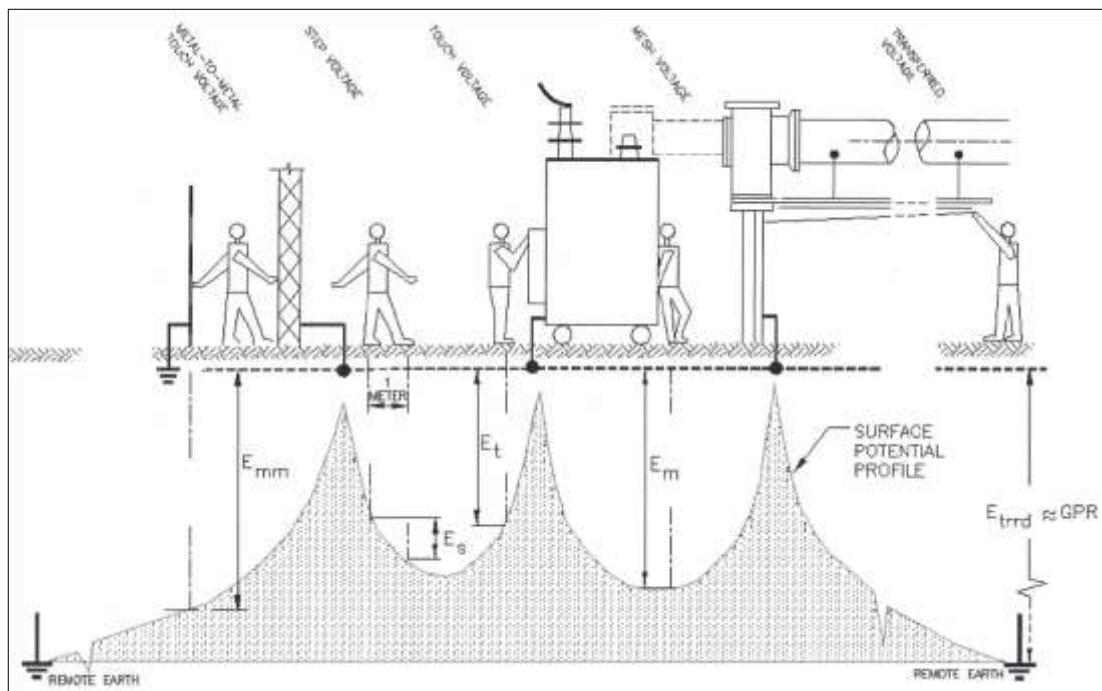


Figure 1: Basic Shock Situations in a Grid Substation [1]

Design of a grid substation grounding system is mainly based on the site parameters which are, land area allocated for construction of grid substation and soil resistivity.

The surface layer resistivity and thickness, installation depth of earth mesh, ground grid conductor size and number of earth rods are based on the design and calculations. Earth fault current and duration depends on the fault level of the particular grid substation.

The ground grid conductor size, riser size, ground grid resistance, maximum grid current and GPR, maximum permissible step voltage and touch voltage of the site can be calculated according to the “IEEE Guide for Safety in AC Substation Grounding”. The maximum step voltage and touch voltages of the designed grounding grid can be calculated according to the same IEEE Guide and shall be compared with the allowable step voltage and touch voltage. In a safe grounding system, step voltage and touch voltage of the designed grid should be less than the maximum permissible step voltage and touch voltage limits.

## **2.2 Soil Structure**

The model of soil resistivity structure of a selected land for construction of grid substation is required to design the grounding system of the grid substation. Most of the soils act as conductors and as dielectrics. However, except for very high frequency and steep-front wave forms, the charging current is insignificant compared to the leakage current. Therefore, the soil structure can be represented as a pure resistance. The results of soil resistivity measurements carried out in the site are used to approximate the model of the soil resistivity structure of the selected land. The factors like temperature, the amount of soluble such as salts, alkalis, acids and moisture content affect the soil resistivity of a selected land. The actual soil structure is normally non-uniform and in the scope of grid substation grounding design, non-uniform soil structures are considered as a two-layer soil model [1]. In Figure 2, a two layer soil model has been illustrated, which is having different soil resistivity in each layer.

The relationship between the soil resistivity and the current flow of a two-layer soil model can be elaborate with the term reflection factor (K).

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

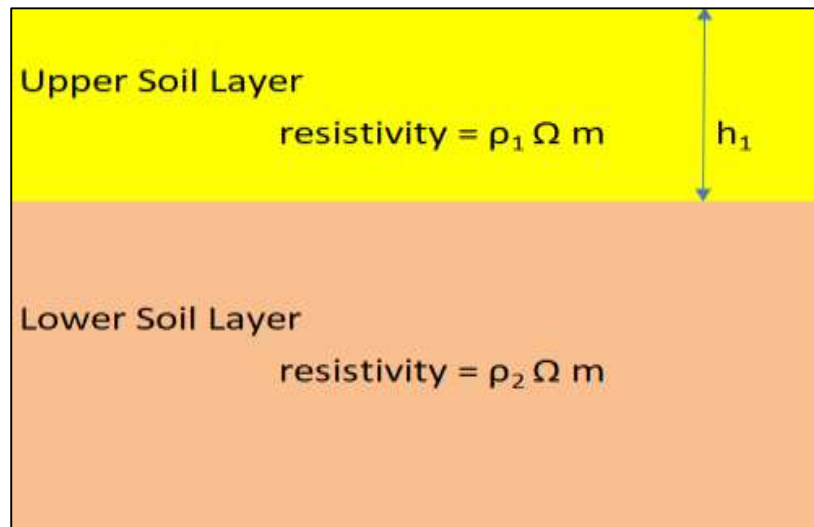


Figure 2: Two-Layer Soil Model

If the resistivity of the upper soil layer is larger than the bottom soil layer ( $K < 0$ ) the injected ground current tends to flow downward and the converse ( $K > 0$ ) the current tends to flow outwards in upper layer [2].

A high resistive material is laid on the surface of the grid substation grounding system so that it increases the contact resistance between the human foot and the earth, and also the negative  $K$  factor forces the current to flow downwards.

In most of the practical cases the two horizontal soil layers come in to picture. However there are instances where the grid substation earthing designs have to be performed for two vertical soil layers as shown in Figure 3.

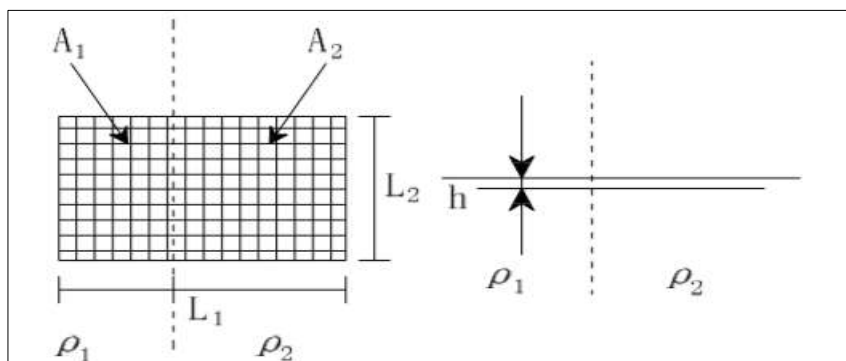


Figure 3: Grounding System in Vertical Two Layer Soil Structure [9]

In [9], it has been discussed on designing grounding systems for vertical two layer soils and worked out engineering equation for calculation of resistance of a grounding grid in vertical two layer soil. The design and validation has been performed using CDGES software.

### **2.3 Grounding System Design**

The grid substation grounding system mainly comprises with earth mesh, risers and rods. The design of the grounding system includes selection of conductor size, spacing of the conductors of the earth mesh and number of rods.

#### **2.3.1 Measurement of soil resistance and develop soil resistivity model**

The soil resistance measurement is required to carry out in order to estimate the soil resistivity structure in a proposed land for construction of grid substation. The ground resistance of a grounding system depends on the resistivity of the soil structure, amount of buried conductors, configuration and extent of the earthing conductors. There are several methods to carry out soil resistance measurement.

- **Variation of depth method or three-point method**

In this method, series of ground resistance measurements are taken increasing the depth of the ground rod. During the test, it applies test currents to deep soil and the measurement can be used to obtain apparent resistivity values for each depth of the rod.

Using ground rods for the ground resistant measurements have important advantages,

- Simplicity in calculating
- Can experience the depth which the rods can reach during the actual installation

The disadvantage of using the ground rod is, it might contact poorly with the soil due to vibration during its driven to deep soil resulting low accuracy level.

Using this method, information on the nature of the soil can be obtained. But for a larger and deeper area, this method is not suitable as several rod locations will give significant variations in ground rod resistance.

- **Four-point method**

This method can be used for measuring apparent resistivity in larger and deeper area. In this method, four auxiliary probes are installed on the earth maintaining same spacing in a straight line and same depth. A test current is applied between the outer probes and the voltage is measured between the inner probes. Then the resistance can be obtained with Voltage/ Current ratio.

In Four-point method, there are two different arrangements.

1. Equally Spaced or Wenner Arrangement

Four probes are equally spaced with ‘a’ distancing and the each probe has been driven to a depth ‘b’ as shown in Figure 4.

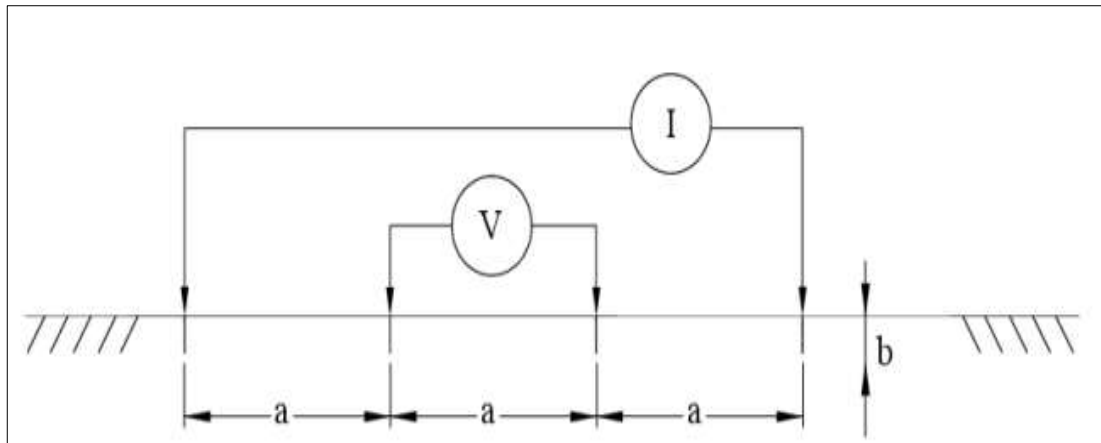


Figure 4: Wenner Arrangement for Soil Resistivity Measurement [3]

Then following equation can be used to calculate the apparent resistivity ( $\rho$ ) [3].

$$\rho = \frac{4\pi aR}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}}$$

Theoretically, these electrodes should be point contacts or they should be hemispherical electrodes with a radius ‘b’. But practically, the electrodes are positioned with equal spacing, ‘a’ and the depth is less than ‘0.1a’ assuming  $b = 0$ . Then the above equation simplifies as follows.

$$\rho = 2\pi aR$$

The approximate apparent soil resistivity for a depth 'a' can be obtained.

Disadvantages of this method are,

- There is a steep drop in potential between inner electrodes when the spacing is larger.
- Repositioning is required for each depth to be measured.

## 2. Unequally Spaced or Schlumberger–Palmer Arrangement

In Schlumberger–Palmer Arrangement, the inner electrodes are placed closer and the outer probes are placed apart from each other as shown in Figure 5.

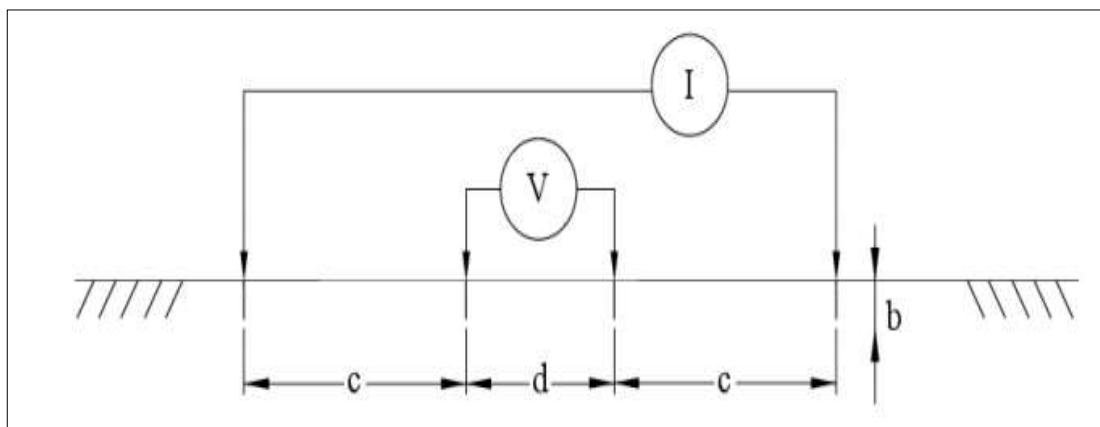


Figure 5: Schlumberger–Palmer Arrangement [3]

The advantage of this method is, not necessary for repositioning of all probes and only required to change the outer probes. Therefore, this method is faster than three-point method for testing different depths.

If the depth of the probe, 'b' is smaller compared to 'c' and 'd' and if  $c > 2d$ , the equation for calculating apparent resistivity is shown below [3].

$$\rho = \frac{\pi c (c + d) R}{d}$$

### 2.3.2 Selection of grounding conductor

Selection of correct conductor material and conductor size for a grounding system is crucial in achieving required performance of the grounding system. In practice, copper

or copper clad steel use as the grounding conductor material. This choice has been attained considering multiple aspects such as high conductivity, resistance to fusing, mechanical strength and performance under corrosion of the conductor. The size of the ground conductor depends on the magnitude of fault current, fault duration, thermal and electrical properties of the conductor material.

The following equation is used in calculating conductor size. [1]

$$I = A_{mm^2} \sqrt{\left(\frac{TACP \times 10^{-4}}{t_c \alpha_r \rho_r}\right) \ln\left(\frac{K_0 + T_m}{K_0 + T_a}\right)}$$

$I$  fault current in kA

$A_{mm^2}$  size of the conductor in mm<sup>2</sup>

$K_0$   $1/\alpha_0$

$T_m$  maximum permissible temperature in °C

$T_a$  ambient temperature in °C

$T_r$  reference temperature for material constants in °C

$\alpha_0$  thermal coefficient of resistivity at 0 °C in 1/°C

$\alpha_r$  thermal coefficient of resistivity at reference temperature °C in 1/°C

$\rho_r$  the resistivity of the conductor at reference temperature in  $\mu\Omega\text{-cm}$

$t_c$  duration in s

$TACP$  thermal capacity per unit volume in  $\text{J/cm}^3 \cdot \text{°C}$

### 2.3.3 Permissible voltages and body current

A person working in a grid substation could be exposed to risk of higher voltages and subsequent body current at a fault condition in the grid substation. Exposing into higher voltages can be touch potential or step potential.

Touch Potential is the potential difference between the GPR of the grounding system and the surface potential of a point where a person standing on while touching a grounded structure at the same time. Step potential is the surface potential difference which is exposed by a person who bridges one meter distance with his feet. These two shock situations are illustrated in the Figure 6.

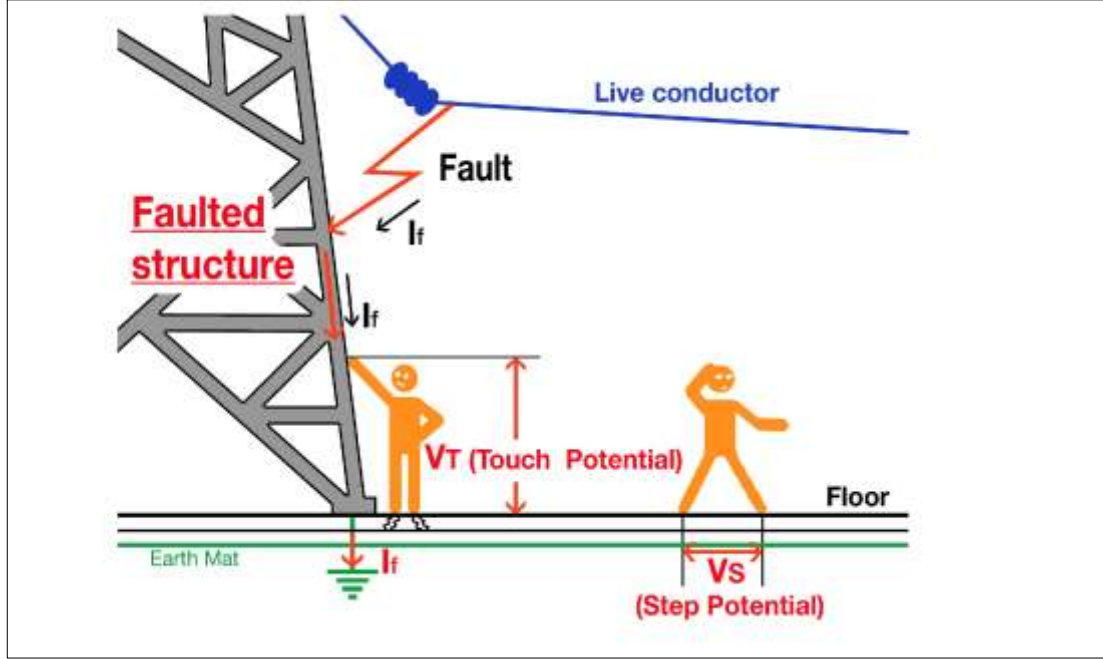


Figure 6: Exposure to Touch Potential and Step Potential in a Grid Substation

The maximum permissible touch potential and step potential for a person with a body weight of 50 kg can be calculated from the following equations.

$$E_{touch_{50}} = (R_B + 1.5C_s \times \rho_s) \times I_B$$

$$E_{step_{50}} = (R_B + 6C_s \times \rho_s) \times I_B$$

Where  $R_B$  is the body resistance which is equal to  $1000 \Omega$ ,  $\rho_s$  is the surface material resistivity and  $I_B$  is the permissible body current limit which is denoted by the following equation.

$$I_B = \frac{k}{\sqrt{t_s}}$$

Where,  $k = 0.116A$  for a person with a weight of 50 kg and  $k = 0.157A$  for person with a weight of 70kg and  $t_s$  is the shock duration. The value of  $k$  has been derived by  $k = \sqrt{S_B}$ , the empirical constant related to electric shock energy tolerated by 99.5% of persons of particular body weight without ventricular fibrillation.

$C_s$  is the surface layer derating factor which is given by following equation.

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

Where  $\rho$  is the resistivity of the soil beneath the surface material,  $h_s$  is the surface material thickness.

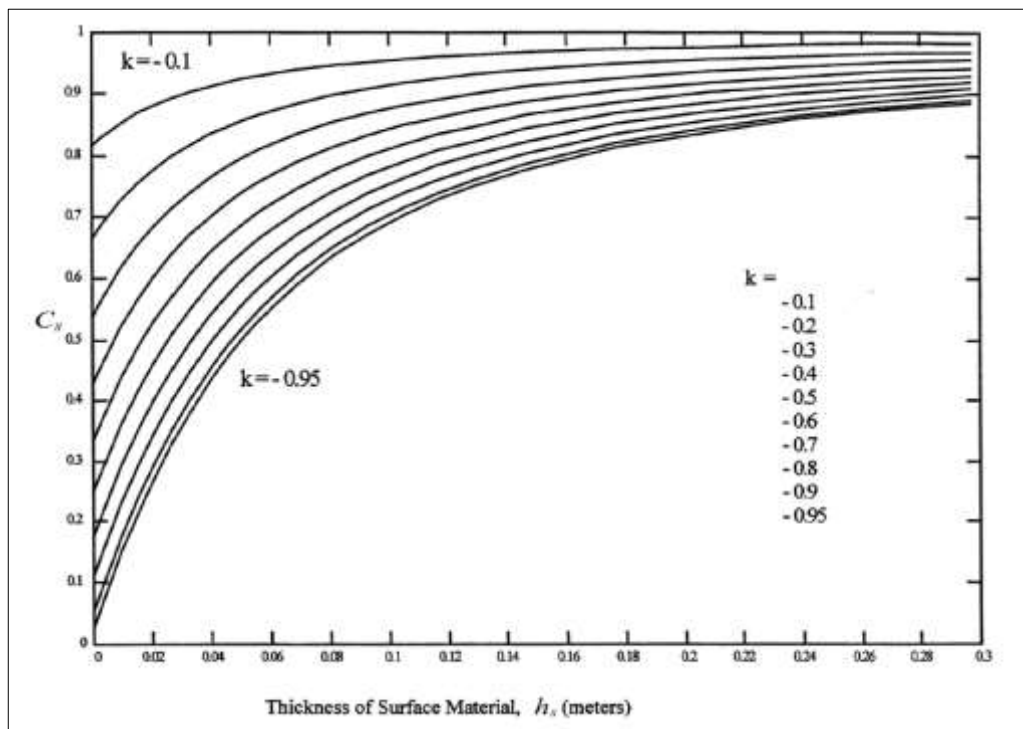


Figure 7:  $C_s$  vs  $h_s$  Curve [1]

The surface layer derating factor represents the effect of surface material laid on the surface of the land. It is used as a correction factor on actual foot resistance. In practice the material used for surface layer is a high resistive material, which increases the contact resistance between the soil and the foot of the personnel in the grid substation. Since the surface layer material resistivity is higher than the upper layer soil resistivity,

the reflection factor between these two layers is larger than zero ( $K < 0$ ), which results in a major portion of ground current to flow outwards in the soil layer [1]. The relationship between the thickness of the surface layer, surface layer derating factor and the reflection factor is shown in Figure 7 which has been developed using computer models.

## 2.4 Ground Potential Rise in Adjacent Lands

The grid substations in urban areas have been built in small land plots with congested designs and are very close to the residential or commercial areas with high presence of people. The grounding design of grid substations in the urban areas must consider not only the safety of personnel of the grid substation but also the safety of people against hazardous touch voltage and step voltage immediately outside the boundary wall of the grid substation. In order to protect public close to the boundary wall (or the fence) of the grid substation, the floor outside the grid station must be paved with high resistive material. [4]

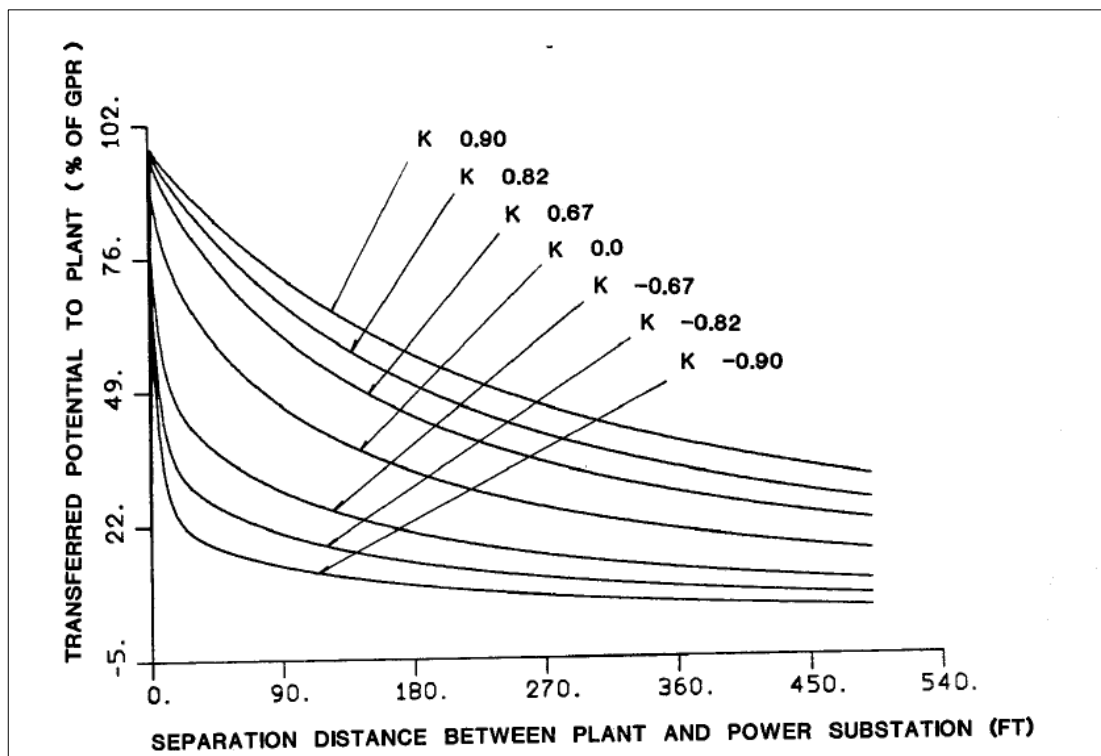


Figure 8: Potential Gradient around a Grid Substation [2]

The soil in the vicinity of the grid substation gets a fraction of the ground potential rise of the grid substation. This measured ground potential rise drops with the distance from the grid substation. If the soil in the upper layer is having a higher resistivity than the soil in the bottom layer, the ground potential drops rapidly. [5]

The computer simulations have performed to develop chart shown in the Figure 8 to illustrate the transfer potential to grounding system of a plant due to rise of ground potential in a neighboring grid substation. The percentage of the transferred potential increases with the increase of “K factor”. According to the chart, the gradient of drop of percentage amount of transferred potential drop is higher at the area close proximity to the grid substation [2].

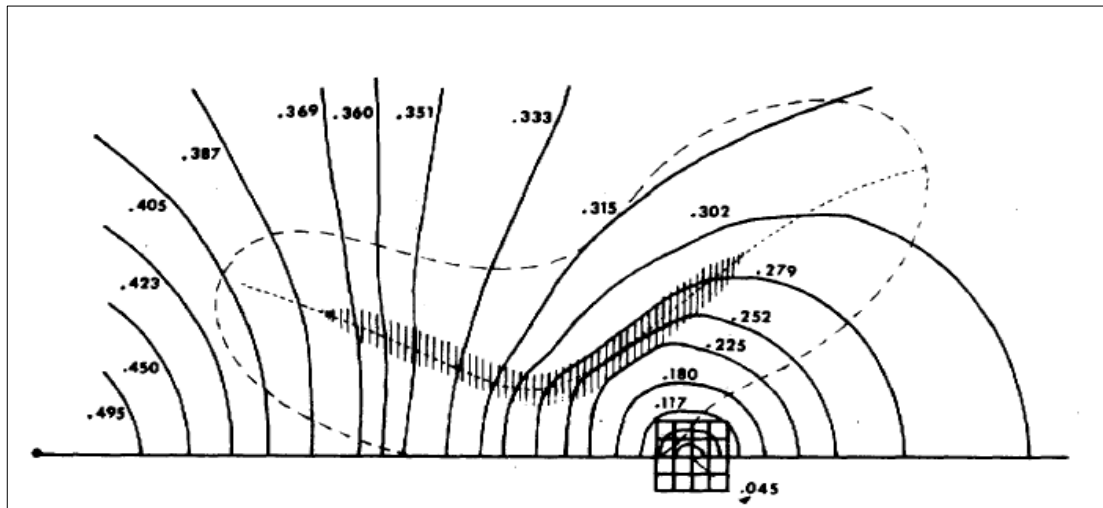


Figure 9: Distortion of Equipotential Lines over a Local Discontinuity of Top Soil Layer

The distribution of ground potential rise can be illustrate using equipotential lines. Considering the earthing mesh as a single ground electrode the equipotential lines, the form of equipotential lines follows the shape of the ground electrode that is earthing mesh in close proximity up to around three to four times of the maximum electrode dimension, the equipotential lines are in identical pattern and beyond the said distance the equipotential lines forms a hemispheric pattern. In close proximity to the earthing mesh, the potential gradient depends only on the resistivity of the top soil as in most of the cases the earthing mesh lies in the top soil layer. The discontinuities of the soil resistivity of the top soil layer due to local variations such as foreign bodies with

different resistivity, causes variations in equipotential lines, however the general pattern remains the same as shown in Figure 9. If the local discontinuity exhibits higher resistivity than the top soil layer, the potential gradient increases over the object causes the discontinuity. [8]

## **2.5 Risk Minimization Techniques**

The design of grounding system of a grid substation requires careful analysis of the soil structure, available space, design of the foundations and maximum fault current. In grid substation construction projects, it could be difficult or impossible to achieve the required safety levels with the traditional methods. There are some site techniques which are used in grid substation construction projects.

### **2.5.1 Decrease ground resistance**

The soil resistivity of the selected site for construction of a grid substation is very important parameter in design of the grid substation grounding system. In areas with higher soil resistivity, it is much difficult to achieve the required levels safe step and touch voltages. The resistance of a grounding system placed in a uniform soil structure can be represented from following formula.

$$R_g = \frac{\rho}{4} \sqrt{\frac{\pi}{A}} \quad [1]$$

$R_g$  - Ground resistance of the grid substation

$\rho$  - Soil resistivity

$A$  - Area of the ground grid

Assuming the required ground resistance is  $0.5\Omega$ , the above formula can be simplified as,

$$A \cong \rho^2$$

According to the above simplified formula, if the soil resistivity is  $200 \Omega.m$ , the approximate area required for the grid substation grounding system is in the range of

$200 \times 200 \text{ m}^2$ , which is nearly ten acres extent. If the soil resistivity is  $1000 \Omega \cdot \text{m}$ , the area required for grounding system is in the range of  $1000 \times 1000 \text{ m}^2$ . This is not practical as the area allocated for grid substations area very limited. Therefore, to achieve the lower ground resistance in high resistive soil structures, the grid substation grounding system is required to extend downward in the soil.

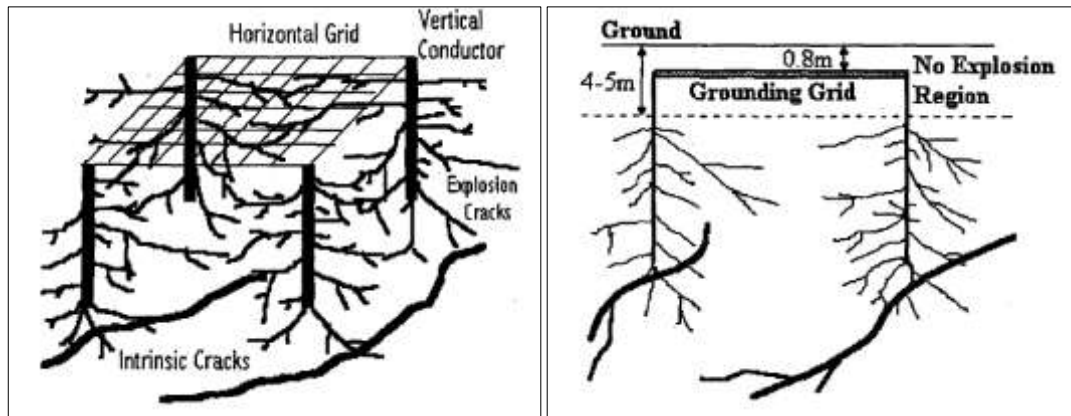


Figure 10: 3-D Grounding System and Side View of It [10]

In the selected land several vertical holes are drilled and create some cracks in the soil by carefully handled explosions. Then install deep driven grounding conductors in the holes and inject low resistivity material into the holes under high pressure, so that the cracks are filled with the low resistivity material. This creates a 3-D grounding network as shown in the Figure 10 [10].

The purpose of deep driven grounding system is to increase the area of the grounding system and easily dissipate the fault current into soil layers in much higher depth from the surface, which are having low resistivity. The effectiveness of this method has been experimentally verified and the method has been successfully applied for some projects implemented in China [10].

### 2.5.2 Satellite grid

The required level of ground resistance of a grid substation in a high resistive soil structure can be achieved by introducing an extra grid to the main grounding system. This is called a satellite grid and is required to install in a neighboring location having

a lower resistivity soil. When the satellite grid is connected to the grounding system of the grid substation it lower the equivalent resistance of the grounding system, as it acts as a parallel resistor with low resistance. The satellite grid can be installed in locations such as clay deposit or a large structure such as concrete mass of a hydroelectric dam [1]. In addition, the penstock of a hydro power station can be used as a part of grounding system if the penstock liner is buried in the earth. The satellite grid can be connected to the main grounding system using overhead conductors or using underground conductors. When underground conductors are used, these wires also act as a part of the grounding system and it is effective than using overhead conductors. But the installation of these underground wires needs to be carefully handled, as it can create hazardous potential gradients and possibility of electric shock to people walk through the site. In a study, for a grounding system located in a soil of a resistivity of  $1000 \Omega \cdot \text{m}$  the ground resistance has been  $17.54 \Omega$  and when it connected to a similar grounding grid located in a soil of  $100 \Omega \cdot \text{m}$  the equivalent grounding resistance has been reduced to  $1.632 \Omega$ . Once the main grounding system connected with the satellite grid, the step voltage and touch voltage has been reduced to 9.3% from the step and touch voltages of the main grid alone in high resistive soil [11].

### **2.5.3 Chemical treatment of soil**

Chemical treatment or backfilling with low resistive material is an effective method in improving the performance of grid substation grounding system. Chemical electrolytic ground electrodes can be used to lower the grounding resistance in the areas of high soil resistivity and low moisture conditions. In high resistive soil, bentonite can be used to improve the soil and lower the grounding resistance. [11, 12].

### **2.6 Grid Substation Fence Grounding**

The grounding system of a grid substation is designed to ensure the safety of the personnel working in the grid substation. High resistive surface material, maintaining safe limits of potential grading around the earthed equipment by carefully designed grounding system and use of protective footwear ensures the safe working conditions against touch and step voltage risks. The same concern needs to be given to the boundary and the area beyond the boundary of the grid substation, however are not

widely taken into consideration. It is not possible to control the activities beyond the boundary of the grid substation, especially in urban areas. The area could be used by general public, where they might be exposed to ground potential rise due to an incident inside the grid substation. Therefore, it is necessary to carefully study and apply remedial actions to mitigate such risks to the general public moving around the grid substation [6].

The grounding of grid substation fence is vital, as the fence is reachable from outside the grid substation. The design of the grounding system needs to ensure that the touch potential on the fence is in safe limits, even from the outside of the grid substation premises. Normally the step voltage falls in the safe limits, once the touch voltage is in safe limits. There are several methods of grounding the grid substation fence;

- Fence is located in the area of ground grid and connected to it. Outer ground conductor is installed beyond the boundary.
- Fence and outer ground conductor approximately coincide.
- Fence is located beyond the ground grid and connected to it.
- Fence is located beyond the ground grid, not connected to it, but connected to a separate grounding electrode.
- Fence is located beyond of the ground grid, not connected to it and not connected to a separate grounding electrode. The fence post creates an effective ground via the concrete base.

The instances where the metallic fence is not connected to the grounding grid of the grid substation might create hazardous conditions. If an energized overhead line falls on the fence and if the fence is not connected to the grounding system of the grid substation the fault current would flow through the local fence grounding. This would create severe damage to the fence and personnel working there would be exposed to higher step and touch voltage. In addition, when the fence is not connected to the main grounding system of the grid substation, the fence attains the voltage of the equipotential lines on the surface where the coupling between earth and the fence is fairly good. At a far location from the said coupling point, the fence might create hazardous touch potential as the voltage on the earth surface might be different to the

voltage of the fence. In practical condition, it is difficult to maintain complete metallic isolation between chain-link fence and grounding system. Hence, if the fence is not coupled to the grounding system, any accidental connections to the main grounding system might create risks along the entire fence at a fault condition. The level of risk can be reduced by using insulated joints in the fence at uniform intervals [1]. In computer simulations carried out to study the effect on different fence grounding methods described above show that, when the outer ground conductor of the grounding system installed inside the fence the touch voltage of the fence increases. However according to the simulation results, surface voltage beyond the fence decreases as the outer ground conductor moved inwards from the fence. This results in decrease of the step potential risk beyond the boundary of the grid substation [1].

In order to minimize the touch potential hazards it is recommend to burry ground conductors beyond the boundary, so that a person touching the fence would stand on the buried conductors and do not exposed to a hazardous electric shock. Alternatively, the fence can be made of non-conductive material or use non-conductive materials to isolate sections of the metallic fence. However the hazard of the Step potential risk has be to carefully address [13].

A study carried out in [14] shows that application of high resistive surface material for a distance of 1 m beyond the boundary of the grid substation provides the required safety for all types of fence grounding configurations. In addition, considering safety and cost segmented fence grounding which has insulated joints between segmented parts of the grid substation fence. These isolated segments connected to the main grounding system considering the probability and severity of the faults and potential rise. The remaining parts are connected to the separate ground electrode and the two fence segments are connected to each other using an insulating fence section. The installation has to be carefully monitored so that it prevents bridging of the isolated fence sections at any situation. The same study has shown that in GIS grid substations which are developed in limited land plot, in the perimeter beyond the fence of the grid substation the step potential exceeds the tolerable maximum limits. This risky area is up to about 4 m from the fence of the grid substation. Since it is not possible to apply high resistive surface material in the area beyond the boundary, alternative methods

have been introduced to reduce the associated risk. These methods are, increasing the installation depth of the outer ground grid conductors and increasing the length of the ground rod at the perimeter. Increasing depth of the ground conductors causes to increase the touch voltage, so the design has to be carefully evaluated and compensated by increasing the length of the ground conductors [14].

## 2.7 Permissible Touch and Step Potential outside the Grid Substation

The maximum permissible touch potential and step potential limits depend on the material used to surface layer. A high resistive material such as crushed rock is laid inside the grid substation premises as the surface layer. The safe voltage limits could be improved by introducing a high resistive layer such as crushed rock or tar macadam immediately outside the boundary of the grid substation. This could be impractical as the utility does not belongs the land beyond the boundary [6].

The following equations are derived in IEEE Guide for Safety in AC Substation Grounding in order to calculate maximum permissible touch and step potentials of an area without a layer of high resistive surface material.

$$E_{touch_{50}} = (R_B + 1.5\rho) \times I_B$$

$$E_{step_{50}} = (R_B + 6\rho) \times I_B$$

Table 1: Permissible Potentials with and without High Resistive Surface Material

With high resistive surface material	Without high resistive surface material
$E_{touch_{50}} = (R_B + 1.5C_s \times \rho_s) \times I_B$	$E_{touch_{50}} = (R_B + 1.5\rho) \times I_B$
$E_{step_{50}} = (R_B + 6C_s \times \rho_s) \times I_B$	$E_{step_{50}} = (R_B + 6\rho) \times I_B$

Where  $I_B$  is the body current,  $R_B$  is the body resistance and  $\rho$  is the resistivity of the upper soil layer [1].

According to these equations since  $0 < C_s < 1$  and  $\rho_s \gg \rho$ , it can be justified that the maximum permissible touch and step potentials of an area without the surface layer of high resistive material are less than the maximum permissible potentials of an area with the surface layer of high resistive material.

**MODELLING CONCEPTUAL GROUNDING SYSTEM**

---

The grid substation grounding system was modeled using the ANSYS Maxwell Software, which is widely used in electromagnetic field simulations in the industry. ANSYS Maxwell uses the high accurate finite element method to solve static, frequency-domain, and time-varying electromagnetic and electric fields. Initially a test model was developed in order to verify the methodology of software modelling.

The parameters for the conceptual model were considered as follows. The soil resistivity of Colombo L grid substation project site were considered for developing soil model.

Soil Resistivity	: 400 $\Omega$ m
Conductor	: Copper (120 sq.mm)
Test Fault Current	: 10kA
Dimensions of Earth Mesh	: 20m x 20m
No. of Conductors	: 5 x 5

**3.1 ANSYS Maxwell Model****3.1.1 Soil Model for Substation Grounding System**

In ANSYS Maxwell Software a rectangular box was created as shown in the Figure 11 and defined as the soil model by setting the dimensions and conductivity of the soil resistivity. In this software, it only allows to program the conductivity and the relative permittivity of the material. So the required soil resistivity has been represented in the form of conductivity of the soil. Since the selected soil was considered as a uniform soil structure with a resistivity of 400  $\Omega$ m, the conductivity of the soil model was programmed as 0.0025 S/m as shown in Figure 12. The relative permittivity of mineral

soil is in the range of 3~5 [7]. In this model the relative permittivity of the soil was considered as 3.

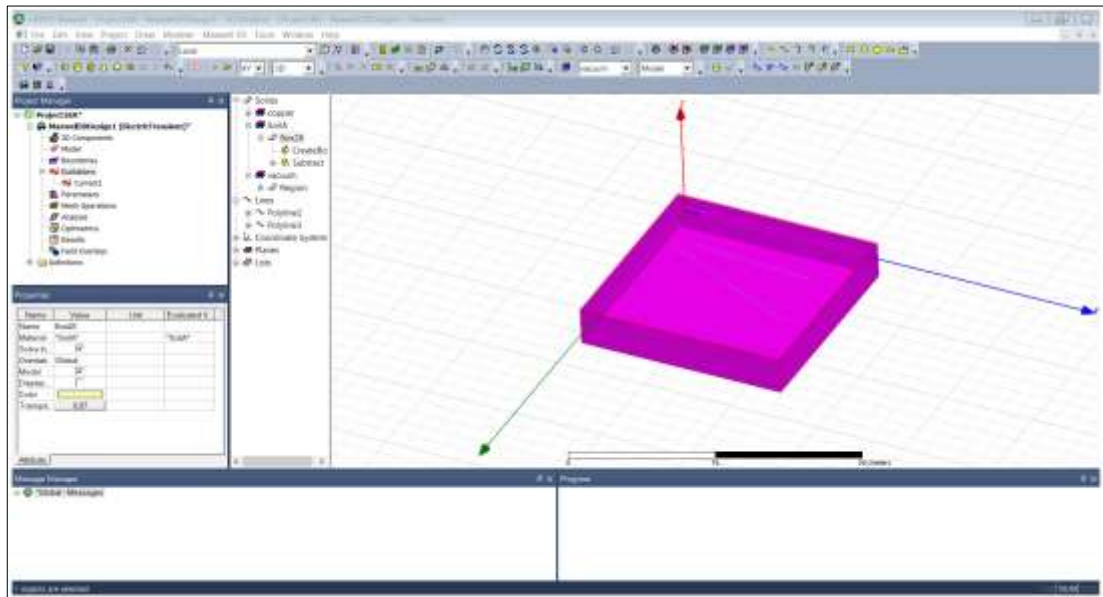


Figure 11: Soil Model

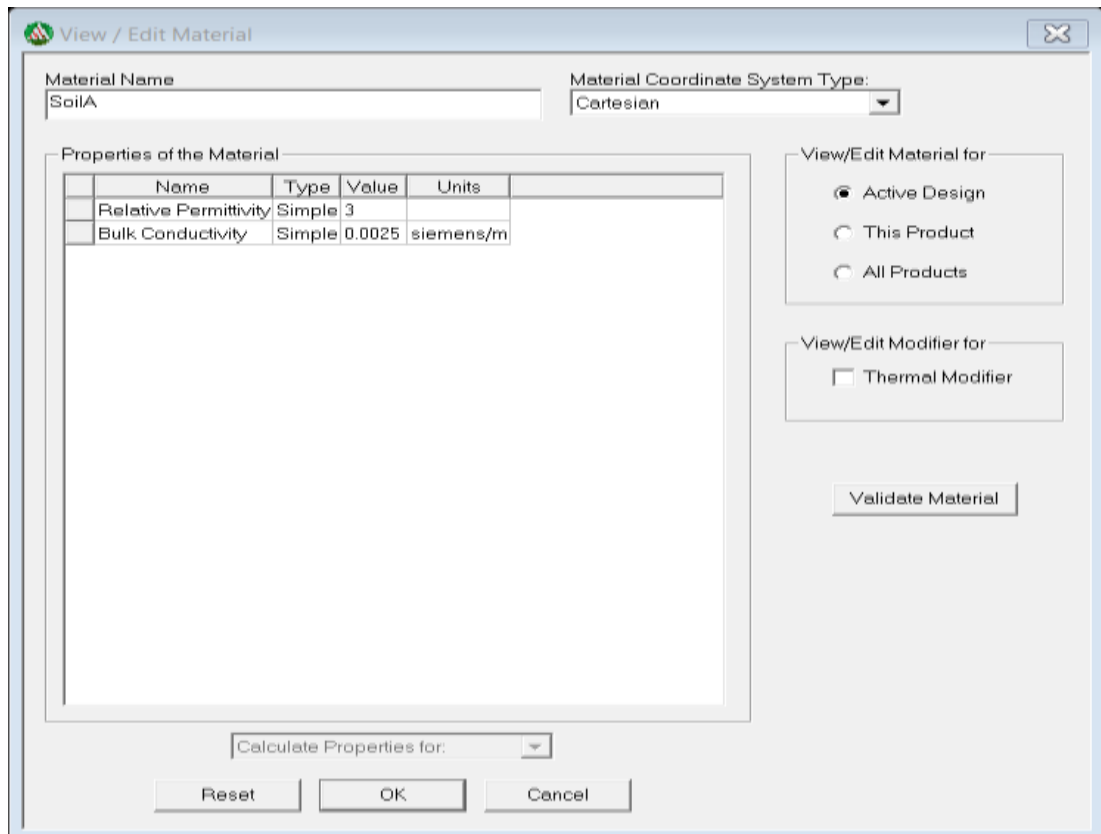


Figure 12: Parameters of Soil Model

### 3.1.2 Model of Grounding System

The earth mesh of the test model was created by copper conductors. The size of the selected Copper conductor is 240 sq.mm and the conductors were placed 5m apart from parallel conductors which creates 5m x 5m earth mesh as shown in Figure 13.

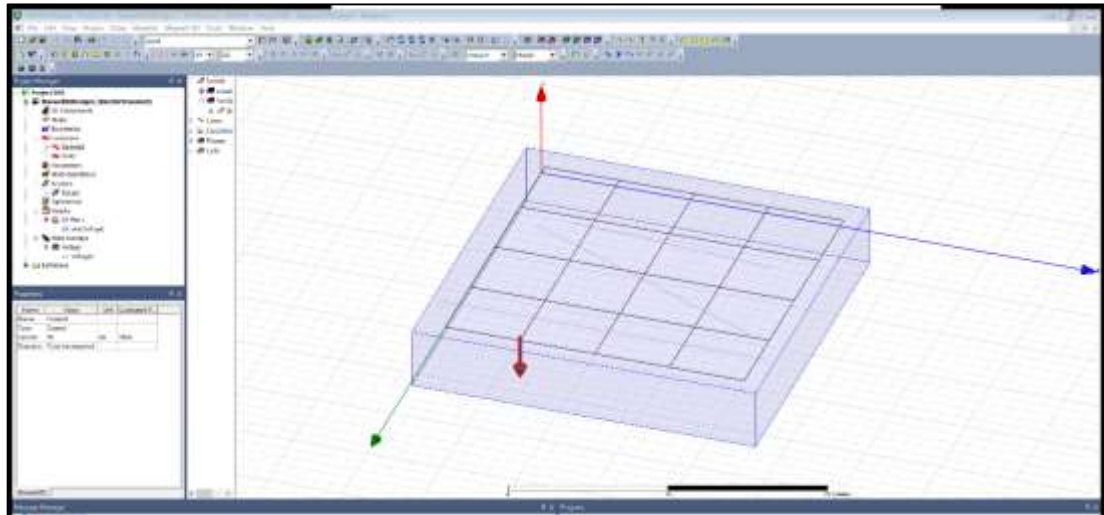


Figure 13: ANSYS Maxwell Test Model

Select Definition

Materials | Material Filters

Search Parameters  
Search by Name:   
Search:

Search Criteria  
by Name (selected) | by Property

Relative Permittivity

Libraries  Show Project definitions  Show all libraries

Name	Location	Origin	Relative Permittivity	Bulk Conductivity	Thermal Modifier
copper	Project	Materials	1	58000000siemens/m	None
copper	SysLibrary	Materials	1	58000000siemens/m	None
coming_glass	SysLibrary	Materials	5.75	0	None
cyanate_ester	SysLibrary	Materials	3.8	0	None
diamond	SysLibrary	Materials	16.5	0	None
diamond_hi_pres	SysLibrary	Materials	5.7	0	None
diamond_pi_cvd	SysLibrary	Materials	3.5	0	None
Dupont Type 100 HN Film (tm)	SysLibrary	Materials	3.5	0	None
Duroid (tm)	SysLibrary	Materials	2.2	0	None
epoxy_Kevlar_xy	SysLibrary	Materials	3.6	0	None
femto	SysLibrary	Materials	12	0.01siemens/m	None
FR4_epoxy	SysLibrary	Materials	4.4	0	None
gallium_arsenide	SysLibrary	Materials	12.9	0	None
GE GETEK ML200/RG200 (tm)	SysLibrary	Materials	3.9	0	None

View/Edit Materials... Add Material... Clone Material(s) Remove Material(s) Export to Library...

OK Cancel Help

Figure 14: Parameters of Copper Conductors

In the Materials library of the ANSYS Maxwell shown in the Figure 14, the parameters of Copper is readily available and the therefore it was not necessary to program the material as done for the soil.

### 3.1.3 Fault Current

In order to observe the ground potential rise, a test fault current of 10 kA was injected to the grounding grid for a duration of one second as shown in Figure 15. In this simulation the test current was injected into the grounding grid using a copper conductor riser modelled with the grounding grid.

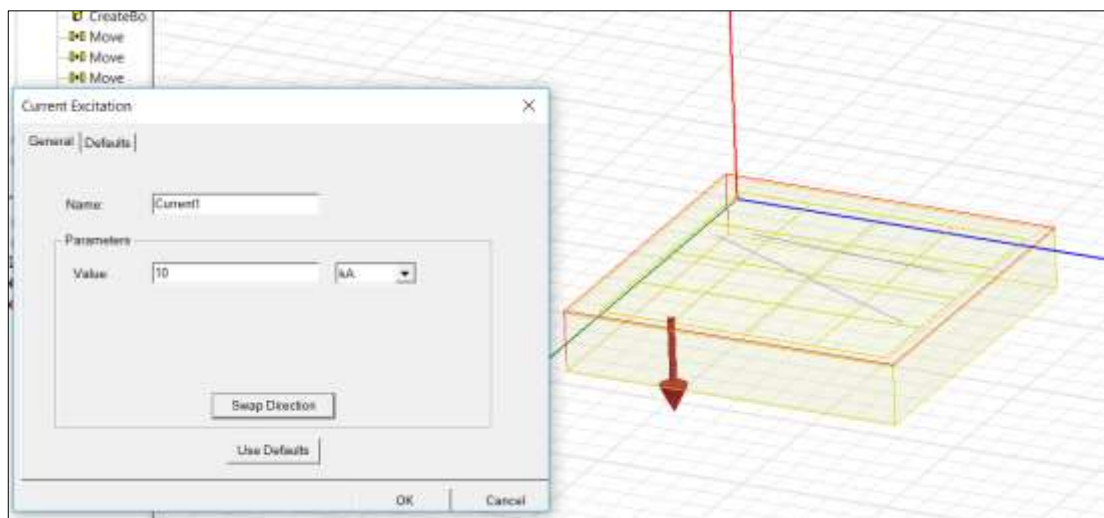


Figure 15: Injecting Test Fault Current

### 3.1.4 Simulation Results

The profile of the potential rise of the test model is shown in Figure 16. The simulated results shows that the higher voltage levels have been built up at the grounding conductors and when moving away from the grounding conductors the ground potential rise drops. It can be clearly identified that when moving away from the grounding grid the ground potential drops further.

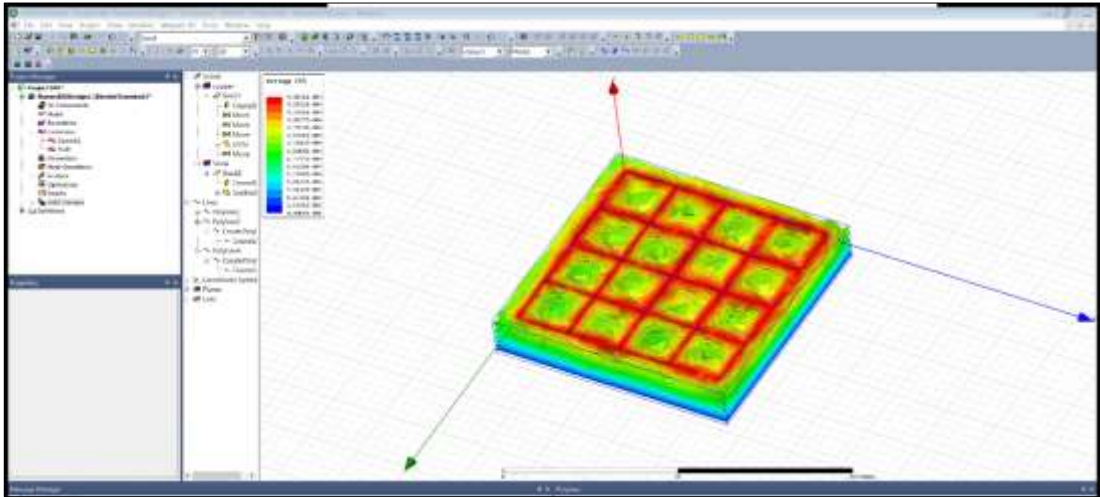


Figure 16: Voltage Profile of the Test Model

The ground potential rise plot along a hypothetical line (polyline) over the surface of the grounding grid was obtained to observe the behavior of the GPR on the surface of the ground grid model. The ground voltage profile was obtained by “Create Field Plots” function of the ANSYS Maxwell software. This hypothetical line was modeled as non-model items in the workspace of the software as shown in the Figure 17.

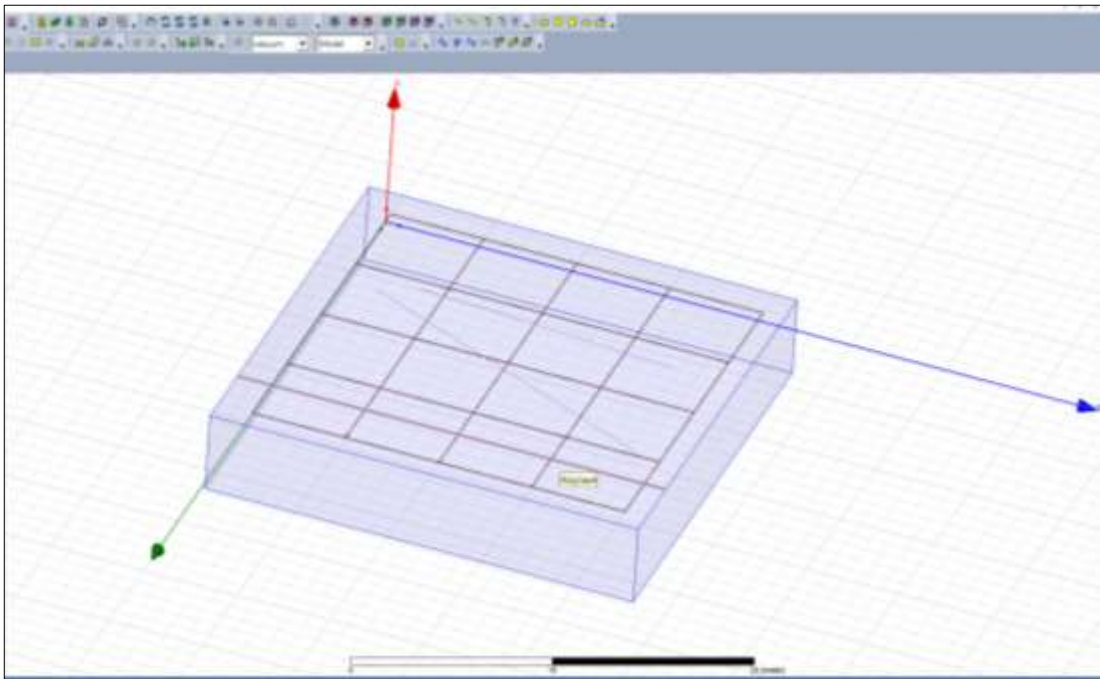


Figure 17: Hypothetical Lines over the Surface of the Ground Grid

The voltage profile along the hypothetical line obtained after the simulation of the above test model is shown in the Figure 18.

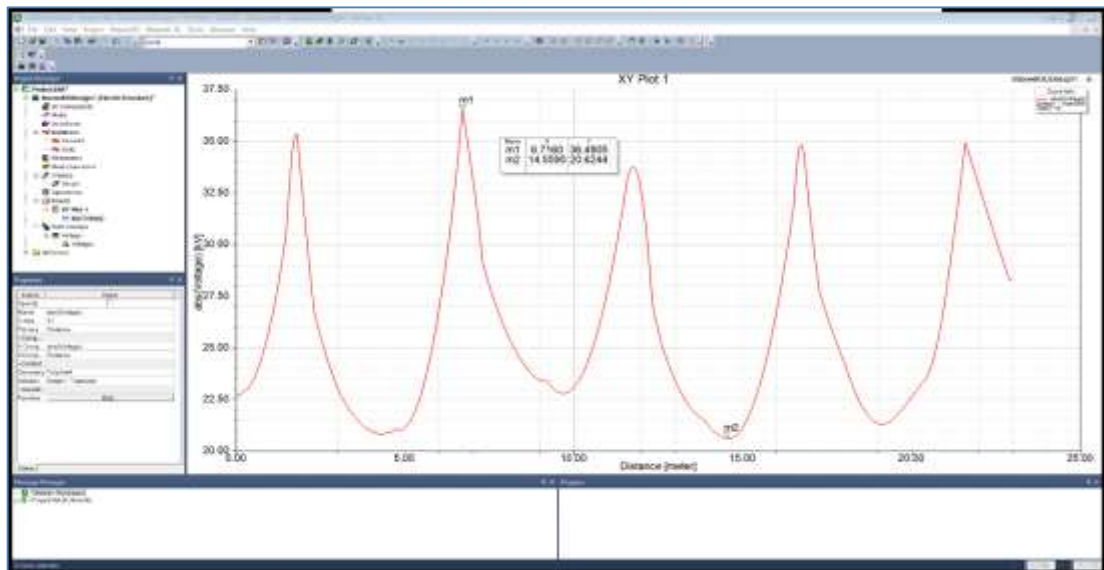


Figure 18: Ground Potential Rise Plot

It can be clearly observed that, at the grounding conductors the ground potential rise reaches to peak and when moving away from the ground conductors the ground potential rise drops. The maximum potential on the surface of the area is 36.47kV and the minimum is 20.62kV.

### 3.1.5 Effect of Different Soil Resistivity

The same ANSYS Maxwell model was used to analyze the ground potential rise of different soil types for the same test current. The model was simulated for different types of soils by varying the soil resistivity while keeping the other parameters such as fault current, fault duration, grounding system arrangement and conductor size unchanged. The soil resistivity of two sites were obtained to develop the soil models.

The simulation result of the model created with the soil model of Colombo N Grid Substation is shown in the Figure 19. The resistivity of the top soil layer is 150  $\Omega\text{m}$ . According to the simulation results the maximum ground potential on the surface of the area is 13.62 kV and the minimum is 7.7 kV.

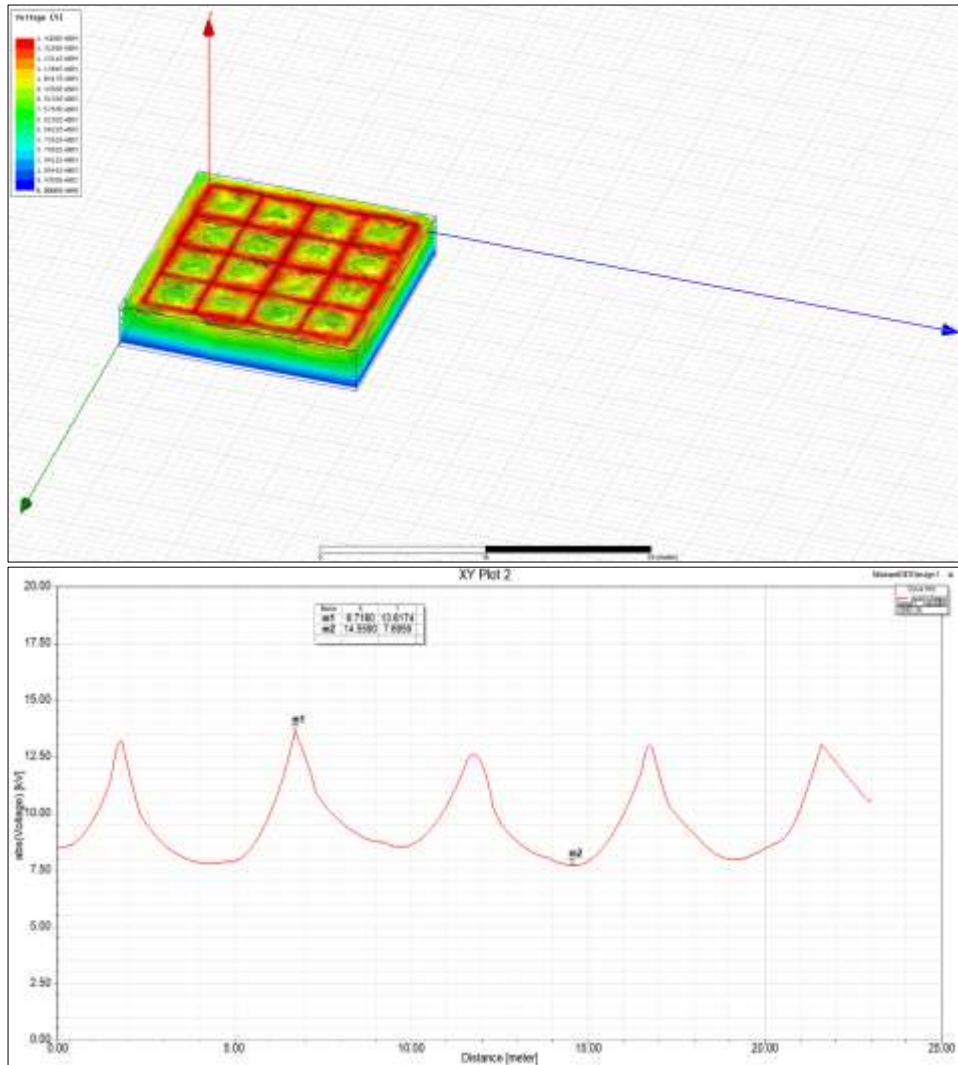


Figure 19: GPR for Soil Resistivity of 150 Ω-m

The simulation result of the model created with the soil model of Colombo M Grid Substation is shown in the Figure 20. The resistivity of the top soil layer is 87 Ωm. According to the simulation results the maximum ground potential on the surface of the area is 7.93 kV and the minimum is 4.48 kV.

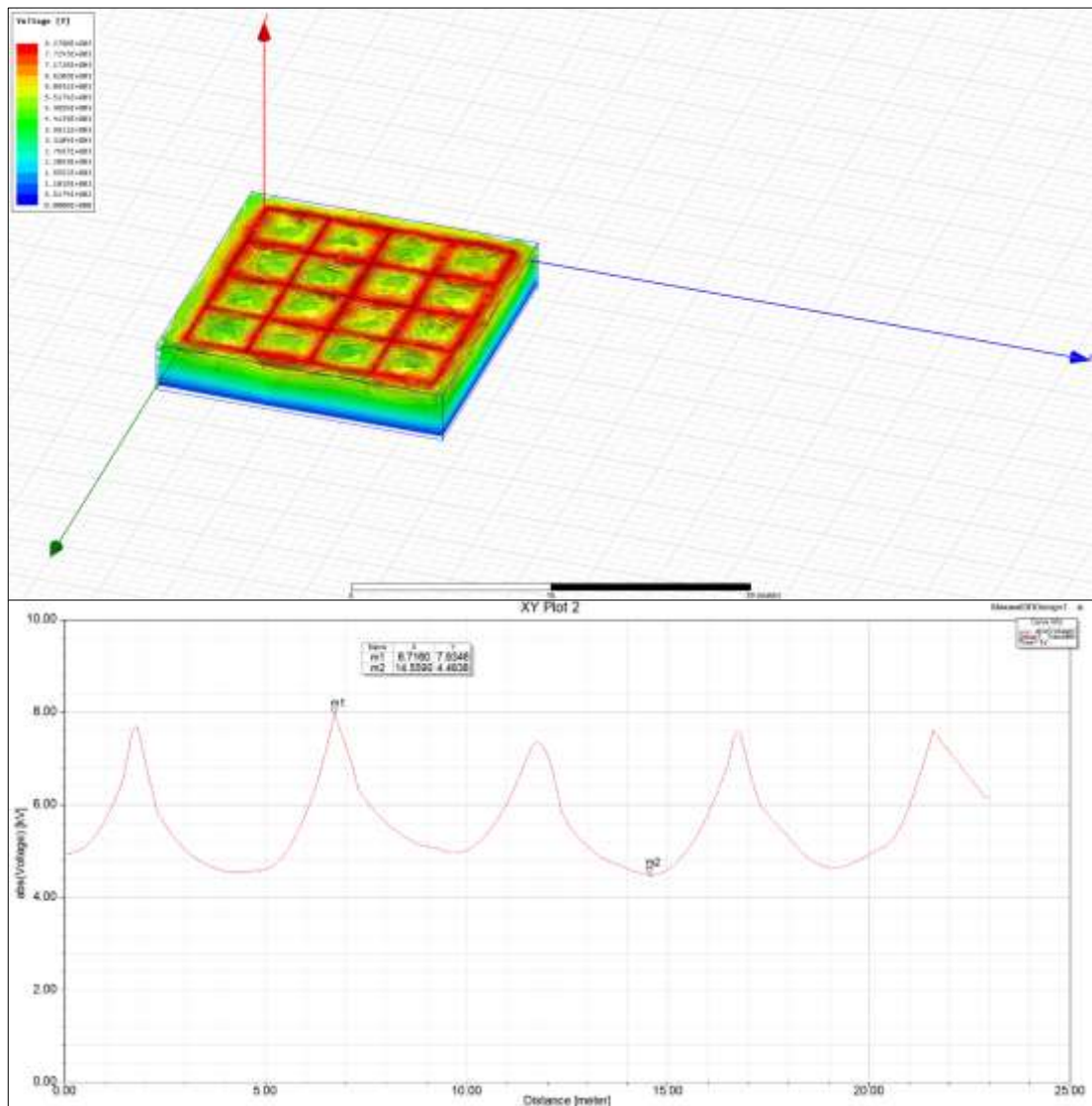


Figure 20: GPR for Soil Resistivity of 87  $\Omega$ -m

According to the simulation results it can be observed that in high resistive soils the GPR is higher than the ground potential rise in low resistive sites.

### 3.1.6 Effect of Different Relative Permittivity of Soils

In general, the relative permittivity is a key parameter in ANSYS Maxwell models. In the conceptual model the relative permittivity was considered as 3. The same ANSYS Maxwell model was used to analyze the effect of different relative permittivity. Since the relative permittivity of mineral soil is in the range of 3~5 [7], the relative permittivity of the soil model was changed to 5 and the soil resistivity was considered

as 400  $\Omega$ -m as shown in the Figure 21 and simulated the model while keeping all other parameters unchanged.

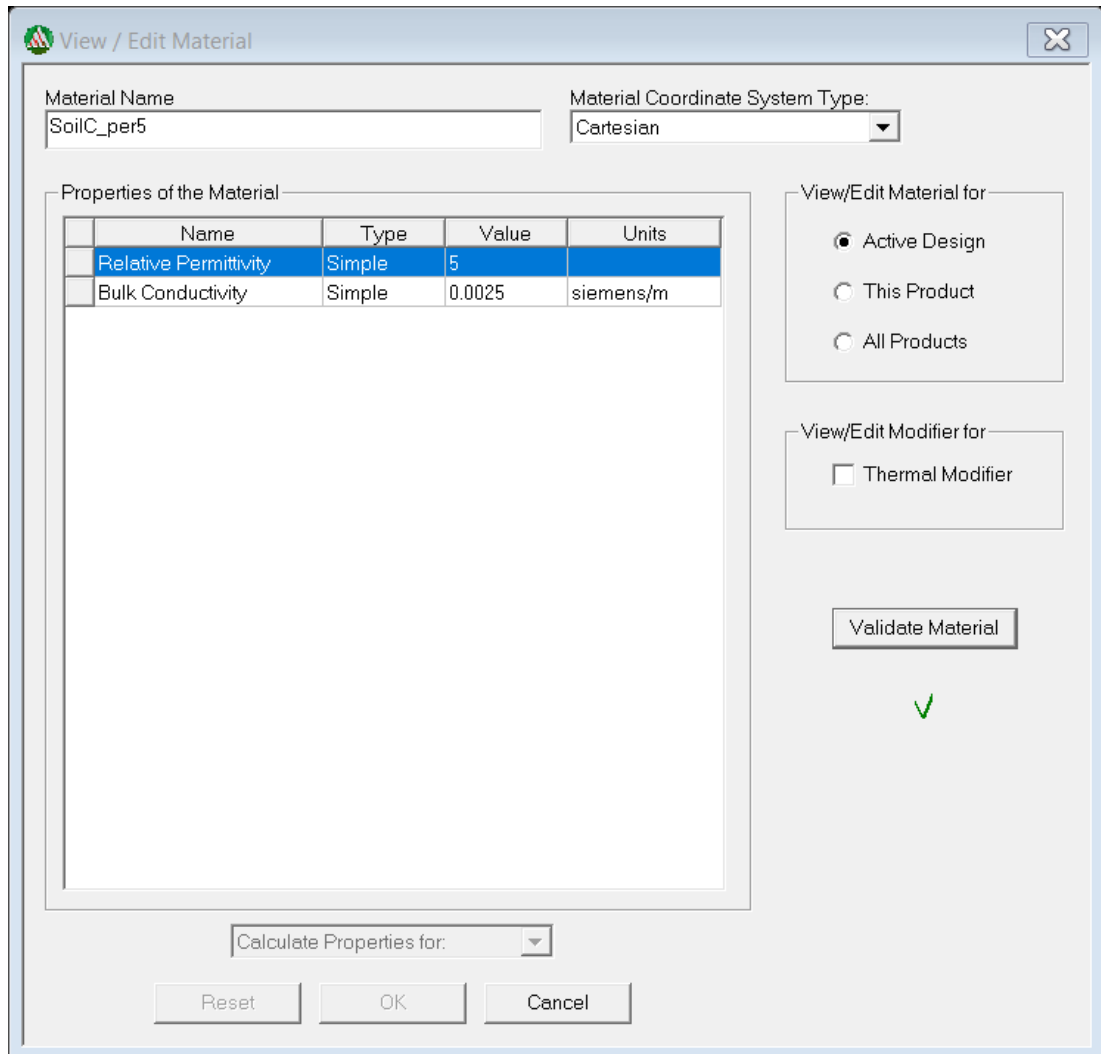


Figure 21: Parameters of Soil Model with Relative Permittivity of 5

The simulation results of the model with relative permittivity of 5, is shown in the Figure 22. A comparison of the GPR profile along the same hypothetical line over the surface of the two soil models are shown in the Figure 23. In both models the potential profile is similar to each other. The maximum potential over the same hypothetical line over the surface of the area is 36.4kV and the minimum is 20.6kV. According to the simulation results it can be observed that change in relative permittivity does not effect on the ground potential rise of the ANSYS Maxwell model of the grounding system.

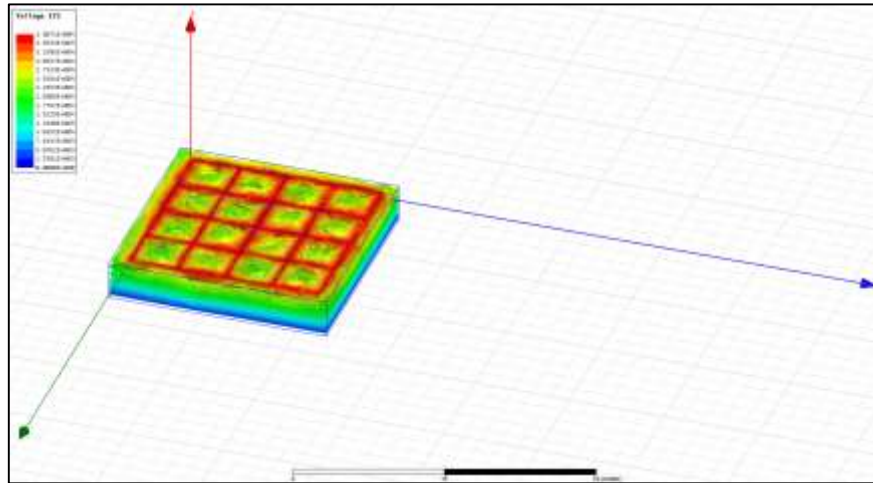
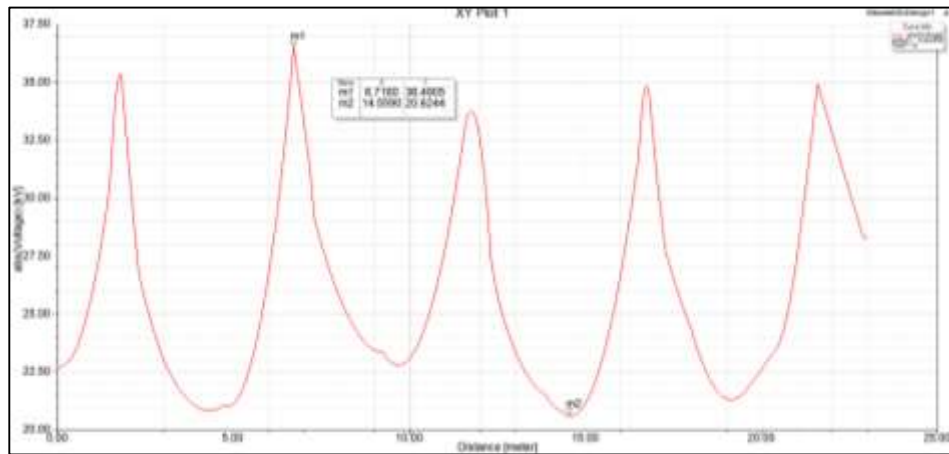
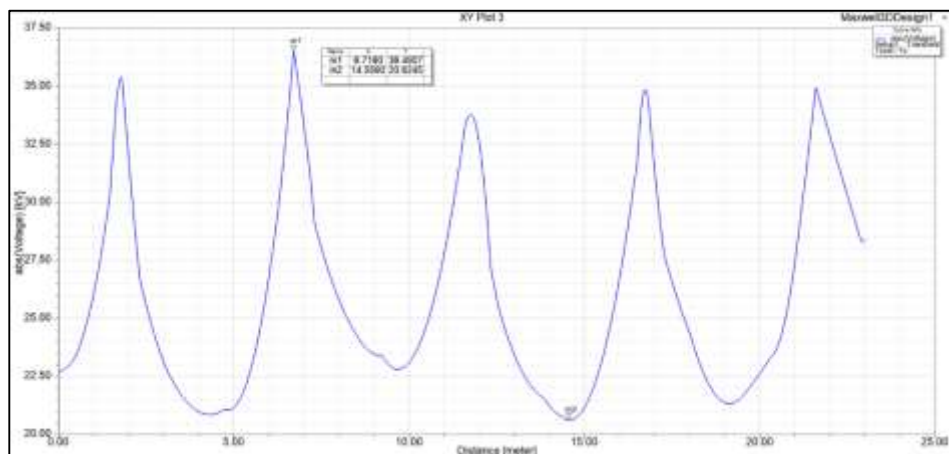


Figure 22: Voltage Profile of the Soil Model with Relative Permittivity of 5



(a)



(b)

Figure 23: GPR Profile along the Same Hypothetical Line (a)  $\epsilon_r = 3$ (b)  $\epsilon_r = 5$

### 3.2 Presence of Ground Potential Rise beyond the Grounding System

The ground potential rise on the surface of the soil model was observed along a hypothetical line which cover a section of the grounding grid and further extended to outside the grid substation grounding system. The GPR in the area outside the grounding grid can also be obtained from the same plot as marked in the Figure 24.

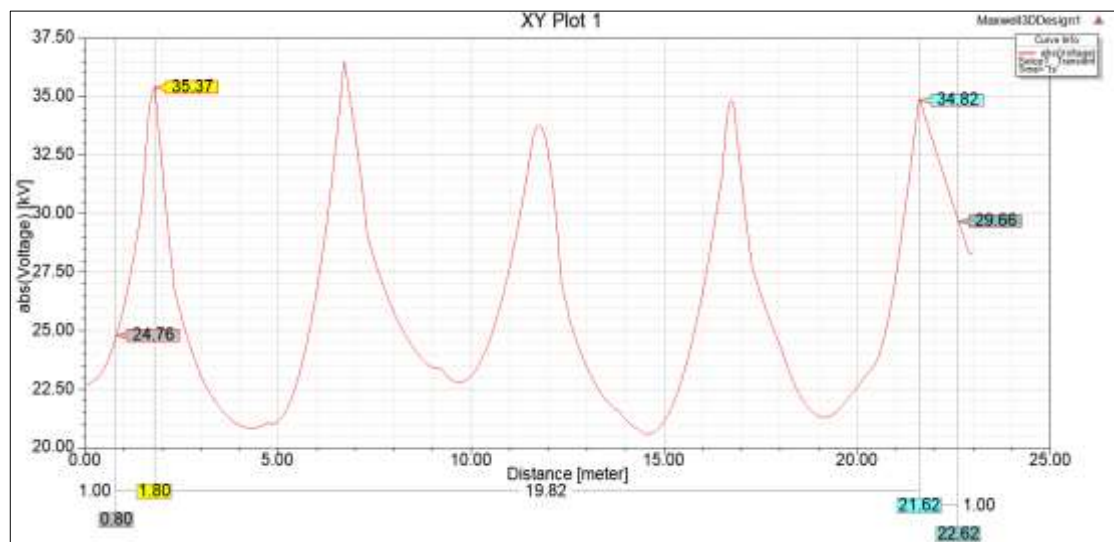


Figure 24: GPR Profile along the Hypothetical Line

The first peak and the last peak of the above plot is related to the ground potential at the first conductors and the last conductor along the hypothetical polyline. According to the plot, there is a ground potential rise beyond these two conductors. This implies the presence of GPR in the area away from the grid substation grounding system. This ground potential rise which is developed in the area outside the grounding system of the grid substation has a significant gradient which can develop hazardous potential difference to the people in the vicinity of the grid substation.

GROUNDING SYSTEM OF AN ACTUAL SITE

The site data of Colombo M Grid Substation was considered in developing actual model of the grounding system for this research.

4.1 Collection of Site Data

The soil resistivity measurement has been carried out in the initial stage of the project. The Wenner Four Pin method has been used to measure the soil resistance. The measurements have been carried out in four routes C1-D1, C1-D2, C1-D3 and C1-D4 as indicated in the Figure 25.

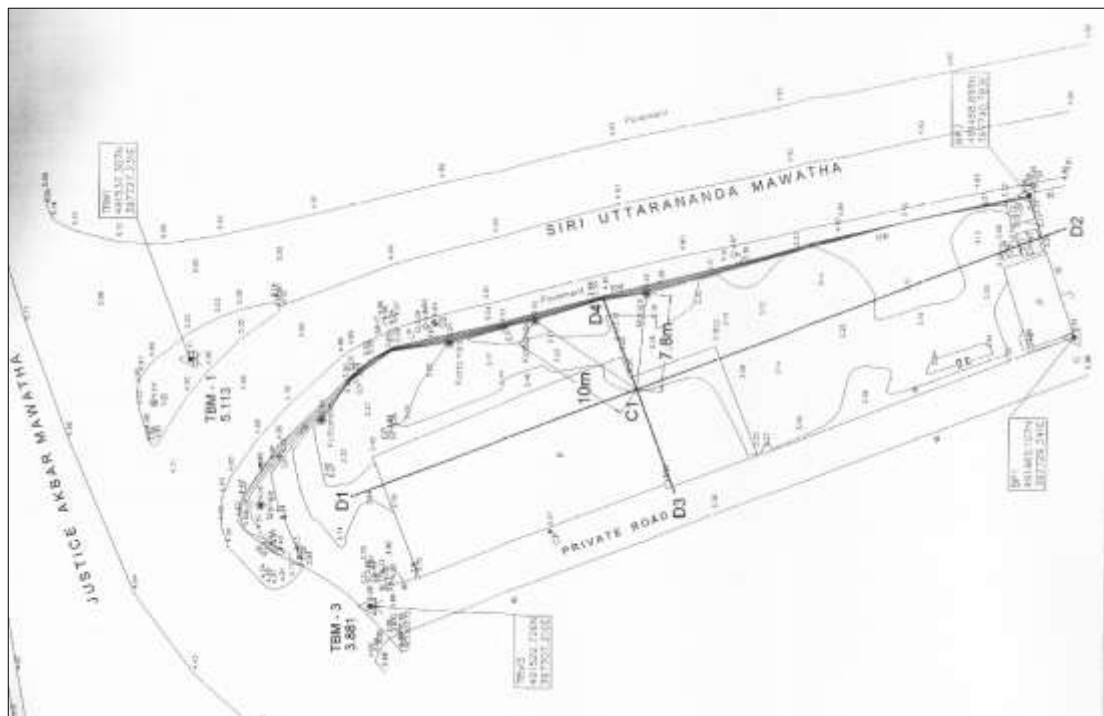


Figure 25: Soil Resistivity Measured Routes of Colombo M Grid Substation

The measured soil resistance along the routes are used to calculate the soil resistivity using the following equation.

$$\rho = 2\pi aR$$

Where,  $\rho$  is the apparent soil resistivity in  $\Omega\text{m}$ ,  $a$  is the electrode spacing and  $R$  is the resistance measured along the route. The measured soil resistances along four routes and the soil resistivity calculated using the measured data is tabulated in the Table 2.

**Table 2: Soil Resistance Measurement of Colombo M Grid Substation**

Electrode Distance $a$ (m)	Soil Resistance ( $\Omega$ )					Soil Resistivity ( $\Omega\text{m}$ ) $\rho = 2\pi aR$
	Route 1	Route 2	Route 3	Route 4	Average	
0.5	30.9	33.9	31.1	33.9	32.45	101.94
1	11.27	14.47	14.14	14.14	13.51	84.85
1.5	8.73	10.27	8.2	8.41	8.90	83.90
2	7.18	7.44	5.1	5.64	6.34	79.67
2.5	5.53	5.93		3.69	5.05	79.33
3	5.43	5			5.22	98.30
4	3.7	4.88			4.29	107.82
5	2.79	3.55			3.17	99.59
6	1.92	2.41			2.17	81.62
7	1.41	1.47			1.44	63.33
8	1.07	1.22			1.15	57.55
9	0.94	0.87			0.91	51.18
10		0.73			0.73	45.87

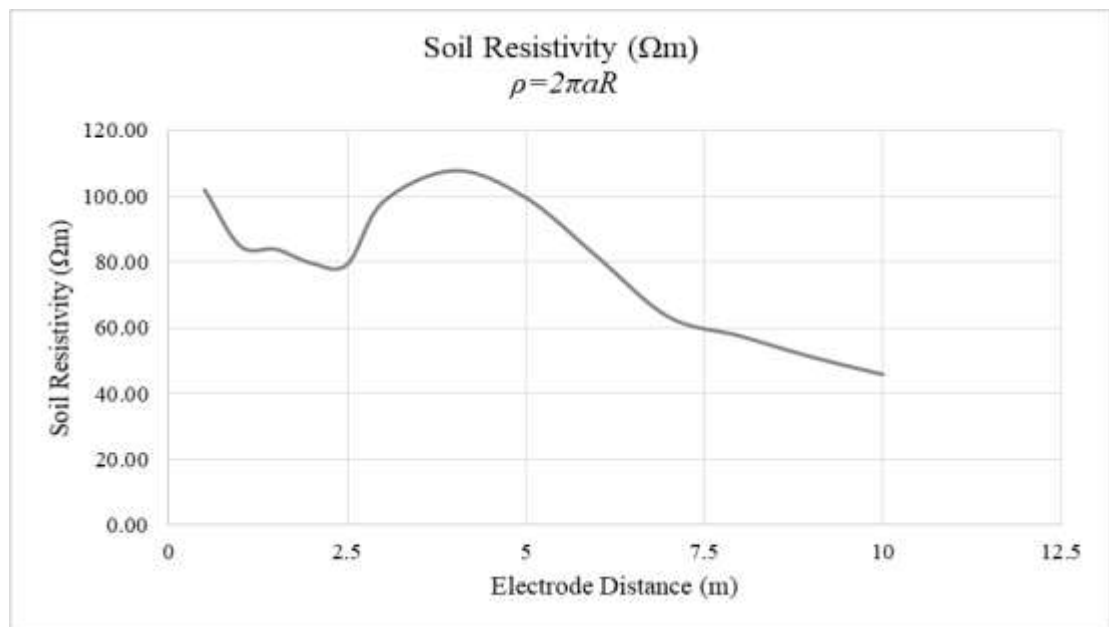


Figure 26: Graph of Soil Resistivity vs. Electrode Distance

The soil resistivity values for each electrode distance is shown in a graph in Figure 26. Using the Sunde's graphical method the soil resistivity of the Colombo M Grid Substation is approximated as shown in the Figure 27. Accordingly the soil structure has two soil layers, the resistivity of the upper soil layer is  $87 \Omega\text{m}$  and the depth of the upper soil layer is 8 m. The soil resistivity of the lower soil layer is  $45 \Omega\text{m}$ .

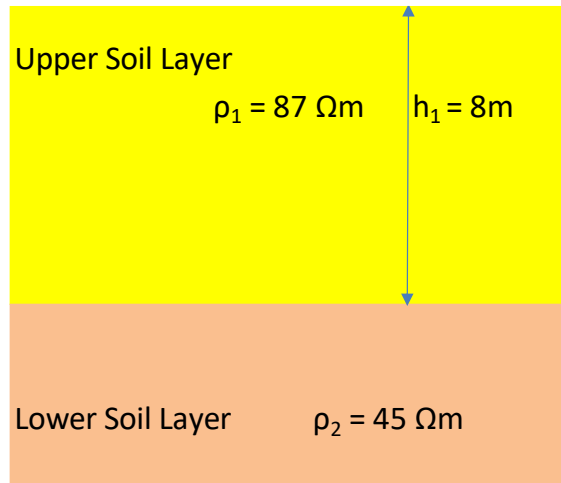


Figure 27: Soil Model of Colombo M Grid Substation

#### 4.2 ANSYS Maxwell Model for Actual Grid Substation Grounding System

The ground mesh layout of the Colombo M Grid Substation is shown in Figure 28.

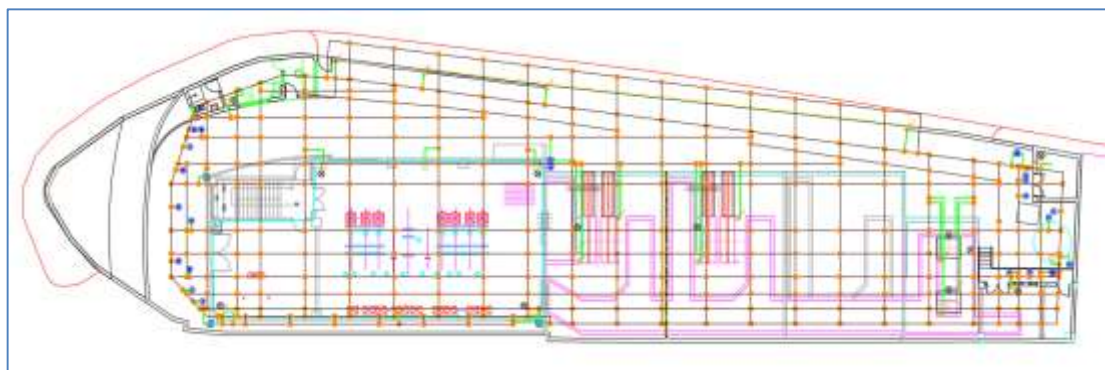


Figure 28: Layout and Ground Mesh Plan of Colombo M Grid Substation

The soil model of the Colombo M Grid Substation was modeled in the ANSYS Maxwell workspace. The resistivity of the upper soil layer is  $87\Omega\text{m}$ .

Table 3: Parameters for Modelling Colombo M Grid Substation

Conductivity of the upper soil layer	: 0.0115 S/m
Dimensions of soil block	: 71.5 m × 25 m × 8 m
Conductor size	: 240 sq.mm
Fault current	: 25 kA
Fault duration	: 1 second

The ground mesh of the Colombo M Grid Substation was modeled with the Copper conductors. In practice, the copper conductors are laid 0.6m below the surface of the upper soil layer. The ground mesh design in the ANSYS Maxwell workspace is shown in the Figure 29.

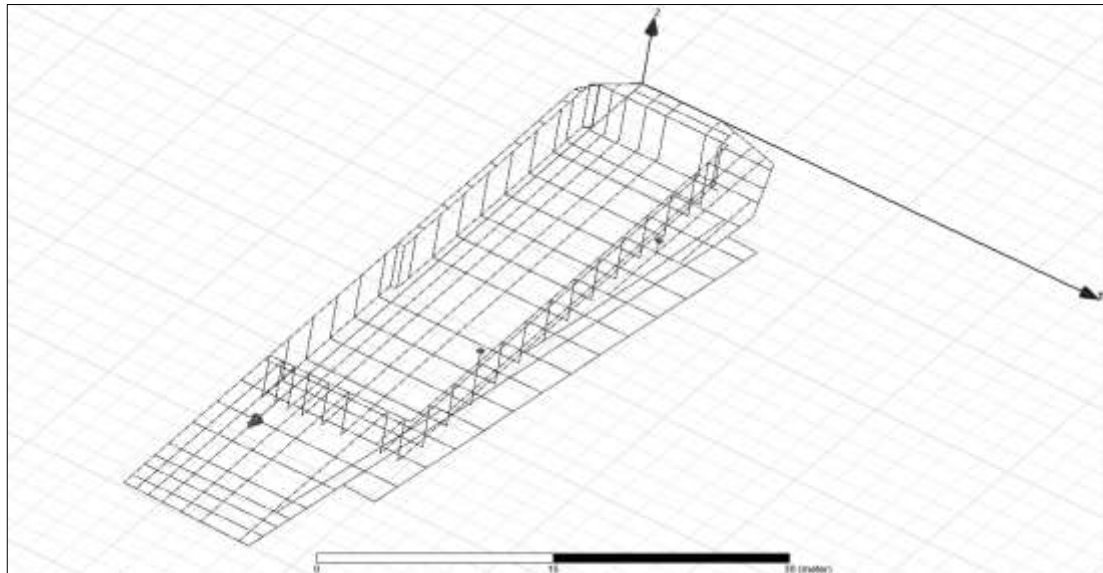


Figure 29: Earth Mesh Model of Colombo M Grid Substation

However in compact designs to maintain the continuity and to maintain the required grounding resistance the copper conductors are laid beneath the buildings, foundations and cable trenches. So the earth mesh design is much complex and it is not possible to analyze using the manual calculations. The ANSYS Maxwell model of grounding system is shown in Figure 30.

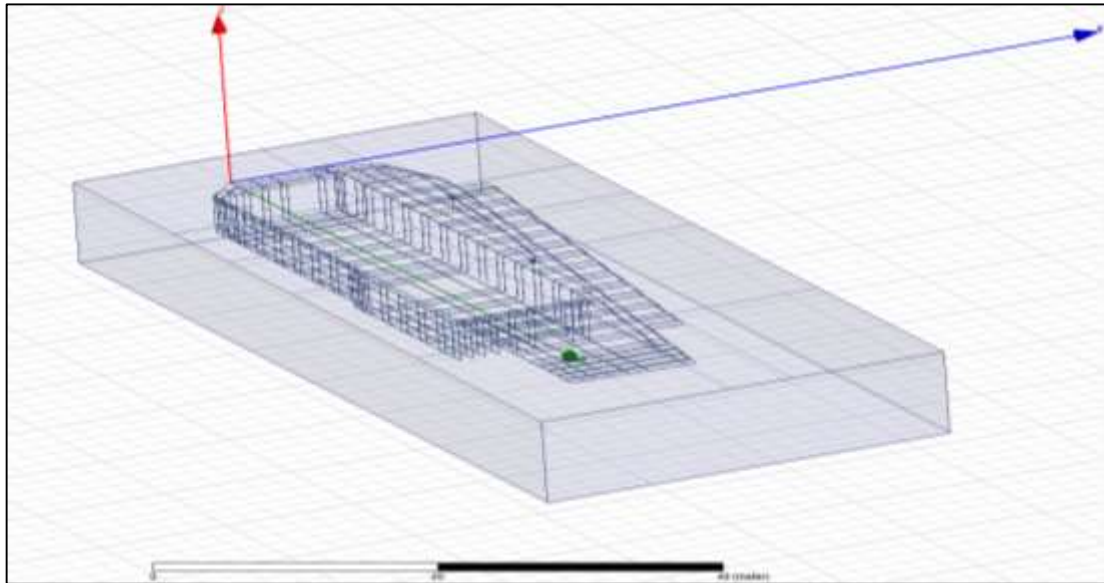


Figure 30: The Model of Actual Grounding System

The simulation result of the model is shown in Figure 31.

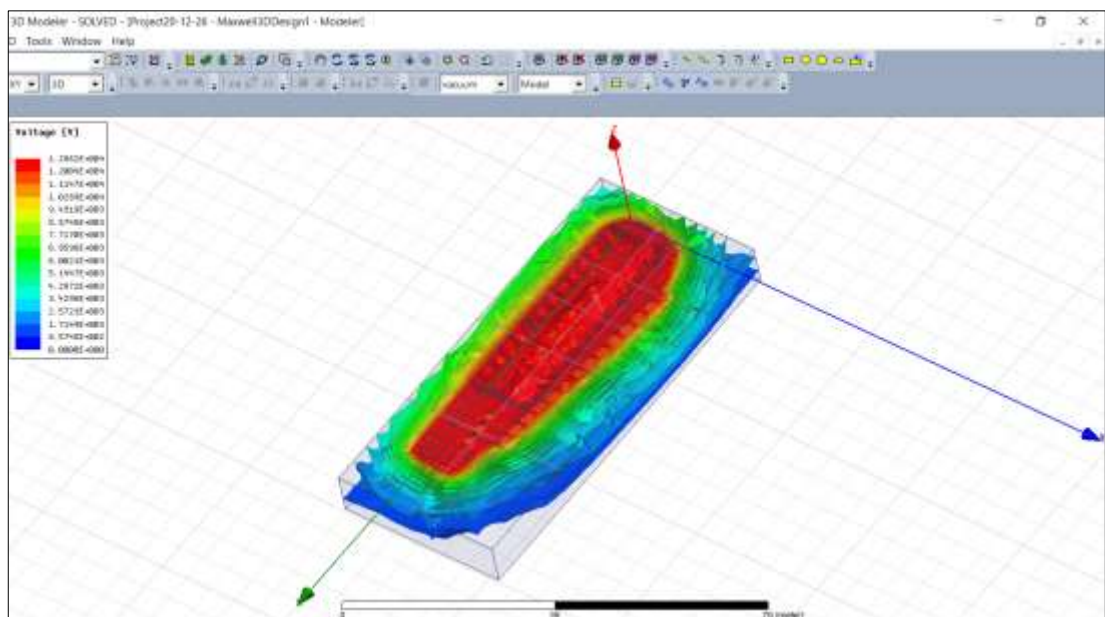


Figure 31: Ground Potential Rise over the Grounding System

The ground potential rise along two hypothetical lines drawn over the surface are shown in following figures. The GPR Profile along a hypothetical line parallel to Y-Axis of the Grounding System is shown in Figure 32 and GPR Profile along a line parallel to X-Axis of the Grounding System is shown in Figure 33.

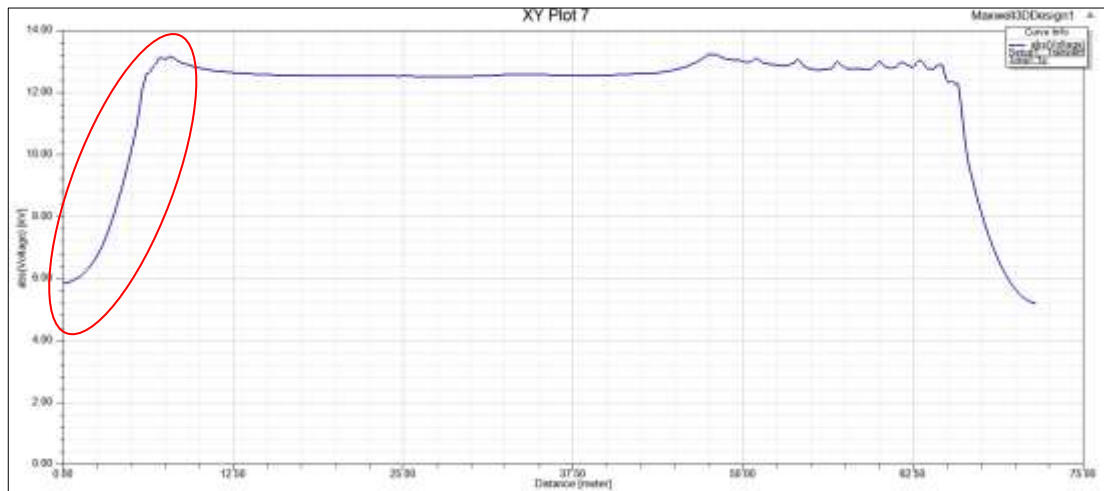


Figure 32: GPR Profile along a line parallel to X-Axis of the Grounding System Model

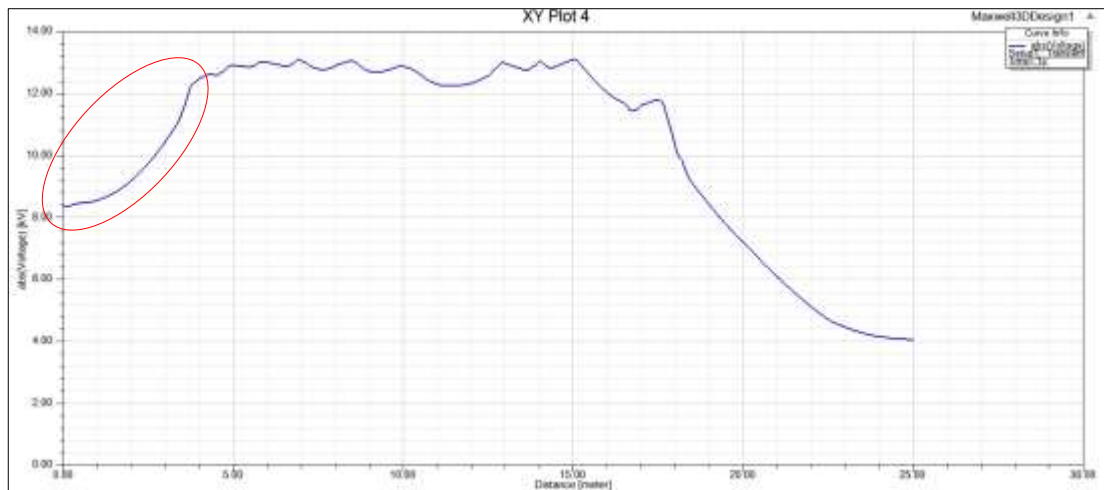


Figure 33: GPR Profile along a line parallel to Y-Axis of the Grounding System Model

### 4.3 Effect of High Resistive Surface Layer

A thin layer of Asphalt has been laid as the surface layer to cover the surface area where the earth mesh exist. The resistivity of Asphalt was considered as  $15,000 \Omega\text{m}$ . [1]. This high resistivity surface layer was modeled into the same design as shown in Figure 34 and simulated to study the effect of high resistive surface layer over the surface of upper soil layer above the earth mesh. The parameter set used to model the surface layer is mentioned in the Table 4.

Table 4: Parameters for Surface Layer

Conductivity of surface material (Asphalt)	: 0.000067 S/m
Thickness of the surface material	: 0.3 m

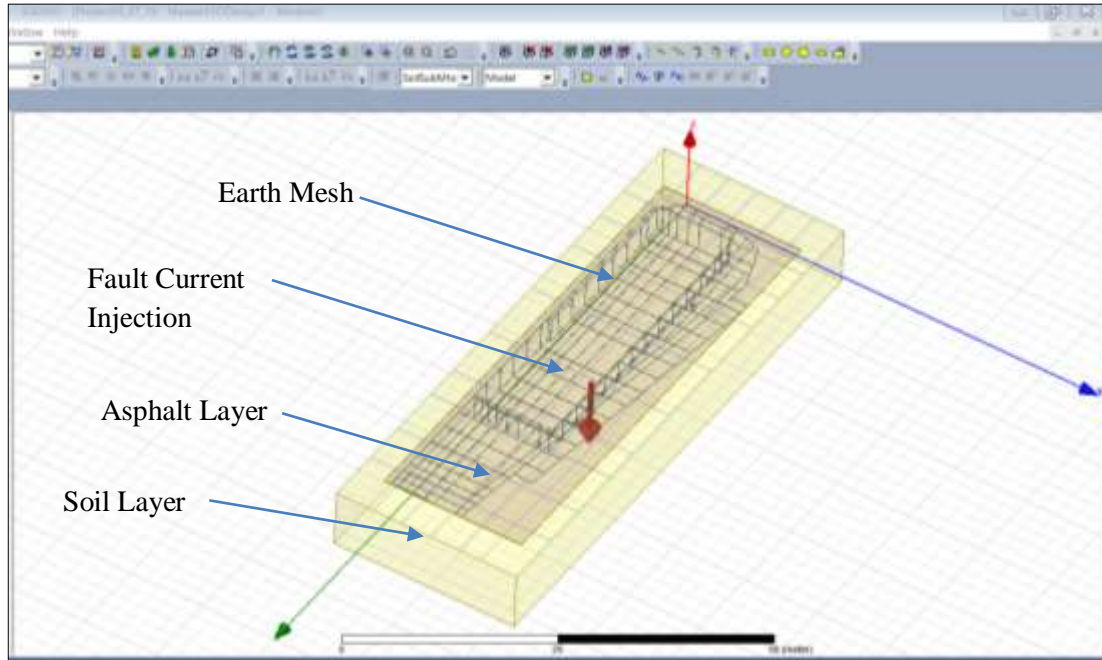


Figure 34: ANSYS Maxwell Model of Grounding System with Surface Layer

#### 4.4 Simulation of Actual Grounding System Model

The above model was simulated by applying a current of 25 kA for a duration of one second. The results of the simulation are shown in Figure 35, Figure 36 and Figure 37.

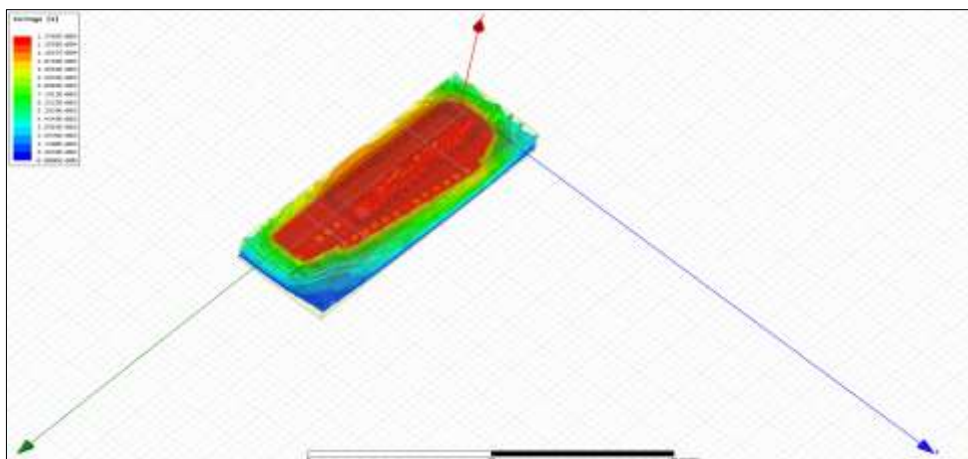


Figure 35: Ground Potential Rise over the Grounding System with Surface Layer

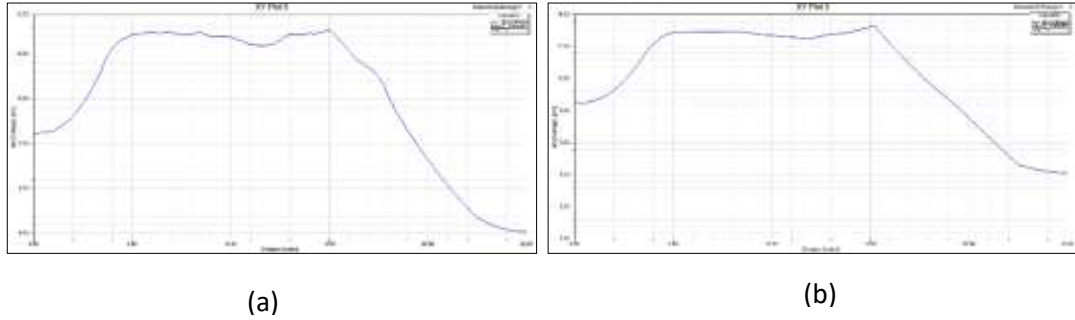


Figure 36: GPR Profile along a Line Parallel to Y-Axis  
 (a) Without Surface Layer (b) With Surface Layer

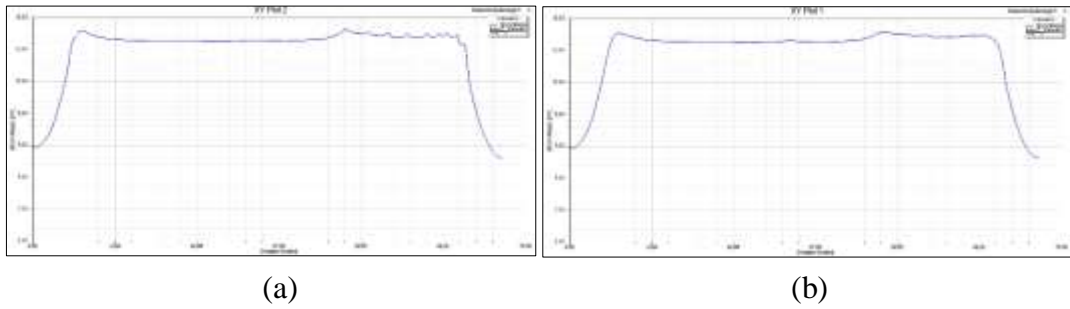


Figure 37: GPR Profile along a Line Parallel to X-Axis  
 (a) Without Surface Layer (b) With Surface Layer

The simulation results show that the high resistive surface layer has caused to smoothen the ground potential rise over the surface of the grounding system. The voltage profile exhibits almost similar pattern and amplitude. The purpose of using high resistive surface layer is to increase the contact resistance between foot and the earth, hence reduce the body current and this does not create a significant impact on ground potential rise on the surface of the grid substation. However, due to the high contact resistance the risk of hazardous electric shock on a person who bridges two points on the surface of the grid substation is reduced with the introduction of high resistive surface material.

#### 4.5 Evaluate the Risk in the Area Outside the Grid Substation

The grid substation grounding system ensures the safety of the personnel working in the grid substation. However it is important to discuss about the safety beyond the boundary of the grid substation.



the gradient of the graph does not change significantly in the area just outside the boundary.

The potential difference of two points on the surface which are one meter apart was obtained from the ground potential graph shown in Figure 38. The step potential is calculated as follows.

$$\begin{aligned}\text{Step Potential at A} &= 11.17 \text{ kV} - 9.30 \text{ kV} \\ &= 1.87 \text{ kV}\end{aligned}$$

$$\begin{aligned}\text{Step Potential at B} &= 9.97 \text{ kV} - 8.23 \text{ kV} \\ &= 1.74 \text{ kV}\end{aligned}$$

The step potential calculated using the graph is significantly higher than the tolerable step voltages of the area beyond the boundary of the grid substation. This implies that a person bridging two points of the surface in the land adjacent to the grid substation could be exposed to a risk of electric shock due to step potential. This area is outside the boundary of the grid substation, therefore it is impractical to do surface treatment or restrict this area to the public. Therefore the risk minimization method for this area need to be implemented from the inside of the grid substation.

### PROPOSED RISK MINIMIZATION TECHNIQUE

---

A properly designed grid substation grounding system protects a person working in the grid substation from the hazardous touch voltage and step voltage. However it is essential to ensure that not only the people working in the grid substation, but also the people in the vicinity of the grid substation outside the boundary of it are also risk free. This study identified the possible risk situation to the people living in the vicinity of the grid substation by exposing into intolerable high voltages.

Surface treatment using a high resistive material such as crushed rock or tar macadam improves the tolerable touch voltage and step voltage limits. The surface treatment increases the contact resistance between human foot and the earth. However since the land outside the boundary of the grid substation is not belongs to the utility company, it is impractical to do the surface treatment there.

The propagation of fault current over earth creates potential rise around the land outside the grid substation boundary. The simulation results of the grid substation grounding systems, indicate this potential rise and how it degrades with the increase of the distance from the grid substation.

#### **5.1 Application of the Effect of Reflection Factor for Vertical Layers**

As discussed in the literature review, the percentage of the transferred potential increases with the increase of “K factor”. The gradient of drop of percentage amount of transferred potential drop is higher at the area close proximity to the grid substation. The same concept was tested for vertical layers of different materials. An ANSYS Maxwell model was created to evaluate the concept of introducing a vertical layer of a high resistive material at the boundary of the grid substation.

As the initial setup the depth of this vertical layer was considered as 1.2 m. The tar macadam (Asphalt) was selected as the high resistive material for making the vertical layer around the grid substation boundary. Figure 39 shows the ANSYS Maxwell

model with vertical Asphalt layer and the concrete foundation of the boundary wall and Figure 40 shows the section view of the arrangement.

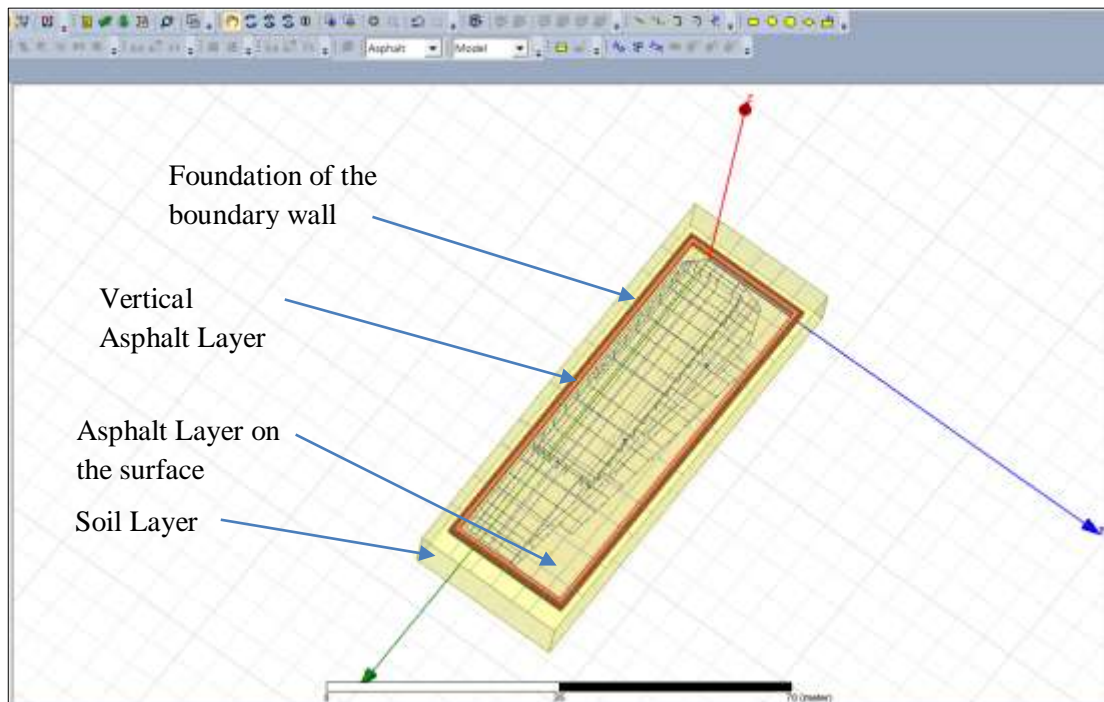


Figure 39: Grounding System Model with Vertical Asphalt Layer around the Boundary

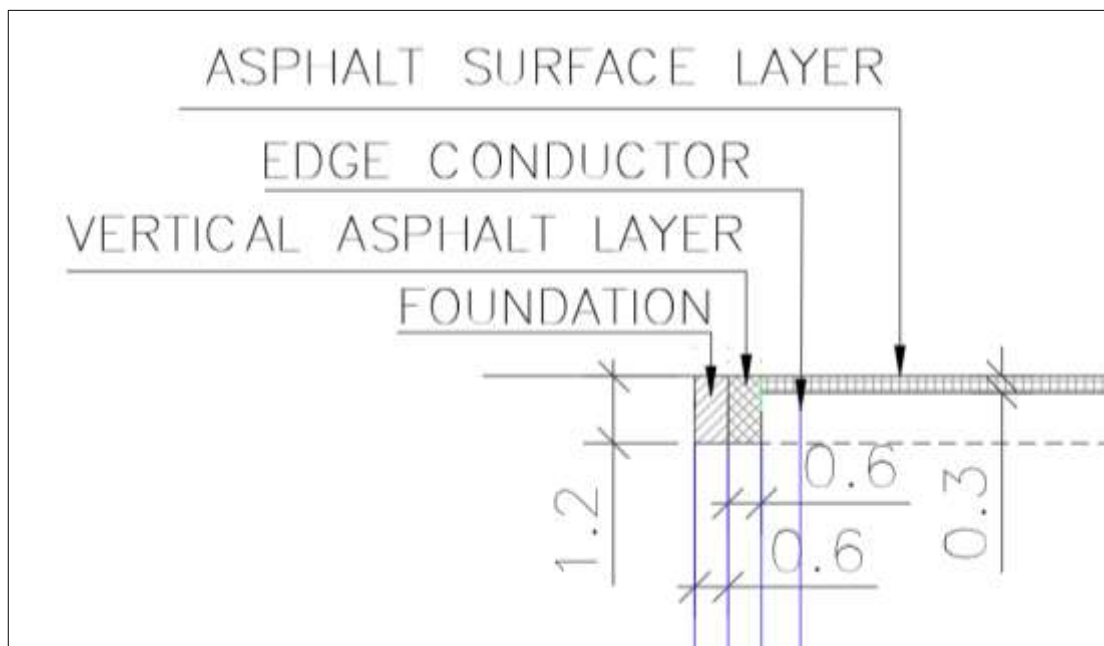


Figure 40: Section View of the Vertical Layers

The above ANSYS Maxwell model was simulated having the same input parameters. The plot of ground potential rise is shown in Figure 41.

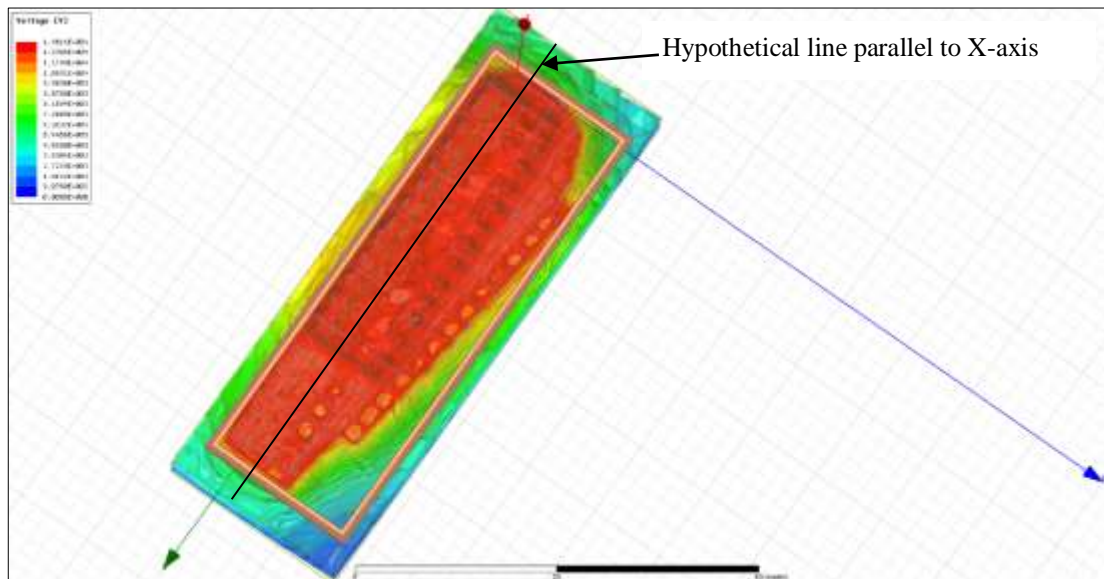


Figure 41: GPR over the Grounding System with Vertical Asphalt Layer

The Ground Potential Rise along a hypothetical line parallel to X axis is shown in the Figure 42.

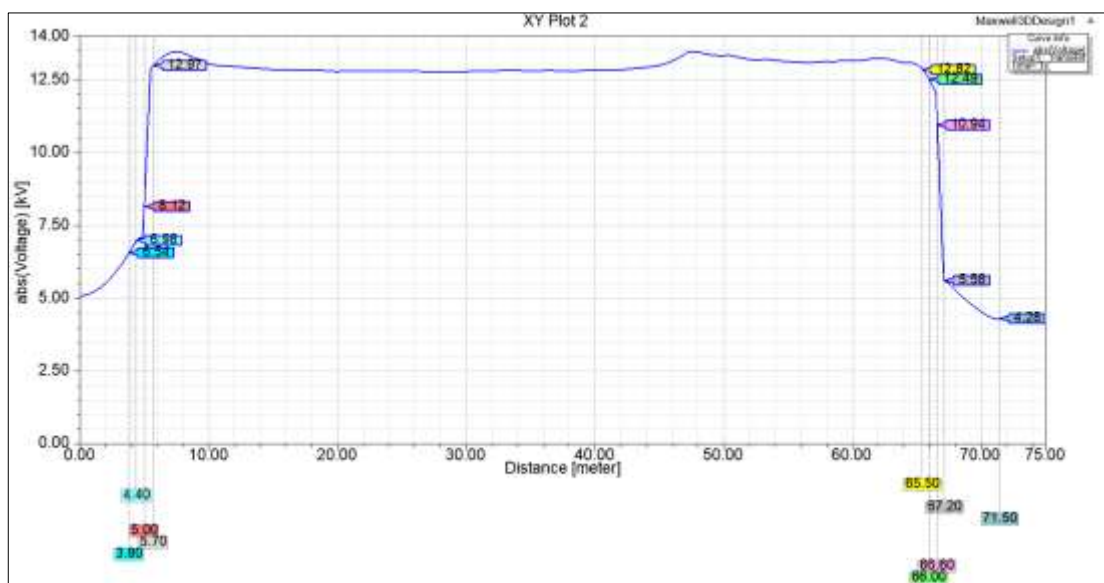


Figure 42: GPR Profile along a line parallel to X-Axis with Vertical Asphalt Layer

The ground potential profile with reference to the vertical section of the soil structure is shown in Figure 43. It can be observed that at the vertical Asphalt layer the potential rise drops in higher percentage. The comparison of ground potential profiles with surface asphalt layer and without vertical asphalt layer and with vertical asphalt layer is shown in Figure 44. It can be observed that the potential gradient in the area beyond

the boundary of the grid substation is reduced after the introduction of the vertical asphalt layer.

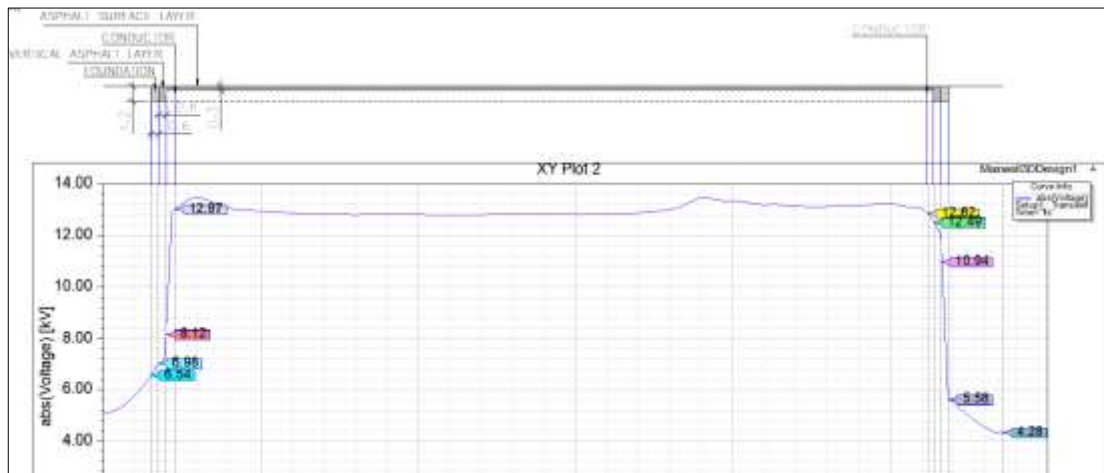


Figure 43: Ground Potential Profile and Section of Grounding System

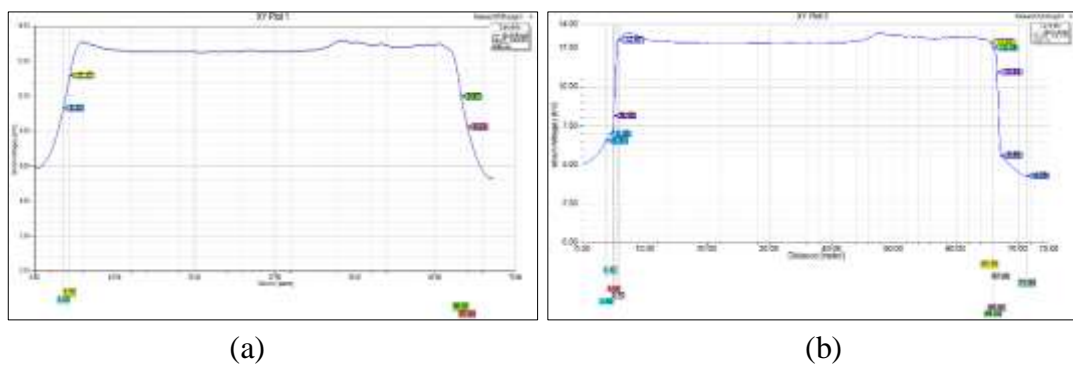


Figure 44: Ground Potential Rise Profile along a Line Parallel to X-Axis  
 (a) Without Vertical Asphalt Layer (b) With Vertical Asphalt Layer

The ground potential rise plot shows a steep drop of ground potential at the boundary of the grid substation after the introduction of vertical layer of high resistive material. This steep drop of ground potential rise occurs within the asphalt layer and the foundation of the boundary wall. This area is barely accessible and it is not possible to bridge two sides of the asphalt layer. Therefore the possibility a person exposing to this potential difference is minimum. The step potential of the area beyond the boundary of the grid substation has been calculated from the results of the simulation considering the difference of the ground potential at the boundary and a points which

is one meter beyond the boundary. These two points were considered to obtain highest potential difference outside the grid substation boundary.

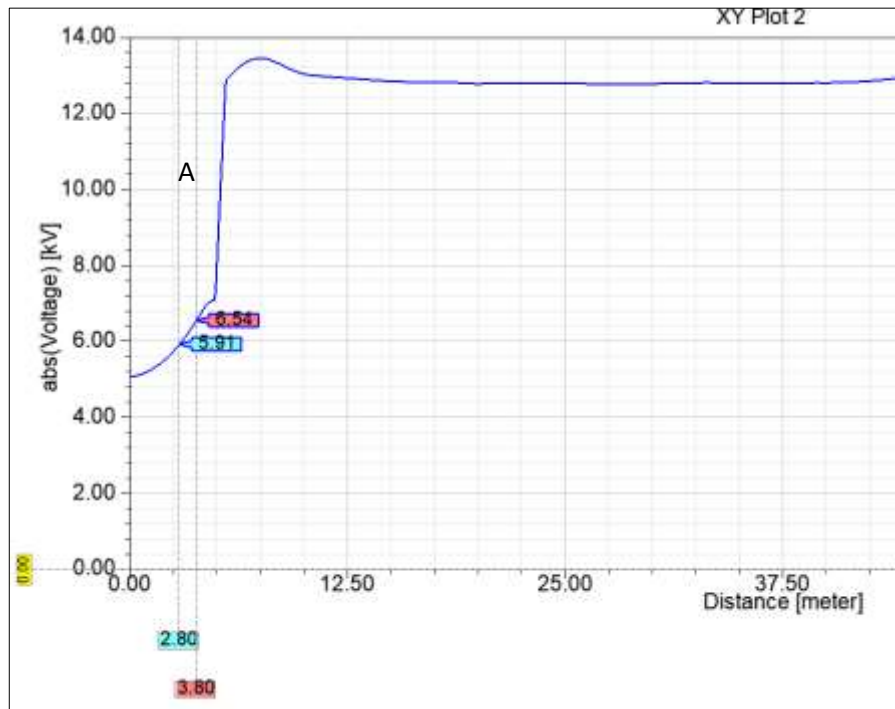


Figure 45: Step Potential at the Boundary of the Grid Substation with Asphalt Layer Depth of 1.2 m

$$\begin{aligned} \text{Step Potential at A} &= 6.54 \text{ kV} - 5.91 \text{ kV} \\ &= 630 \text{ V} \end{aligned}$$

The step potential just outside the grid substation boundary before the introduction of vertical asphalt layer was 1.87 kV and with the vertical asphalt layer the step potential has dropped to 630 V. Since the tolerable step voltage for the soil model used for the analysis is 176.6 V, the effect of the used vertical asphalt layer is not sufficient for the site. Therefore, further analysis was done for different dimensions of the asphalt layer to determine the optimum size of the asphalt layer. The dimensions of the Asphalt layer was considered by increasing the depth of it and perform the simulation first and then increase the width of it and perform the simulations. However, there is a constraint on increasing the width of the asphalt layer, as it consumes considerable land area of the grid substation which we cannot accept in a congested design.

## 5.2 Simulation for the Different Depths of the Asphalt Layer

The analysis was performed for different depths of the Asphalt layer by increasing the depth by 0.3 m for each step of simulation. The width of the Asphalt layer was kept at 0.6 m and the depth was increased from 1.2 m to 1.5m, 1.8 m, 2.1 m, 2.4 m, 2.7 m and 3.0 m.

The depth of the Asphalt layer was increased to 1.5m and perform the simulation. The Ground Potential Rise Profile along X-Axis is shown in the Figure 46.

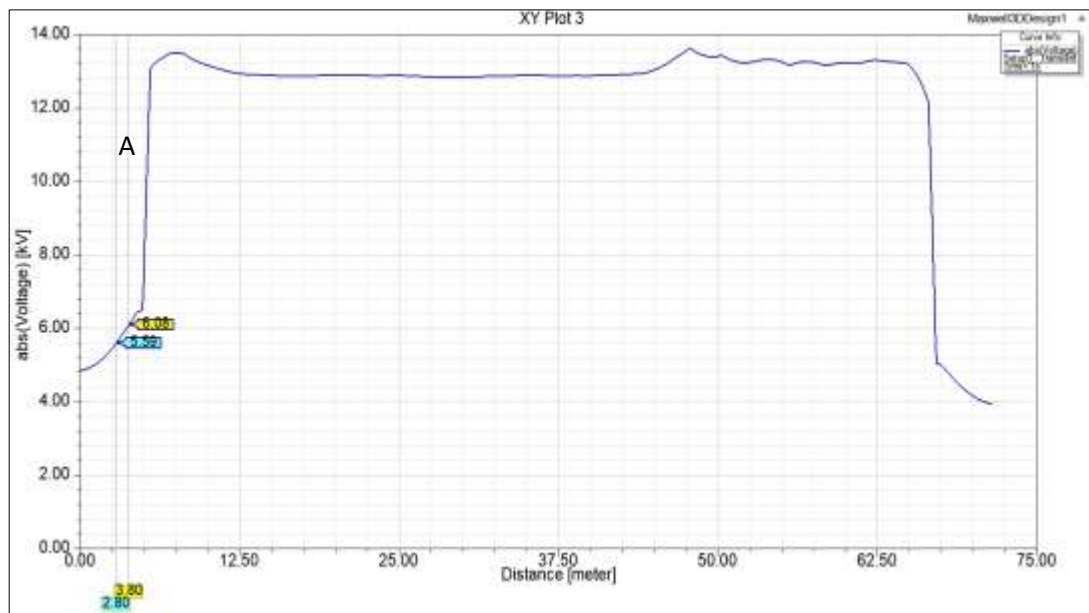


Figure 46: Step Potential with Asphalt Layer Depth of 1.5m

The step potential at the same position was obtained as follows.

$$\begin{aligned}\text{Step Potential at A} &= 6.08 \text{ kV} - 5.59 \text{ kV} \\ &= 490 \text{ V}\end{aligned}$$

Similarly, the simulations were carried out for different depths of the Asphalt Layer while keeping all other parameters unchanged. The Ground Potential Rise profiles along a line parallel to X-Axis for each depth of the vertical layer are shown in the Figure 47 to Figure 51.

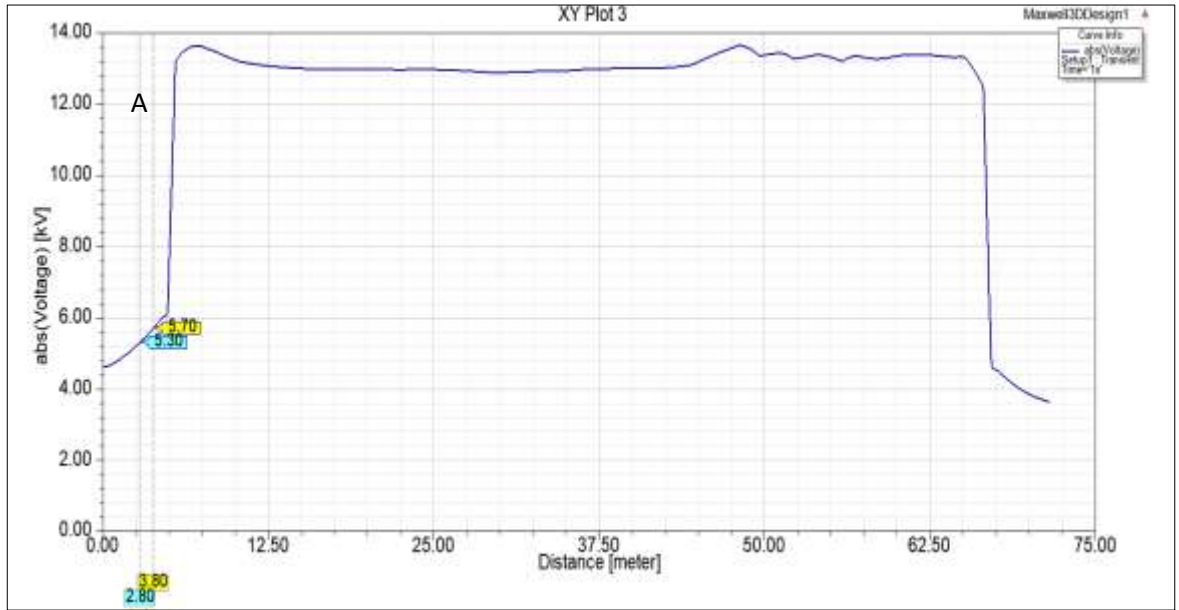


Figure 47: Step Potential with Asphalt Layer Depth of 1.8m

$$\begin{aligned} \text{Step Potential at A} &= 5.70 \text{ kV} - 5.30 \text{ kV} \\ &= 400 \text{ V} \end{aligned}$$

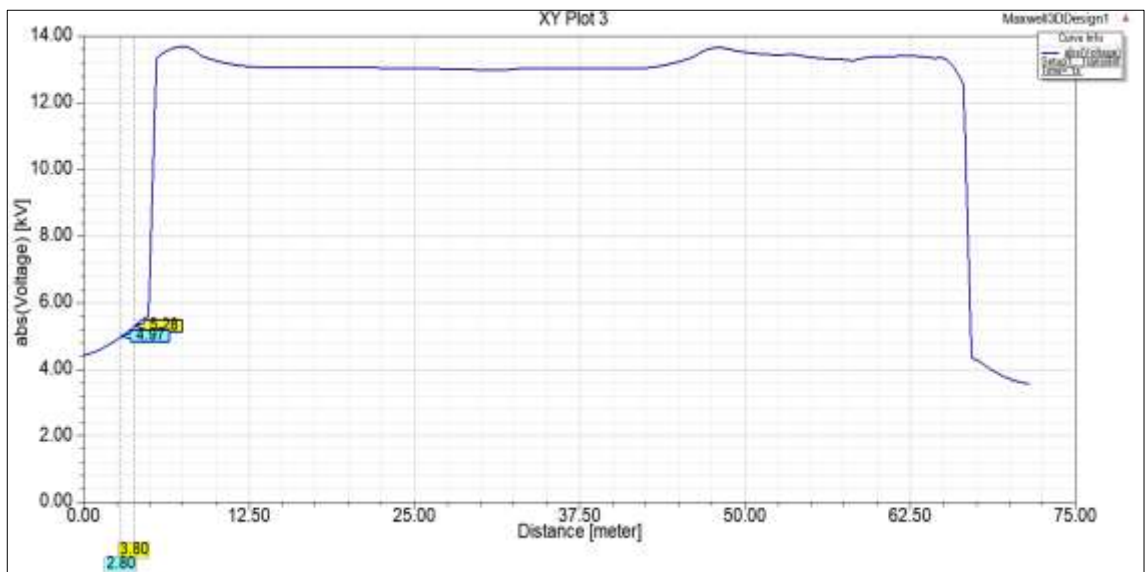


Figure 48: Step Potential with Asphalt Layer Depth of 2.1 m

$$\begin{aligned} \text{Step Potential at A} &= 5.28 \text{ kV} - 4.97 \text{ kV} \\ &= 310 \text{ V} \end{aligned}$$

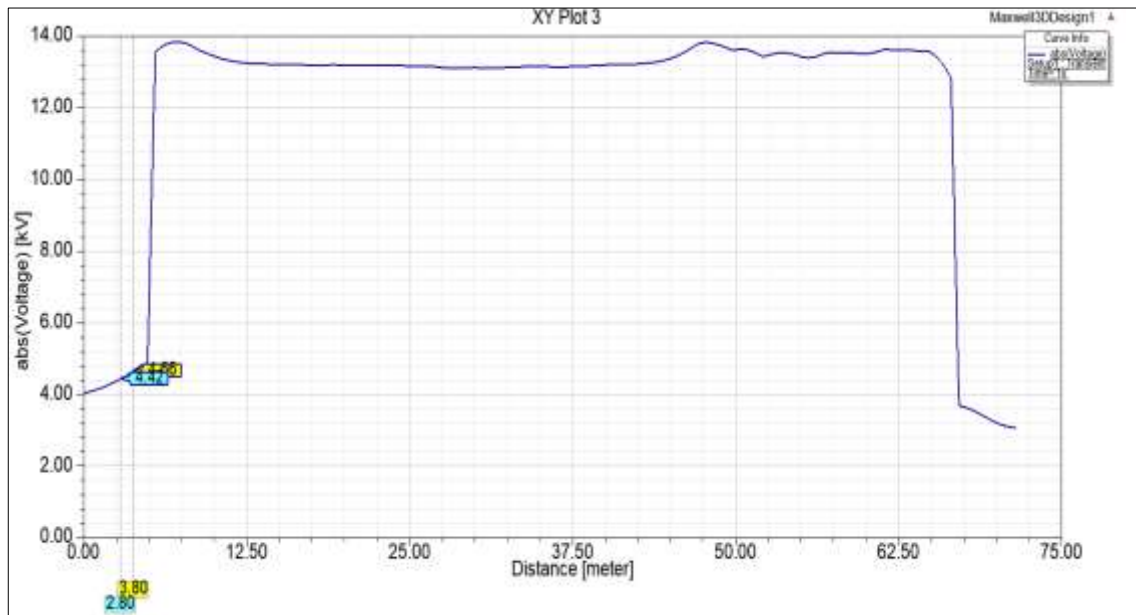


Figure 49: Step Potential with Asphalt Layer Depth of 2.4m

Step Potential at A = 4.66 kV – 4.42 kV  
= 240 V

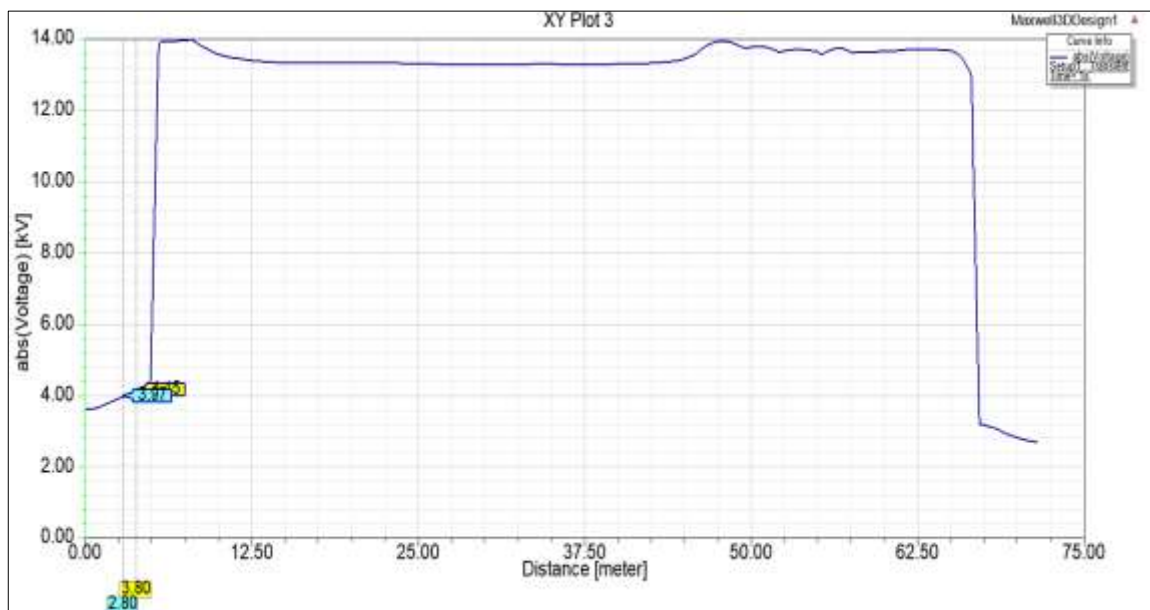


Figure 50: Step Potential with Asphalt Layer Depth of 2.7m

Step Potential at A = 4.15 kV – 3.97 kV  
= 180 V

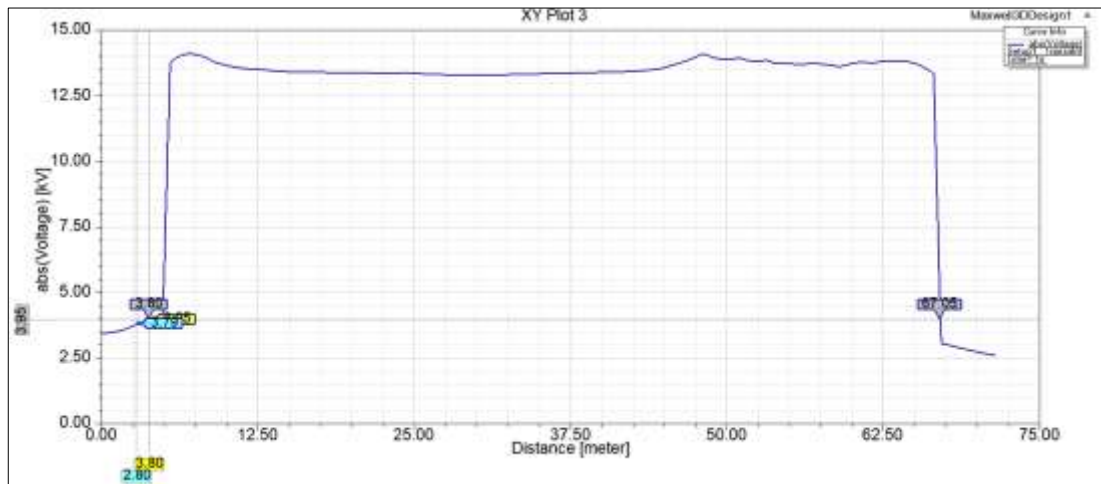


Figure 51: Step Potential with Asphalt Layer Depth of 3.0m

$$\begin{aligned} \text{Step Potential at A} &= 3.95 \text{ kV} - 3.79 \text{ kV} \\ &= 160 \text{ V} \end{aligned}$$

### 5.3 Simulation for the Different Widths of the Asphalt Layer

In order to examine the effect of the width of the Asphalt layer, analysis was done for different widths of the Asphalt layer. It is not practical to increase the width of the vertical Asphalt layer, similar the depth of the vertical layer increased. Therefore, the width was increased from 0.6m to 0.7 m, 0.8 m, 0.9 m and 1.0 m, keeping the depth of the Asphalt layer at 1.2 m. The simulation results are shown in the Figure 52 to Figure 55.

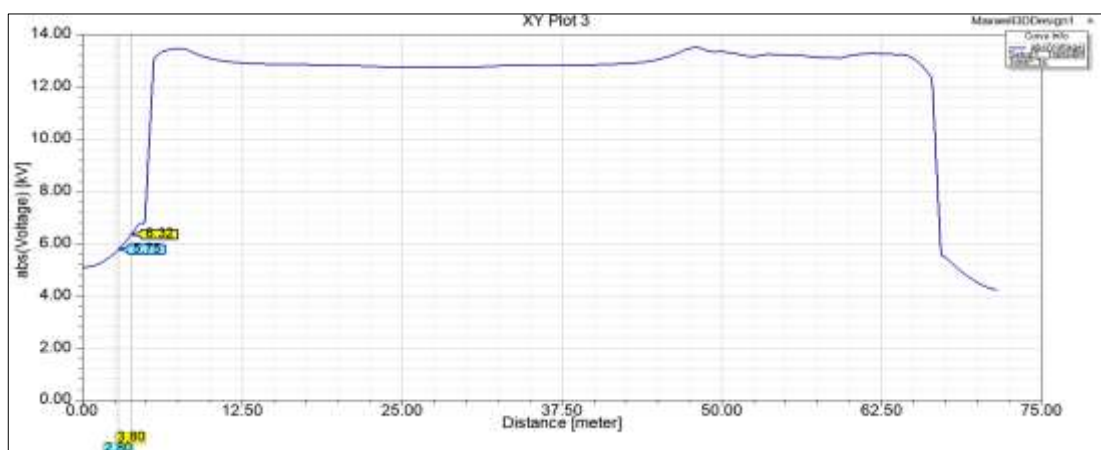


Figure 52: Ground Potential Profile with Asphalt Layer width of 0.7 m

Step Potential at A = 6.32 kV – 5.75 kV  
= 570 V

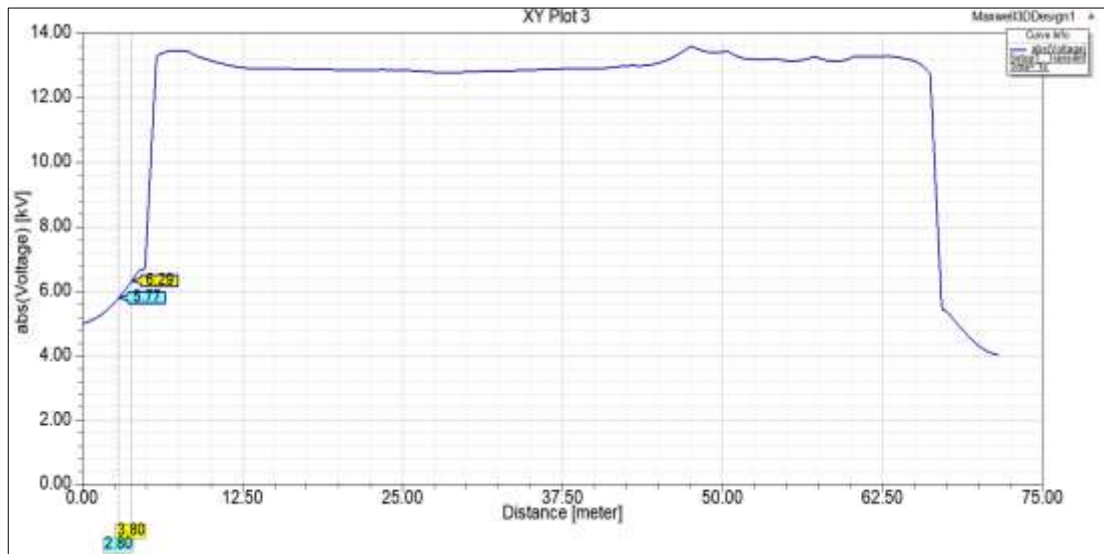


Figure 53: Ground Potential Profile with Asphalt Layer width of 0.8 m

Step Potential at A = 6.29 kV – 5.77 kV  
= 520 V

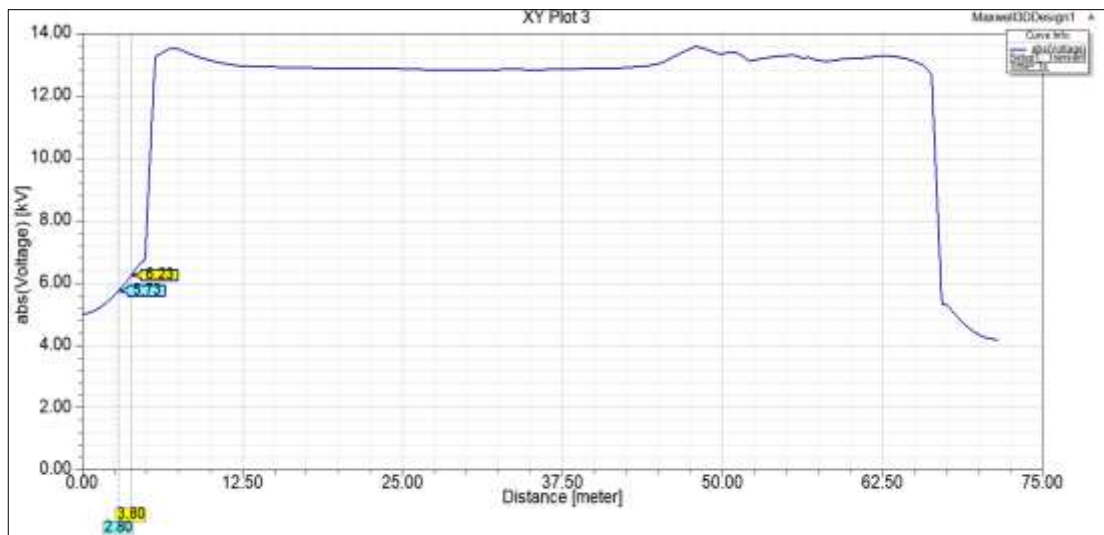


Figure 54: Ground Potential Profile with Asphalt Layer width of 0.9 m

Step Potential at A = 6.23 kV – 5.73 kV  
= 500 V

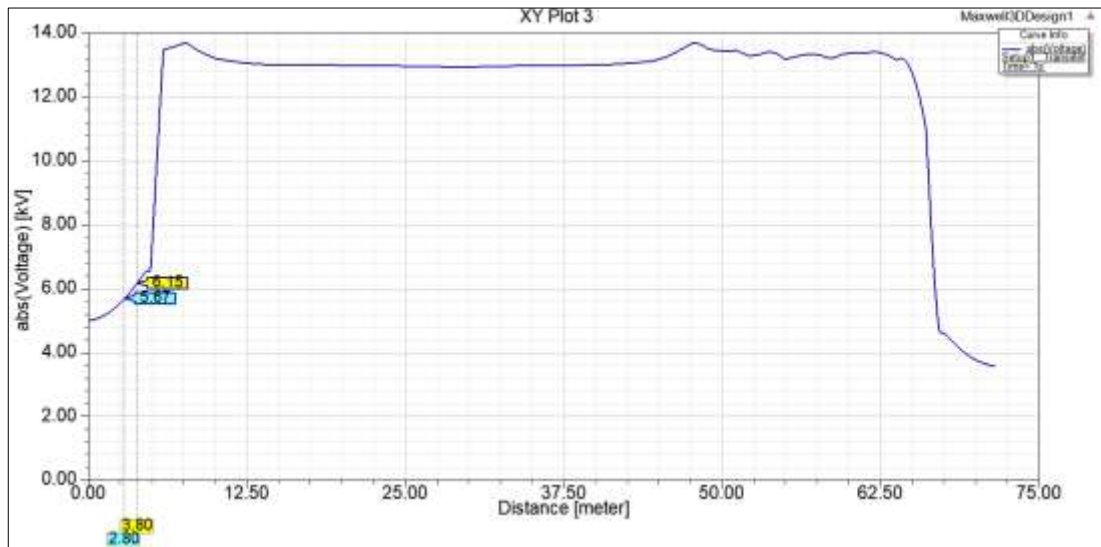


Figure 55: Ground Potential Profile with Asphalt Layer width of 1.0 m

$$\begin{aligned} \text{Step Potential at A} &= 6.15 \text{ kV} - 5.67 \text{ kV} \\ &= 480 \text{ V} \end{aligned}$$

**6.1 Summary of Simulation Results for Different Depths of the Vertical Asphalt Layer**

The step potential at the boundary of the grid substation was obtained from simulation results by varying the depth of the Asphalt layer, while keeping the width of the Asphalt layer at 0.6 m. The results have been summarized in the following Table.

Table 5: Step Potential at the Boundary of the Grid Substation for Different Depths of Asphalt Layer

Depth of Asphalt Layer (m)	Step Potential at Boundary (V)
1.2	630
1.5	490
1.8	400
2.1	310
2.4	240
2.7	180
3.0	160

The above results are plotted in a graph shown in the Figure 56.

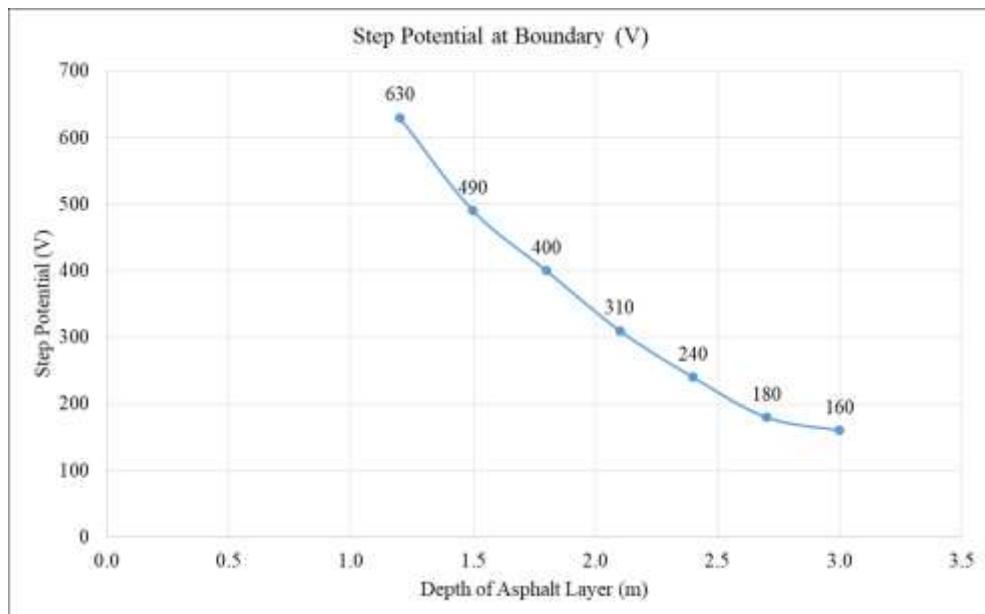


Figure 56: Step Potential vs. Depth of Asphalt Layer

According to the simulation results, the increase of the depth of the vertical Asphalt layer around the boundary of the grid substation has significant effect of the potential rise in the land area adjacent to the grid substation. The step potential at the boundary of the grid substation reached to the tolerable limits with a vertical Asphalt layer which is having dimensions as a depth of 3 m and a width of 0.6 m. These results were further analyzed as follows.

### 6.1.1 Drop of Step Potential with the Increase of Depth of Asphalt Layer

According to the simulation results, the step potential at the boundary of the grid substation drops with the increase of the depth of the Asphalt layer. The percentage change of step potential relative to the increase of the depth of Asphalt layer is calculated as follows.

$$\begin{aligned} \%drop\ of\ V_{Step\ at\ 1.5m} &= \frac{V_{Step\ 1.2\ m} - V_{Step\ 1.5\ m}}{V_{Step\ 1.2\ m}} \\ &= \frac{630 - 490}{630} \times 100\% \\ &= 22\% \end{aligned}$$

$$\begin{aligned} \%drop\ of\ V_{Step\ at\ 1.8m} &= \frac{V_{Step\ 1.5\ m} - V_{Step\ 1.8\ m}}{V_{Step\ 1.5\ m}} \\ &= \frac{490 - 400}{490} \times 100\% \\ &= 18\% \end{aligned}$$

$$\begin{aligned} \%drop\ of\ V_{Step\ at\ 2.1m} &= \frac{V_{Step\ 1.8\ m} - V_{Step\ 2.1\ m}}{V_{Step\ 1.8\ m}} \\ &= \frac{400 - 310}{400} \times 100\% \\ &= 23\% \end{aligned}$$

The percentage change step potentials were calculated for all other sizes of the Asphalt layer and tabulated in Table 6.

**Table 6: The percentage change of step potential with the increase of the depth of Asphalt layer**

Depth of Asphalt Layer (m)	Step Potential at Boundary (V)	Percentage change of Step Potential ( $x_i$ )
1.2	630	
1.5	490	22%
1.8	400	18%
2.1	310	23%
2.4	240	23%
2.7	180	25%
3.0	160	11%

The above results are plotted in a graph shown in the Figure 57.

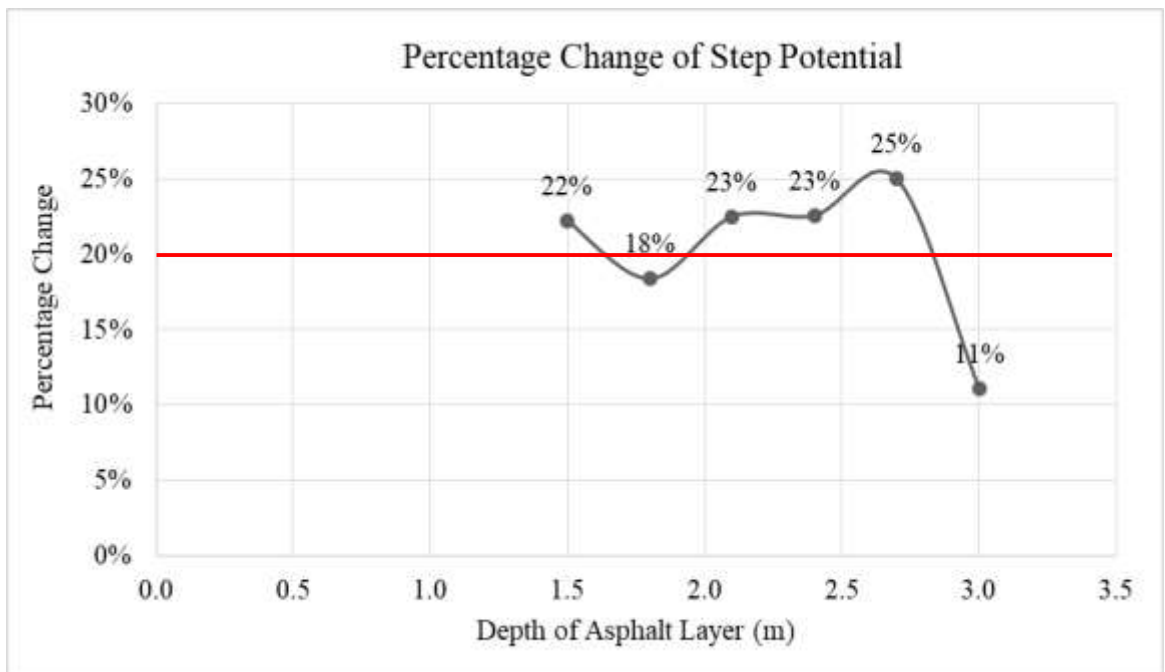


Figure 57: Percentage Change of Step Potential vs. Depth of Asphalt Layer

$$\begin{aligned}
 \text{Average Percentage change of Step Potential} &= \frac{22\%+18\%+23\%+23\%+25\%+11\%}{6} \\
 &= 20\% \\
 \text{Standard deviation} &= \sqrt{\frac{1}{6} \sum_{i=1}^6 (x_i - 20)^2} \\
 &= 5\%
 \end{aligned}$$

According to the above results, it can be seen that when increasing the depth of the vertical Asphalt layer by every 0.3 m, the average percentage change of the Step Potential at the boundary of the grid substation is 20% at a standard deviation of 5%.

## 6.2 Summary of Simulation Results for Different Widths of the Vertical Asphalt Layer

The step potential at the boundary of the grid substation was obtained from simulation results by varying the width of the Asphalt layer, while keeping the depth of the Asphalt layer at 1.2 m. The results have been summarized in the Table 7.

Table 7: Step Potential at the Boundary of the Grid Substation for Different Widths of Asphalt Layer

Width of Asphalt Layer (m)	Step Potential at Boundary (V)
0.6	630
0.7	570
0.8	520
0.9	500
1.0	480

The above results are plotted in a graph shown in Figure 58. According to the simulation results, the increase of the width of the vertical Asphalt layer around the boundary of the grid substation reduces the potential rise in the land area adjacent to the grid substation. These results were further analyzed by calculating the percentage change of step potential relative to the increase of the width of Asphalt layer.

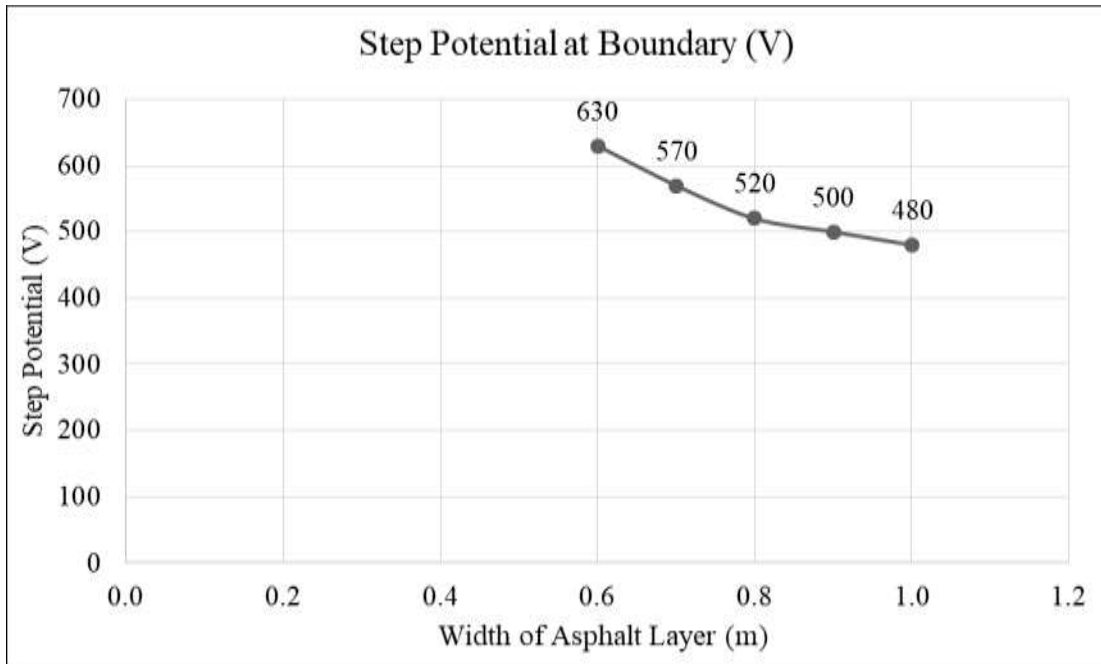


Figure 58: Step Potential vs. Width of Asphalt Layer

$$\begin{aligned}
 \%drop\ of\ V_{Step\ at\ 0.7m} &= \frac{V_{Step_{0.6m}} - V_{Step_{0.7m}}}{V_{Step_{0.6m}}} \\
 &= \frac{630 - 570}{630} \times 100\% \\
 &= 9.5\%
 \end{aligned}$$

The percentage change step potentials were calculated for all other sizes of the Asphalt layer and tabulated as in the Table 8.

Table 8: The Percentage Change of Step Potential with the Increase of the Width of the Asphalt Layer

Width of Asphalt Layer (m)	Step Potential at Boundary (V)	Percentage Change of Step Potential
0.6	630	
0.7	570	9.5 %
0.8	520	8.8 %
0.9	500	3.8 %
1.0	480	4.0 %

The above results are plotted in a graph shown in the Figure 59.

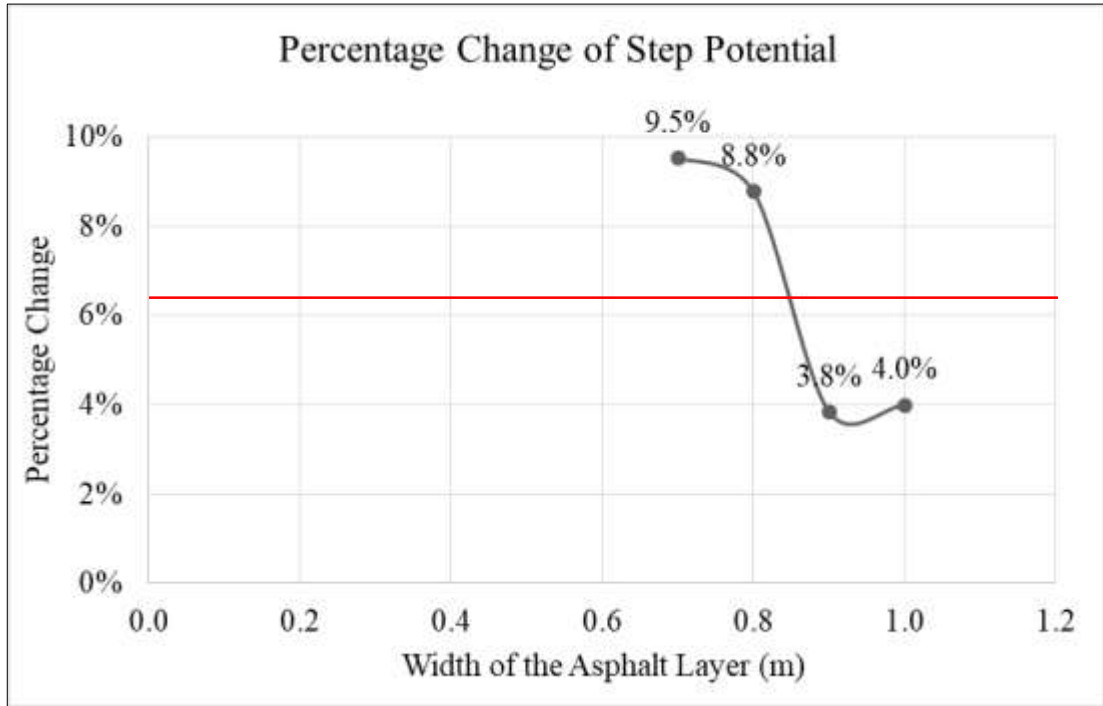


Figure 59: Percentage Change of Step Potential vs. Width of Asphalt Layer

$$\begin{aligned} \text{Average Percentage change of Step Potential} &= \frac{9.5\% + 8.8\% + 3.8\% + 4\%}{6} \\ &= 6.5\% \end{aligned}$$

$$\begin{aligned} \text{Standard deviation} &= \sqrt{\frac{1}{6} \sum_{i=1}^6 (x_i - 6.5)^2} \\ &= 3\% \end{aligned}$$

According to the above results, it can be seen that when increasing the width of the vertical Asphalt layer by every 0.1 m, the average percentage change of the Step Potential at the boundary of the grid substation is 6.5 % and the standard deviation of the Percentage Change of Step Potential is 3%.

The step potential values at 0.6 m and 0.9 m widths were considered in order to compare with the drop of step potential for the increase of the Asphalt layer depth by 0.3m.

$$\begin{aligned}
\%drop\ of\ V_{Step\ at\ 0.6m\ to\ 0.9m} &= \frac{V_{Step0.6\ m} - V_{Step0.9\ m}}{V_{Step0.6\ m}} \\
&= \frac{630 - 500}{630} \times 100\% \\
&= 20.63\%
\end{aligned}$$

It can be seen that the increase of the width of the vertical Asphalt layer by 0.3 m reduces the step potential at the boundary by 20.63%. However it is not practical to increase the width of a vertical Asphalt layer around the grid substation, as it consumes considerable land area of the grid substation which we cannot accept in a congested design.

**5.1 Discussion**

In Sri Lanka, demand for electricity is growing at a rate of 5-6% per annum. It is required to add more power plants and develop transmission infrastructure in order to cater this growing electricity demand. Construction of grid substations and transmission lines comes under transmission infrastructure development. In urban areas, it is costly and difficult to find suitable lands for construction of grid substations. Therefore the designs of the grid substation are limited to smaller land extent. The grid substation grounding system helps to ensure the safe working environment for the personnel in the grid substation. At a fault condition, the fault current passes to the earth through the grounding system. A properly designed grounding system provides lower grounding resistance, safe step potential and safe touch potential. However the grounding system does not provide protection to the area beyond the boundary of the grid substation. In some cases, the increase of ground potential of the area surrounding the grid substation could be hazardous, especially in the urban areas.

The risk minimization methods discussed in the literature review are mainly focused on decreasing the ground resistance and decreasing the potential rise of the grounding system. This would reduce the potential rise in the area beyond the grid substation. However, the discussed methods such as connecting main grounding system of the grid substation to a satellite grid could be not practical in an urban area due to unavailability of suitable lands. In addition, the connection between two ground grids would again develop hazardous environment to the people in the vicinity. The methods such as extending the grounding system beyond the boundary of the grid substation is not practical in the urban areas as it is not belonged to the utility company.

Apart from that, increasing burial depth of the ground conductors in order to attain safe step voltage outside grid substation would result in increase of touch voltage inside the grid substation. Installing the outer ground conductor inside the grid substation fence by keeping a higher gap between the fence (or the boundary wall) and

the grounding mesh is not practical in a design made for a limited plot of land. Such methods decrease the amount of buried conductor in the grounding design hence would increase the grounding resistance.

The flow of fault current to the ground increases the ground potential in the grid substation and the area surrounding the grid substation. The flow of electrical current depends on the resistivity of the soil. According to the resistivity of soil layers, the flow of current through the soil could be towards the adjacent land area or downwards into the earth. This has been represented using a term called reflection factor for the horizontal soil layers.

In this study, the soil structure of the selected site and the ground grid design was modeled in ANSYS Maxwell software. First the ground potential rise of the selected site was analyzed by injecting fault current into the ground grid. The simulation results were used to justify the ground potential rise over the surface of the grid substation and the land beyond the boundary of the grid substation. According to the simulation results and calculation of tolerable voltages, it was identified that the area beyond the boundary of the grid substation is not safe due to high potential gradient.

The concept of reflection factor was tested in the model, by introducing an artificial vertical layer of Asphalt. Asphalt is a high resistive material in both dry and wet conditions. The simulations were done for different sizes of the Asphalt layer by increasing the depth and the width of it.

The simulation results show that increasing the depth of the Asphalt layer by every 0.3 m, the average percentage change of the Step Potential at the boundary of the grid substation is 20% at a standard deviation of 5%. Also the results show that increasing the width of the vertical Asphalt layer by every 0.1 m, the average percentage change of the Step Potential at the boundary of the grid substation is 6.5 % and the standard deviation of the Percentage Change of Step Potential is 3%.

## **5.2 Conclusion**

According to the results obtained, it can be concluded that introducing vertical layer of high resistive material such as Asphalt around the boundary of the grid substation reduces ground potential rise in the area beyond the boundary of the grid substation, which results in reducing the risk of step potential shock.

## **5.3 Recommendation**

The results of the study show that introducing a vertical layer of high resistive material such as Asphalt around the boundary of the grid substation reduces the risk of step potential risk in the area beyond the grid substation. A vertical layer of Asphalt having a width of 0.6 m reduces the Step Potential at the boundary by 20% for each 0.3 m increase of depth of the model used in this study. The dimensions of this vertical layer need to be quantified according to the simulation results of the model of the soil structure, grounding system of the particular grid substation and the material used as vertical layer.

## **5.4 Limitations of the Study**

The results of the study is limited to a particular grid substation grounding system and the simulations were done only for the soil model of the particular grid substation. The surface of the area beyond the boundary of the grid substation was considered as unpaved and having the same soil resistivity as it in the grid substation premises. Since the different sites have different soil resistivity structures the modelling has to be done for each and every site as required. The results can be verified at a site measurement after implementing the proposed solution with a vertical layer of high resistive material. In addition, the ANSYS Maxwell software which was used to model the grounding system was not specifically built for modelling the grounding systems. This software is widely used in solving problems using finite element method. Finite element method is highly preferred in the industrial software particularly built for analyzing the grid substation grounding systems.

## REFERENCES

- [1] IEEE 80-2013, "IEEE Guide for Safety in AC Substation Grounding", New York, U.S.A.
- [2] A.Y. Wu, A.P. Meliopoulos, "Analysis of Ground Potential Gradients around Power Substations", 1990 IEEE International Conference.
- [3] IEEE 81-2012, "IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System", New York, U.S.A.
- [4] J.A. Sa'ed, M.L. Di Silvestre, E. Riva, P. Colella, E. Pons, "On the Hazardous Situations due to the Presence of HV/MV Substations in Urban Areas", 2017 IEEE International Conference.
- [5] Y. Rajotte, J de Seve, J. Fortin, R. Lehoux, G. Simard, "Earth Potential Rise Influence near HV Substation in Rural Areas", 18<sup>th</sup> International Conference on Electricity Distribution, 2015.
- [6] N.A.A. Rahman, A.M.A. Marican, "Assessment of Substation Fence Earthing", 2010 IEEE International Conference.
- [7] Electrical and Magnetic Properties of Rocks, Soils and Fluids, Nigel J. Cassidy, in Ground Penetrating Radar Theory and Applications, 2009. <https://www.sciencedirect.com/topics/earth-and-planetary-sciences/permittivity>
- [8] D. Mukheddar, Y. Gervais, F. Dawalibi, "Modelling of Potential Distribution around a Grounding Electrode", 1973 IEEE PES Winter Meeting, New York.
- [9] X. Cao, G. Wu, S. Li, W. Zhou, R. Li, "A Simple formula of Grounding Grid Resistance in Vertical Two-Layer Soil", 2008 IEEE International Conference.

- [10] Q. Meng, J. He, F.P Dawalibi, J. Ma, “A New Method to Decrease Ground Resistances of Substation Grounding Systems in High Resistivity Regions”, IEEE Transaction on Power Delivery, Vol 14, No. 3, July 1999.
- [11] A. Kumar, H.R Seedhar, “Grounding System for High Resistivity Limited Area Substations in Hilly Region of Himachal Pradesh”, 16<sup>th</sup> National Power Systems Conference, 15<sup>th</sup> – 17<sup>th</sup> December, 2010.
- [12] W. F. H. Wan Ahmad, Y. J. Voon, J. Jasni, M. Z. A. Ab-Kadir, C. Gomes, “Performance of Bentonite, Fly Ash and Wood Ash Mixtures as Grounding Enhancement Materials”, 2018 IEEE 7th International Conference on Power and Energy.
- [13] E. J. Rogers, R. H. Hall, and J. F. White, “Fault induced voltages on metallic fencing located in the vicinity of a high voltage substation”, IEEE Transaction on Power Apparatus and Systems, Vol. PAS-101, No. 3, March 1982.
- [14] Zacharias G. Datsios, Pantelis N. Mikropoulos, Andreas Teneketzoglou, Dimitrios Tzikas, “Safety Performance Evaluation if Fence Grounding Configurations in High Voltage Installations”, 49th International Universities’ Power Engineering Conference (UPEC), Cluj-Napoca, Romania, September 2014.