ESTIMATION OF EARTH ELECTRODE RESISTANCE OF ANTENNA STRUCTURES LOCATED IN NON-HOMOGENOUS GEOGRAPHIC TERRAIN USING FINITE ELEMENT ANALYSIS AND PREDICTIVE MODELLING

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Degree of Master of Science

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

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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

Signature of the supervisor: Date :

Dr. Asanka S. Rodrigo

DEDICATION

To my beloved parents, my wife & siblings and my workplace assisting co-workers for their endless guidance and support given throughout.

ACKNOWLEDGMENT

First, I would like to convey my sincere thank my research supervisor Dr. Asanka Rodrigo, Senior Lecturer, Department of Electrical Engineering, Faculty of Engineering, University of Moratuwa for the guidance, continuous support and the expertise knowledge sharing in the field of earthing and measurements to make this masters research a success.

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Finally, my heartiest gratitude shall to all members of my family, friends and colleagues who provided tremendous support throughout the research study.

ABSTRACT

The telecommunication sector is consisting of firms that facilitates communication on a mass scale, through the phone or the web, as wired or wireless services. These firms created their infrastructure that permits sending voice, audio, or video and kinds of data or information to be sent anyplace in the world. These companies created their infrastructure that allows transmitting voice, audio, or video and forms of information or data to be sent anywhere in the world.

It is observing that the Telecom infrastructure growth is in an aggressive mode even in Sri Lanka due to increase of the user groups and their complex needs for information sharing. As mobile devises become the most attractive device for the customers, operators have to provide these services through higher number of tower structures considering the countries geography and population distribution. With the increasing number of tower constructions and deployment of sensitive equipment with advance features observed due to increasing demand.

The tower is a high-elevated structure in the environment. The typical height of the structure may be around sixty meters and may reach up to hundred meters. The towers act as direct grounding path for lightning strike. Providing a sufficient grounding path to such situation is important to mitigate the hazardous nature to the equipment and the livelihood around the structure. A proper earthing system with low earth resistance shall be recommended avoiding possible hazards by ground potential rise.

Due to the located small land-plots for tower structures, carefully designed earthing network shall be implemented to achieve a lower earth resistance measurement at the tower. Operators have to maintain the earth resistance at tower sites as per the regulator bench marking. Telecommunications Regulatory Commission Sri Lanka (TRCSL) guideline for antenna structures imposed a recommendation to maintain the resistance level below 5 ohms for classified zones.

In order to comply for the guidelines, telecom operators have to deploy optimized earthing networks depending on the tower sites. The tower earthing system consists with copper conductors such as tapes and number of conductive rods to maintain a lower earth resistance value.

Estimation of earth resistance is a complicated practice effected by multiple factors due non-homogeneity of soils. Key observations are the variance in resistivity and resistance readings. At the time of designing, design itself get complex due to parallel conductor formation and its

interconnection conductor’s contribution to the results. In order to identify the earth networks effectiveness to surges and lightnings, the site’s earth resistance measurement is the main parameter which we can be measured at a site.

This thesis specifically discusses the effects and reasons for directional deviations observed in measured and theatrical values. Site earth resistance measurements have taken along various directions associated with resistive values and assessed with the measurements in four main directions of the sites along the tower legs. Earth networks would be simulated thorough ANSYS Maxwell to achieve earth resistance values. Numerical model will used to represent the resistance value in a single figure. Earthing network profile has been discussed and elaborated in relation calculate the resistance values from the simulation. Validation of the results has been performed through the comparison between simulation results and measurement values.

Analysis has done for various soil types in different geographies in different areas of the Mobitel network and possible limitations for study have been discussed. Thesis concludes with a model to represent the accurate earth resistance for the site. Further includes the general assumptions and the possibilities for the further studies of the model proposed in the thesis.

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ABBREVIATIONS

3D	- Three Dimensional
AC	- Alternative Current
ART	- Attached Rod Technique
DC	- Direct Current
GPR	- Ground Potential Rise
TRCSL	- Telecommunication Regularity Commission Sri Lanka
EPR	- Earth Potential Rise
LPL	- Lightning Protection Level
LPS	- Lightning Protection System
LV	- Low Voltage
MV	- Medium Voltage
RBS	- Radio Base Station
SPD	- Surge Protective Device

1 INTRODUCTION

1.1 Background

Sri Lanka has a very vibrant and dynamic telecommunication sector. This sector significantly contributes to economic growth by investment, employment, and innovation with the introduction of latest technologies. Modern telecom services are very important requirement for fast economic and social systems' growth of a country. Telecommunications Regulatory Commission of Sri Lanka (TRCSL) is mainly responsible in the aspects of spectrum management, network interoperability, licensing, competition, and compliance, quality of service, consumer relations, policy and international relations. Different approaches have been taken by the telecommunication operators to cater the higher demand and quality service.

The wireless telecom network provides voice and data communication services to the cellular phone customers. In a wireless network, the geographic area is divided into smaller geographic cells. These cells have their own tower and the base station equipment. Most of the cellular network a cell site consists with antennas and electronic communication equipment and mostly they are the higher location. Its' main items are antennas and transceivers, power sources and cabinet or shelter structures. With the rapid growth of the GSM technologies to provide wireless communications, telecom tower has become more important as it is the main component and the foundation of the access and transportation networks. These towers are taller up to 100m and has a higher vulnerability of exposing to lightning strike. In order to mitigate such risks from lighting and surges, earthing networks are deployed as per the guides provided by TRCSL.

With reference to the physical structural appearance, different types of cell phone towers are used in the industry. The main types of towers used in Sri Lankan cell phone network are described below.

- Monopole: Structure consists of single foundation point and implemented up to 200 feet.
- Lattice tower: These towers are commonly used in Sri Lanka. Mainly deployed as three and four leg structures.

• Guy-mast: Towers are less expensive compared other models. The main disadvantage is the need of a large area. Support the tower through the guy wires connected to the ground.

• Camouflaged: This type of towers is provided for special purposes such as maintaining aesthetic value of the tower location.

1.2 Problem Statement

Depending on the construction there are different types of towers used in telecommunications networks. Main purpose of the towers is to position the telecom hardware in higher elevations for a wider coverage and support there transportation networks such as microwave links. It needs to properly ground the facility to provide a well-bonded conduction between telecom hardware and the earth. These connections protect both personnel and equipment damages exposing to the surge voltages. These incidents happen due to various unexpected electrical scenarios such as lightning strikes and power line surges.

An increasing demand for complex electronic systems in telecom facilities, which are very much vulnerable for electrical surges, has noticed an increase in the importance on grounding and earthing methods. The recent advancements of the industry have led further development of more complex earthing networks. Grounding system of a telecom tower is one of the most important parts of the installation in relation to lightning and surge protection. Achieving lower ground resistance is a challenging task due space limitation, soil properties, and geography and climate conditions of the site. Installation material used for earthing network also affecting the resistance values.

Frequent measurement of earthing network resistance is very important to maintain a healthy ecosystem. Reading of the earth resistance value is a representation of the health level of the earthing network, which is also an accessing factor by the TRCSL. Figure 1-1 shows the typical earthing arrangement of a telecommunication station.

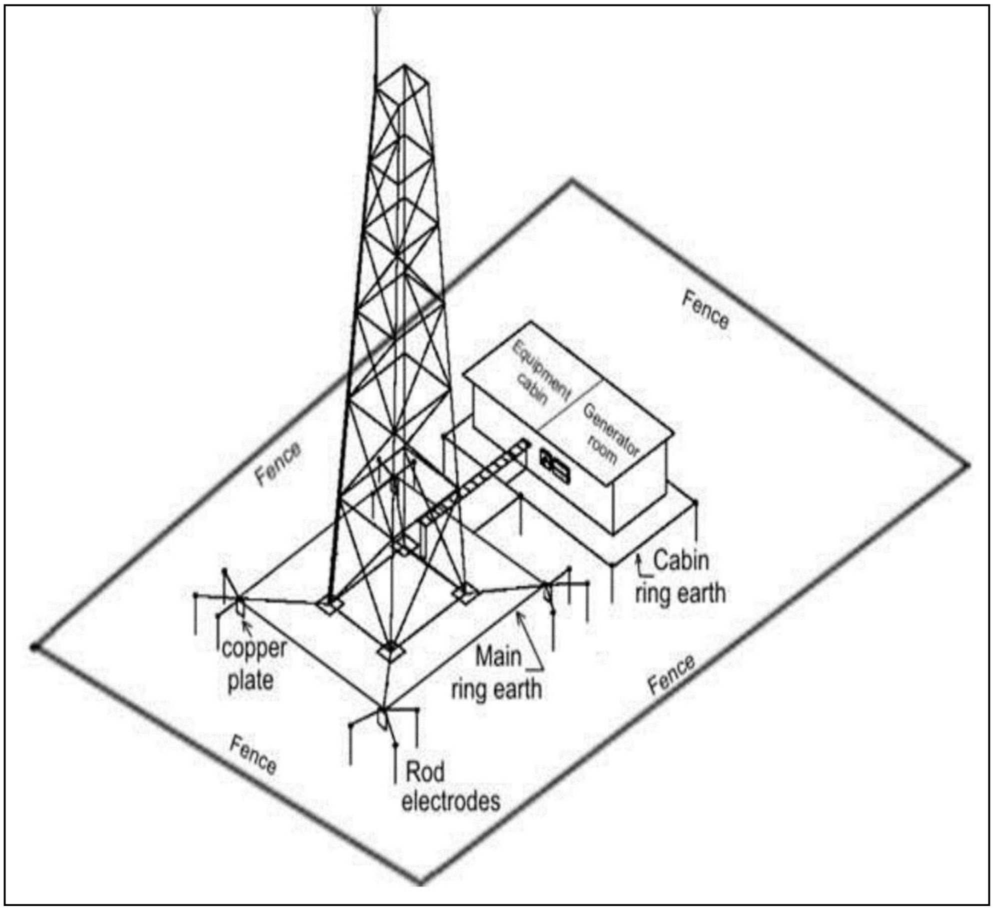


Figure 1-1Typical Arrangement of Telecom Tower Earthing Network

Typical telecom tower structures are in range of 40 m to 100 m height and perimeter around the basement of the tower is around 40 m.

Most of the time Telecom operator uses limited space for their cellular sites as site rentals increased with the covering area. Due to this reason, development of the earthing network is much challenging and complex to get lower resistance values.

The direct lightning strikes to the tower structure cause the physical damage and injury. Earth potential rise (EPR) due to lightning conditions and propagating through common power feeds are one of the main methods of electronics equipment damages. These types of damages are referred by IEC 62305-2. The earth-termination system of the tower shall comply with IEC 62305-3, and same requirement is followed and included in the TRC guidelines.

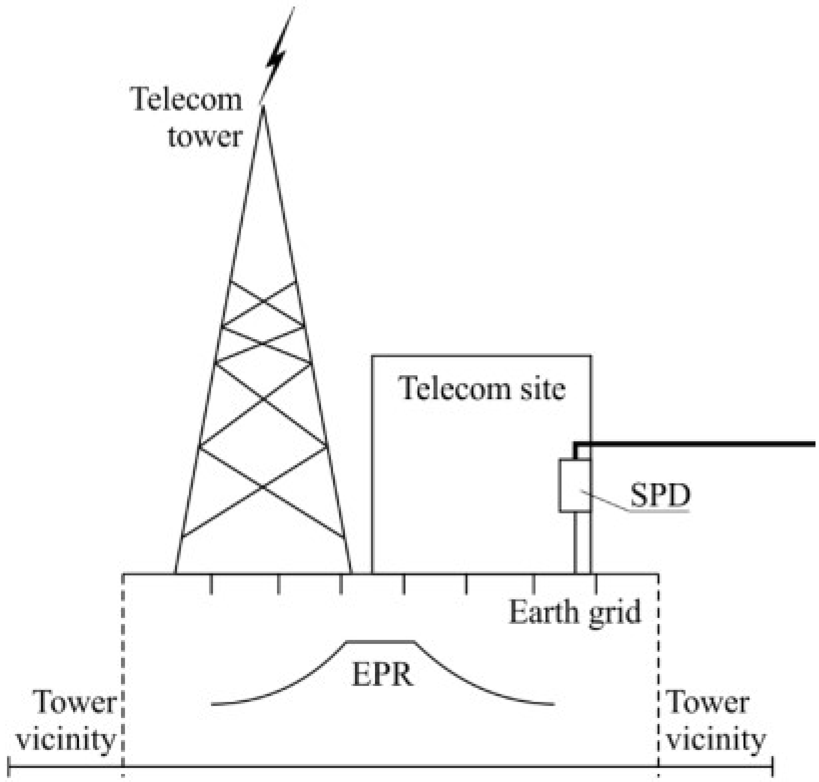


Figure 1-2 Tower Protecting Area

Normally a limited space is available for the earthing network. Air termination is equipped by a franklin rod made of copper to ground the lightning. A down conductor, which is connected to air terminal, transfers the current which comes down along the tower to connect it with the earthing network. Figure 1.2 shows the telecommunication tower structure details.

Necessary lightning protection level (LPL) is determined through a risk assessment, and it derives the safety distances and the design of protection measures. The earth network is typically a complex design as it needs to maintain a proper equipotential bonding around the tower and the equipment cabinet.

Main components of the grounding, lightning protection and surge protection system at a telecommunications facility,

1. Indoor bonding setup
2. Outdoor grounding setup

3. Power lines surge protection
4. Communication lines surge protection
5. Lightning protection on direct strikes

Round cables or flat tape are the commonly used shapes for grounding conductors in telecom earthing networks. Flat tape type conductors show lower inductance and shows better capacitive coupling properties with the ground. As result a comparatively lower impedance earth system is stablished at high frequencies at the time of lightning [5].

Exposing of telecom towers for the direct lightning strikes are a reasonably regular occurrence, as they are installed in high altitudes. An air termination device on the top of the tower , network of conductors buried under ground and a down conductor connects these two components are the traditional approach to lightning protection system implemented in tower structures.

A typical earthing network consist of ring conductor around the tower and rod and tape distribution from tower leg area. Down conductor is positioned at the leg having lesser number of equipment and it will be directly connected to the grounding network making an equipotential connection for all equipment installed in the facility including the boundary constructions such as fences.

1.2.1 Variation in Earth Resistance Measuring

Measuring earth resistance of the tower site is carried out as a periodic compliance practice for assurance of the safety of the site equipment, the surrounded vicinity and the local community. There are number of methods to measure earth resistance. Widely used measurement method is the fall of potential method. Due to many reasons, the reading collected in a single site show different in different direction. Wenner four Probe test is considered as one of the most common soil resistivity testing method. Due to various reasons, the resistivity readings are varying directionally.

Due to the variation of the measured earthing resistance direction wise, it has become issue to benchmark the telecom tower safety measures in the aspect of lightning protection. This leads to a doubtful situation for the field level assessing officers. In addition, telecom operators have to spend huge cost for the earthing network improvements due to the variation of resistance values.

As the geometries of the earthing network is complex, designers face difficulties of providing best suited network design.

Considering the geographical difficulties field offices find it difficult to make measurements accurately. Due to the disturbance from the other factors such as soil layer formations, earthing conductor interference, interference from neighbour community on earthing arrangements, the sites' earthing readings lead to an inaccurate value.

1.2.2 Aims and Scope of the Thesis

The study will physically measure the typical readings of selected earthing networks, analyze, and elaborate the reasons for variation in deviated earth resistances in different directions. The elaborations cover different soil conditions and theoretical calculations for the comparison of such with similar earth arrangement.

Ansys Maxwell software will be used for software modelling of the earth networks with finite element methods and to obtain relevant resistance value through voltage current characteristics.

Numerical model will be derived to represent the site's earth resistance value in a single representation through the directional resistance and resistivity values.

Finally, this thesis will provide the sites actual earth resistance value as an outcome of the validated results and analysis.

Chapter 1 is for the introduction and problem identification and illustrate the objectives of the research.

Chapter 2 is the literature review of the research.

Chapter 3,4 elaborate the methodology of the research followed by the theoretical aspects.

Chapter 5 is the detailed technical analysis is presented in

Chapter 6 Validation of the simulated results is presented in the Chapter

Chapter 7,8 is for result analysis and the discussion on concluding remarks and the future work.

2 LITERATURE REVIEW

2.1 Background

Electrical earthing system is a critical part of a telecom tower installation. Its correct functionality is important for the safety of the users and the telecom operators, in the aspect of protection of the systems. It helps the proper operation of sensitive electronic such as transmission equipment and network devises. Therefore, the earthing system need to be designed and dimensioned to perform these important features [1] [2]. The conventional methods for calculating the grounding resistance of rods, meshes, loops or of their combinations, are derived from a set of simplified formulas and in some cases it is observed the use charts and graphs. Providing the precise value for the resistance of earthing network is a challenging task considering the effecting variable count on the calculation.

Earth resistance reading of an earthing network is affected by various factors. Key factors are soil resistivity of the site and physical geometries, which represent non-homogeneity of the premises. The material for earthing network design directly affects the resistance values as human factors. The tools used for the measurement too contribute to the accuracy of the reading as many devises are not fully validated for all soil conditions.

Theoretically the built earthing network having a resistance towards the ground which should be represent as a single value. Finding the resultant earth resistance value is challenging in a typical telecom earthing network which has used number of rods and interconnecting conductors. By analyzing the filed data with currently used measuring techniques, earth resistance values are varying from point to point in typical earthing network installed in a telecom tower site. Earth resistance of simple networks can be calculated and their methods available to define the same using tables and graphs. These methods have limitations for use.

2.2 Earthing of a Telecom Tower Station

2.2.1 Telecom Base Transceiver Station

The Base Transceiver Station (BTS) is a telecommunication infrastructure supports wireless communication between mobile device and the operator network. The device could be mobile phone, wireless data devices. Depending on the technology used telecom service provider network could be with GSM, TDMA or CDMA technologies.

A BTS has a Transceiver (TRX) to manage transmit and receiving of signals; sending and reception of signals from the core network which controls many more BTS equipment. RF amplifier aids in signal amplification from TRX for transmission through the antenna. The Antenna is the external part of the BTS which is fixed in the higher poisons of the tower structure.

The BTS equipment are usually housed in a shelter or outdoor cabinet, which protects the telecommunication equipment from external conditions such as dust, corrosion, rust, theft etc.

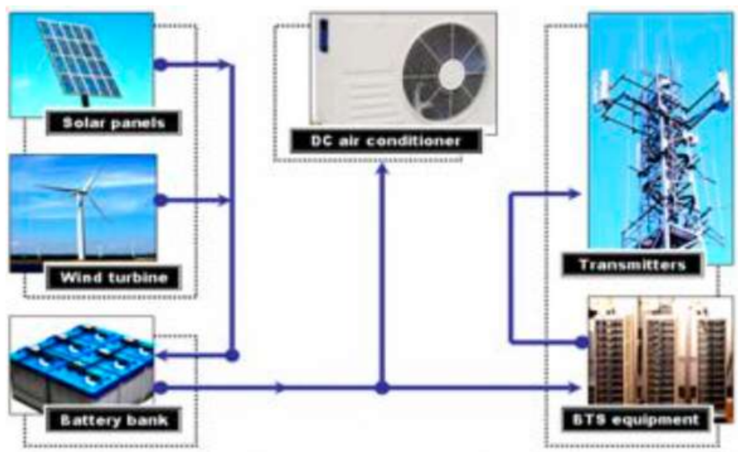


Figure 2-1BTS energy flow diagram

A telecom tower station is the major element in the access network of a telecom operator specially in case of a mobile operator. The site has two main categories, Active and Passive infrastructure. Passive infra structures are used to fix the telecom equipment and its supportive utilities. Tower, fence, and building are the key passive items of the site. Earthing network is considered as a passive item, which directly connects to the active components.

Reliability and the quality of the service have to be maintained to the TRCSL accepted benchmark values. Therefore the faults have to be minimized in maintaining the availability of the network.

Damages caused by lightning and surges to the system and the tower is a frequent mode of site failure. These damages are leading to impacts on neighboring communities and taking necessary action to mitigate is an important fact for the better relationship on operational activities.

2.2.2 Telecom Earthing Network Arrangement

Site space and the earth resistivity reading are the key parameters used for the design of the earthing network. Main objectives at the design stage are to design a system safer to site equipment and livelihood while achieving required earth resistance to meet the regulatory compliance. Key intentions of the earth network are, .

- Prevention of livelihood from electrical shock
- Provide electrical grounding of the power system
- Efficient discharge of lightning current
- Equipment equipotential bonding

IEC 62305 is the following standard to compliance and various materials are recommended with specific dimensions which used at the earthing network [3] [4] and in Sri Lankan telecom operators uses Copper, Aluminum and its combination for the light network deployments.

2.2.3 Earth Resistance & Resistivity Measuring Methods

2.2.3.1 Earth resistance

The resistance offered by the earth electrode for the flow of current through the earth is called earth resistance. Theoretically, resistance is equal to the ratio of the potential of the earth electrode against current that it discharges. The earth resistance is commonly measured by the potential drop method.

The resistance of the earth electrode is distributed on the ground around the electrode. Earth resistance is given as the ratio of build voltage and flow current.

Where V is a voltage measured between the voltage peak and I is the current injected when measuring the earth resistance across the electrode.

$$Earth\ Resistance = \frac{Potential\ to\ eath\ electrode}{Current} = V/\mathrm{I}$$

2.2.3.2 Earth resistance measurement

There are different test methods for Measuring Earth Resistance and the selection of the method depend on the application. Following are the main methods to measure earth resistance,

1. Four Point Method (Wenner Method)
2. Fall-of-potential Method
3. Clamp-on test method
4. Two-point Method (Dead Earth Method)
5. Star-Delta Method
6. Slope Method

2.2.3.3 Industrially use Earth Resistance Measuring Methods

There are different types of methods used in measuring earth resistance in industry as per the application. The typical methods are two-point method, fall of potential method and three-point method. Further there are methods called single clamp earth resistance testing, double clamp earth resistance testing, staged fault test and attached rod technique which are being used for the special scenarios.

2.2.3.3.1 Fall of Potential Method

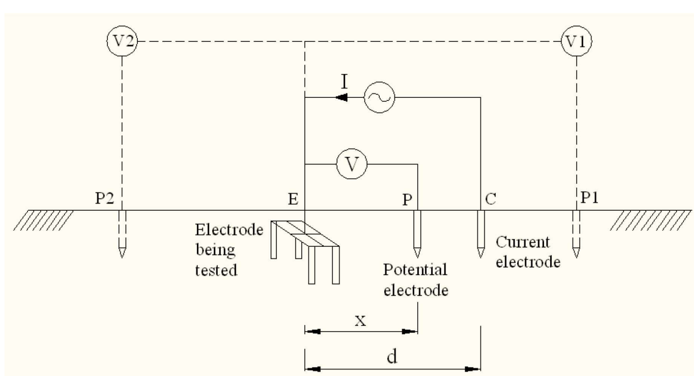


Figure 2-2 Fall of potential method

This method is involved a current probe and a potential probe to measure voltage. Earth electrode which resistance to be measured is selected to inject current between. Current electrode C is placed at the far most distance. Resistance is measured in terms of voltage build between earth electrode under test and potential electrode P as shown in above figure. Normally before taking a measurement earth electrode is disconnected from the earthing system to not being affected by leakage currents by the system.

When current is injected between earth electrode under test and current electrode voltage will be distributed as the current flows along the earth. The potential will be measured along the distance between rods. The ratio V/I = R will be resistance measured and will be plotted against the distance of the measurement. Under the test condition, the potential probe moves away from the electrode in steps and the resistance value will be measured for respective distance. The plotted graph will be used for obtaining the true or apparent resistance of the earth electrode under test.

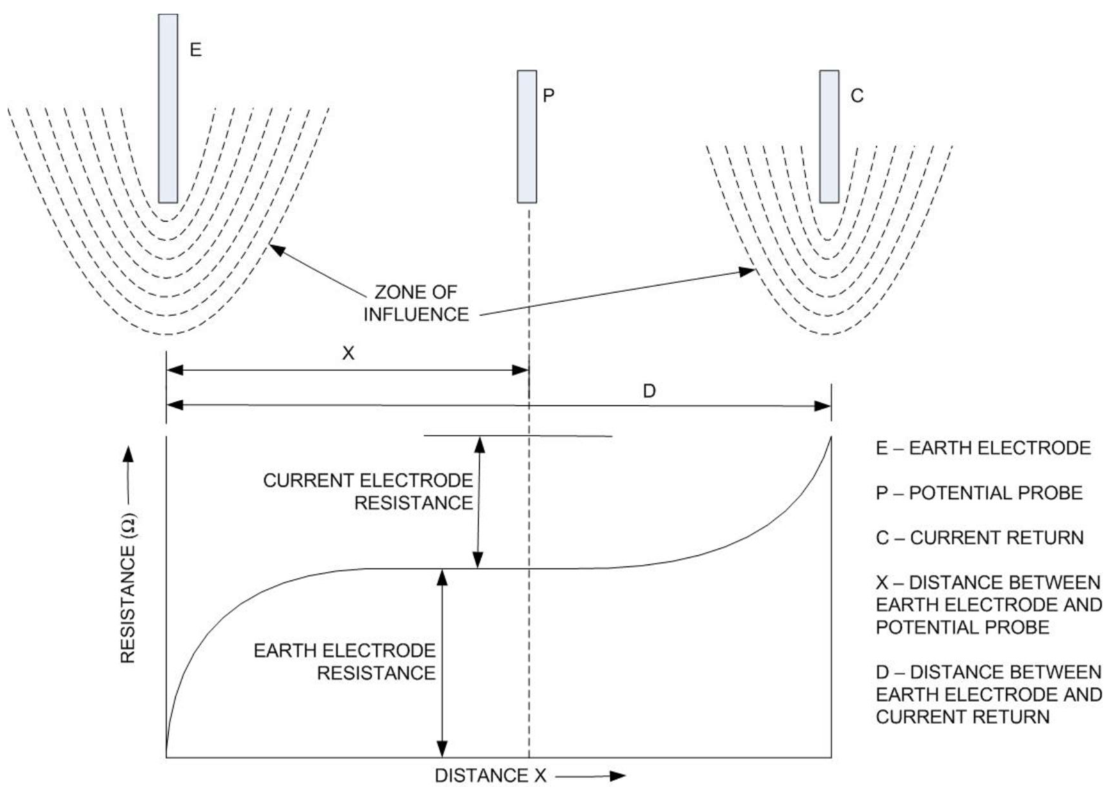


Figure 2-3 Resistance variation along the distance

Current electrode needs to place outside the influence in order to obtain a flatten curve. It's recommended to have the area of the electrode under test as per above figure. When using fall of potential method large spacings are required as current probe has to place in a distance to avoid influence of electrode under test.

The accurate distance has to maintain when achieving correct results from a measurement. When the earthing arrangement is complex placing of probes has to done with excess care. The most reasonable resistance will be obtained when probe spacing x between potential and electrode under test placed between current probe and electrode under test when the x/d =62% where d is the distance between electrode under test and current probe.

To obtain 62% distance and get an accurate result following factors has to be maintained.

a. Uniform Soil
b. Spacing between E & C shall be large.

2.2.3.3.2 Single Clamp Earth Resistance Testing Method

Similar as in fall of potential method, this method also use a current probe to inject current and potential measurement probes are not needed to measure the earth resistance. Disconnection between earthed body and electrical system is not required. Ohm's Law (R=V/I) is based for the formulation of this method

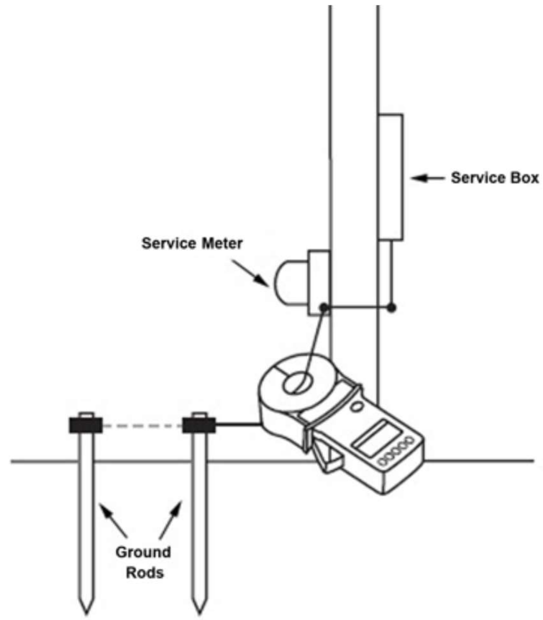


Figure 2-4 Clamp on method

As illustrated in above figure, a known voltage is applied inductively to complete circuit using the source coil built inside the clamp of the earth tester. Induced voltage by the clamp will be applied. There will be a current induced in the earthing circuit due to that voltage and it will be measured by the same clamp inside the earth tester which induced the voltage. Resistance calculation will be done by dividing the current flowed in the earthing circuit by the induced voltage in it. Verification should be done to ensure the incorporation of the earthing system for the circulation current loop. Clamp on earth tester measurements calculate the resistance using the current flow path. Basic assumption is that the earth system under test contributes significantly for the resistance measured.

The clamp on method is fast to measure resistance as it does not involve earth probes in measurement and the earthing system does not need to be isolated. Also, the reading may indicate the high resistance value as the grounding conductor is used as part of the return. Following disadvantages are explained by the manufacturer.

- The accuracy of the readings is seriously affected when frequency of the injected current into the earth by the tester is same as the disturbance current in the earth.

- This method will be only applicable in situations where multiple grounds are in parallel as return path need to be present. Therefore, isolated single rod earthing arrangements, this test cannot be used as there will not be any return path.
- For applications such as cellular towers or substations it is not recommend conducting the tests.
- Measurement accuracy will be having effects due to mutual inductance between the current loops and the voltages of the clamp tester.
- The operator must have a thorough idea of the earthing arrangement as return path necessary to complete the current loop at the time of using clamp on test method for earth resistance measurement.

2.2.3.4 Finite Element Model

For the simpler earthing networks, the resistance value could be represented in simple equations. The simple equations can be used to model finite elements. In order to model the complex problem, such could be modeled into a larger set of equations. Finite element model is a methodical approach of approximation by reducing the error supported by the error function.

In relation to determination of ground resistance, finite element analysis is capable to do the computation even in multi rod, non-uniform soil models. Two-layer or multilayer soil model need to perform in nonhomogeneous conditions.

2.2.4 Soil resistivity

The measure of the resistance for flow of electricity in the soil structure, is called the resistivity of the ground. Soil resistivity is affected by various factors such composition of the soil, humidity, temperature. The soil is not homogeneous in general and depth from the surface has a direct impact for the measurement. It is rational to have low resistance for a easier and economical design to achieve the benchmarking standards. Ohm-meter (Ωm) or ohm-centimeter (Ωcm) is the unit represent the soil resistivity measurement.

Soil resistivity of the soil is inversely proportionate to observed in soil resistance. Referred literature shows that soil resistivity varies from sample location, or the soil types and it is varying due to many factors. Generally, the physical compositions of the soil, grain sizes, dissolved salts, moisture content, and soil distribution. The soil shows a high resistivity, create a negative effect on flow of currents and it reduces the effect of the earth electrode.

Following are the contributions of each factor for the reading,

i. Soil condition: Lower resistive soil shows a higher corrosive nature while lower resistance leading to a higher resistance value on the electrode.

ii. Moisture: High moisture content assist the conductive paths and reduces resistance reading.

iii. Dissolved salts: dissolved salts assist to flow of currants and higher the dissolved salts reduce resistance on electrodes.

iv. Climate condition: This will directly affect the salt and moisture content and resultant effect will be observed in the measurement.

v. Area available: In order to achieve the required distribution, area is a major concern to eliminate overlapping effects.

vi. Obstructions: Obstructions reduce the paths for current flow and increase resistance values. Obstructions are a major constrain in a telecom earthing network deployment.

2.2.4.1 Soil resistivity measurement

Soil resistivity is generally measured by the four spike method. In this test four numbers of spikes arranged in a straight line are driven into the ground with similar gap. The current passes between electrodes C1 and C2 is known and the drop in potential (V) is measured between the spikesP1 and P2. An electric field is developed due to the Current I which is proportional to the current density and resistivity of the soil. The voltage measured (V) is proportional to this developed field.

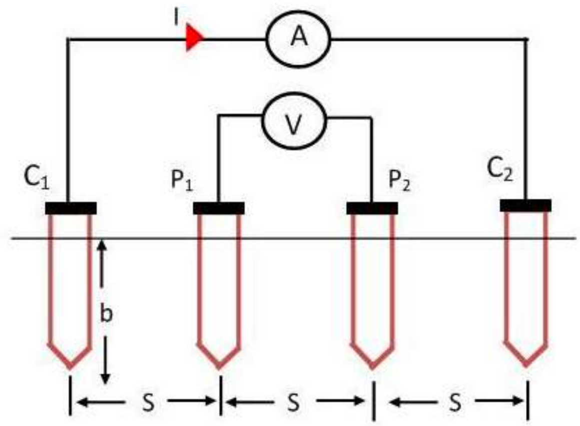


Figure 2-5 Measurement of soil resistivity

The soil resistivity is proportional to the voltage V and current I and is given as soil-resistivity

$$\rho = \frac{\frac{4\pi SV}{I}}{1 + \frac{2S}{\sqrt{S^2 + 4b^2}} - \frac{2S}{\sqrt{4S^2 + 4b^2}}}$$

The resistivity of the soil (ρ) is measured in Ωm. The horizontal space S between the spikes measured in meters and b is the depth of burial in meter.

2.2.4.2 Earth Resistivity Measuring Methods

2.2.4.2.1 Wenner Method

For the measurement of earth resistivity, four terminal method is used. It is the most common method used and is known as Wenner Method.

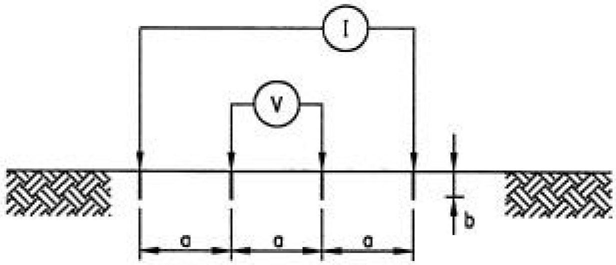


Figure 2-6 Wenner Method of Earth Resistivity Measurement

The measuring method is shown in above figure and apparent resistivity is given by following equation.

$$\rho_E = \frac{4 \cdot \pi \cdot a \cdot R_W}{1 + \frac{2 \cdot a}{\sqrt{a^2 + 4 \cdot b^2}} - \frac{a}{\sqrt{a^2 + b^2}}}$$

$\boldsymbol{R_W}$ = Wenner resistance measured as V/I in Ω.

$\boldsymbol{\rho_E}$ = measured apparent soil resistivity (Ωm)

b = depth of the electrodes (m)

a = electrode spacing (m)

If ***b*** is small compared to ***a***, as in the practical scenario where penetrated distance of the electrode is negligible compared to the inserted distance and equation will be deduced to following.

$$\rho_E = 2 \cdot \pi \cdot a \cdot R_W$$

2.1.1 Schlumberger Method

This method is using four electrodes similarly in Wenner Method. The voltage probe distance and current probes are taken as ***a, c***.

$$\rho_E = \pi \frac{c \cdot (c+a)}{a} R_S$$

$\boldsymbol{P_E}$ = measured apparent soil resistance

$\boldsymbol{R_S}$ = Schlumberger resistance measured as "V/I"

b = depth of the electrodes

a = electrode spacing

c = electrode spacing

2.2 Methods Used in Ground Analysis

2.2.1 Grounding system size-based analysis

In this method grounding systems are categorized in to three sub systems depend on the size of the earthing grid arrangement as follows.

I. Small grounding systems - 40mx60m
II. Medium grounding systems - 280mx140m
III. Large grounding systems - 440mx280m

Further three approaches are used for analysis of ground for above three grounding systems. In the first method it is most commonly used and it is based on assumptions that the grounding system as an equipotential structure. The results will be accurate for grounding networks which are non-extensive at low frequencies.

Second one is the method where voltage drop along the grounding network taken into account. Then the assumption made as grounding system to be an equipotential structure is eliminated. It is computing potentials at almost every position in the earthing system and it does not reflect the inductive and capacitive relations among conductors in the system.

In the third method of grounding analysis field theory approach has been used and it is not most commonly used and does not consider the grounding system as a equipotential structure system and consider self-impedance and the interactions due to capacitive and inductive components of the grounding conductors.

When analyzing different sizes of grounding systems using the above three different approaches results will be as follows.

- Small & Medium grounding systems – Almost equal GRP values for all 3 approaches
- Equipotentiality of the grounding system is the assumption for the commonly used grounding analysis algorithm where such gives reasonable results for small grids

2.2.5 Computing Techniques Used for Ground Analysis -Differential Approach

Differential approach is using Finite Element Method (FEM) for analysis of ground potential. Commonly for analysis, computer based software are used such as MATLAB, ANSYS, etc. [14] Modeling of the grounding system will do using three kinds of elements. Conductors and rods will be model with unidimensional elements. Layers will be model with bidimensional elements and soil would be model with tridimensional elements[14].

In telecommunication tower base station site, earthing system is multi rod system and site terrain is not flat in most cases. Therefore, theoretical equation is not available to calculate the equivalent earth impedance.

Uniform models and simplified assumptions will be used to resolve simple systems but may not suitable for the complex systems. For the complex Earthing systems like substation earthing, Telecommunication tower earthing, different numerical techniques like Finite Element Method (FEM), Boundary Element Method and Finite Different Method are available. By considering the commercially available software packages; appropriate software package should be selected with the concerns such as the accuracy of the solution, solution speed, the management of memory requirement of the solution. Ansoft Maxwell was selected by considering the above factors and the capabilities of drawing the 3D site model with higher accuracy, having more solution possibilities, delivering a dynamic analysis of the considered model.

Electro transient analysis has been performed using FEM is used in this solution. Electro static analysis also can be used when there is no need of analyzing the transient behavior of the inflowing the lightning, surge time value in the FEM analysis.

In Ansoft Maxwell simulation process, First solution method (Electro static or Electric Transient) should be selected and 3D model of the site earthing layout should be defined in the Cartesian coordinate system.

Figure 2-7 shows the flow chart of the overall simulation process. Figure 2-8 shows the FEM analysis.

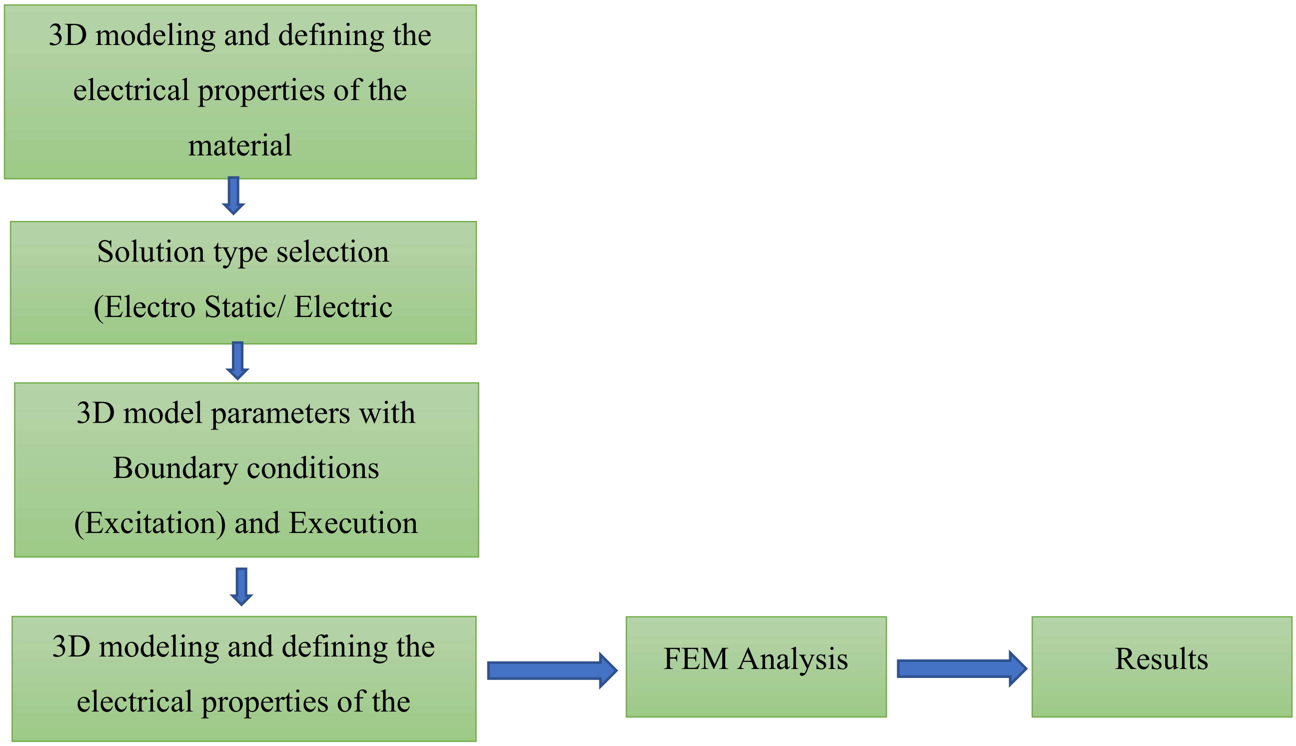


Figure 2-7 Overall simulation process

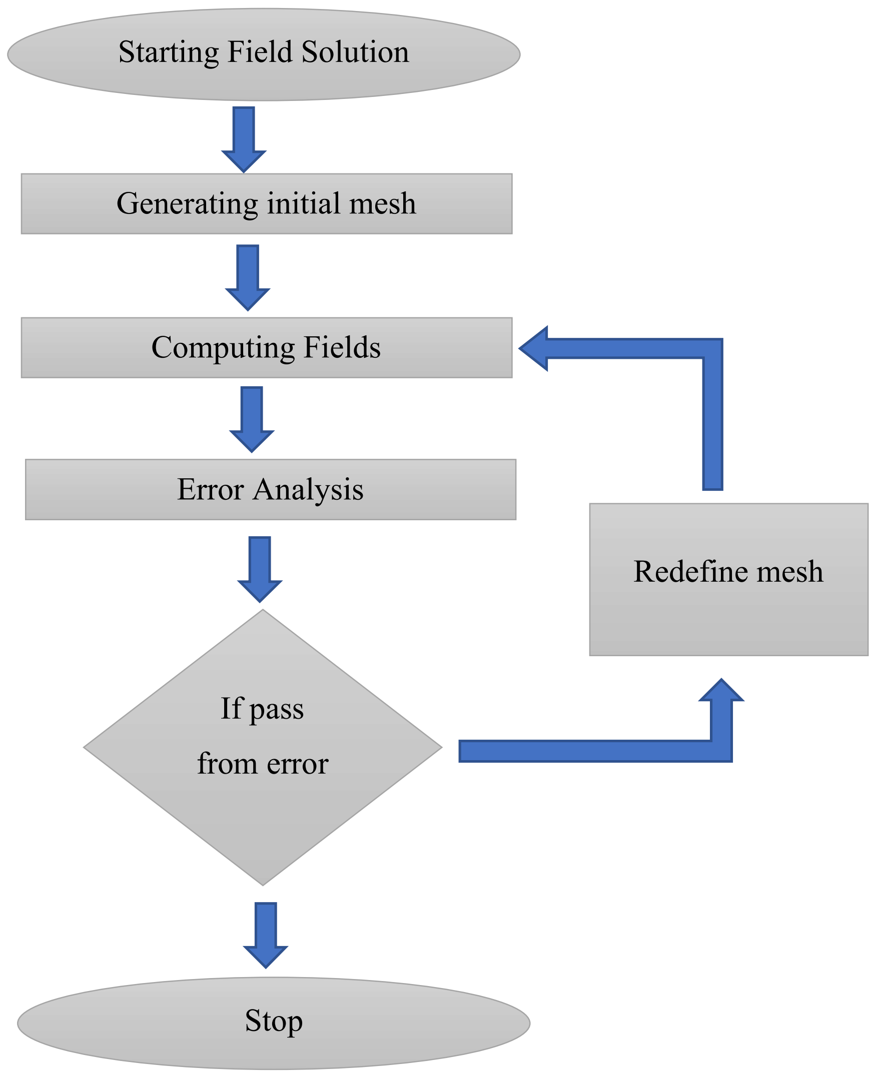


Figure 2-8 Finite Element Analysis (FEM) in Ansoft Maxwell

2.2.6 Simulation Methodology

2.2.6.1 Basic theory based on the simulation

An increase of the property of transient performance of an earthing system or the system's ability to discharge transient energy into the ground which reduces the earth potential rise would ensuring that equipment and personnel are safe from any danger.

To evaluate the transient performance of an earthing system under transient conditions, peak voltage anticipated for a given current and how the transient energy flows to the ground would be major two areas which should be addressed.

The impulse impedance Z_p is defined as bellow

$$Z_p = \frac{V_p}{I_p}$$

The proper analysis of the effect of the earthing system behaviour by injecting a current impulse of similar shape and then measuring how the earthing system response to this with actual ground potential rise (GPR). But making the simulation more simple and less time consuming with available hardware resources, here we have considered a static state of peak voltage (GPR) and the peak current value to find out the impulse impedance of the earthing system.

After modeling the actual site earthing system in the Ansoft Maxell software, the Peak voltage rise value has been assigned to the earthing system and find out the peak current injects to the ground with that GPR value which directly shows the effective impulse impedance of the earthing system.

2.2.6.2 Earthing system modeling

The studies have shown, with the lightning incidents where the rapid rise times associates, parallel path of few tens of meters will present the impedance which will limit their ability to divert a significant amount of surge to the earth. With this study 40 meter radius earthing system is decided to carry out the simulation with the results get from the simulation and the above rule of thumb.

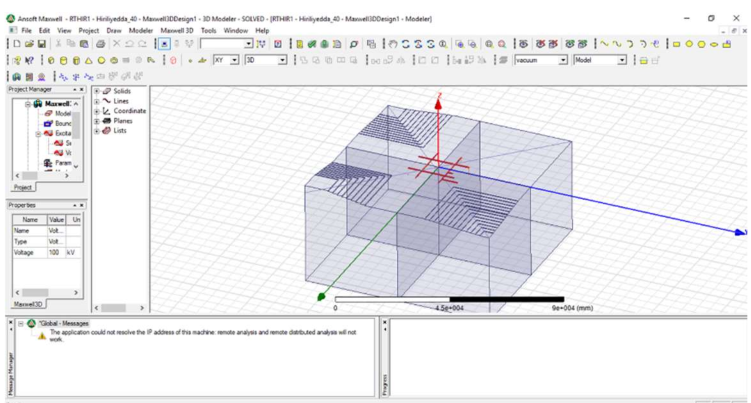


Figure 2-9 Modeling in Ansoft Maxwell

2.2.6.3 Material and sources

Ansoft Maxwell has a library of material including copper with their electric properties and facility to define the soil material with customized resistivity values. With the field measurements for each site, Site 3D model could be well defined with the much-needed electrical properties.

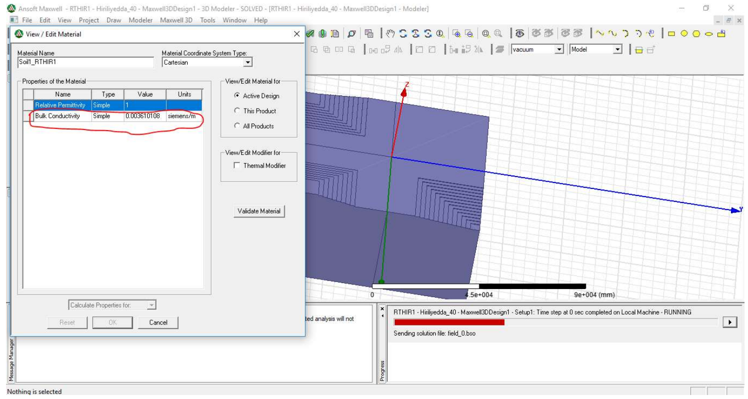
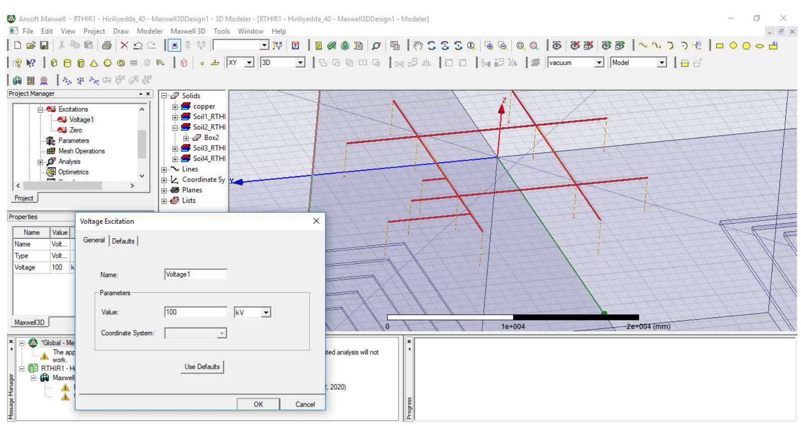


Figure 2-10 Modeling in Ansoft Maxwell - Material

2.2.6.4 Boundary conditions

As per the above-based theory peak voltage (GPR value) has been assigned as the excitation value of the Earthing system and excitation of the boundary of the soil layer has been assigned as the sink.



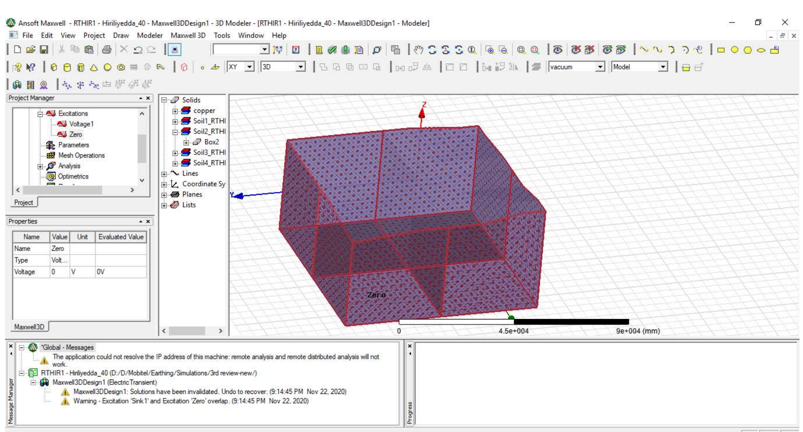


Figure 2-11Modeling in Ansoft Maxwell - Boundary

2.2.6.5 Analysis

With the analysis results obtained through the field overlays as a graph, 3D/2D plot, Table. Field Calculator allows calculating the total dissipated current to the ground with the given GPR.

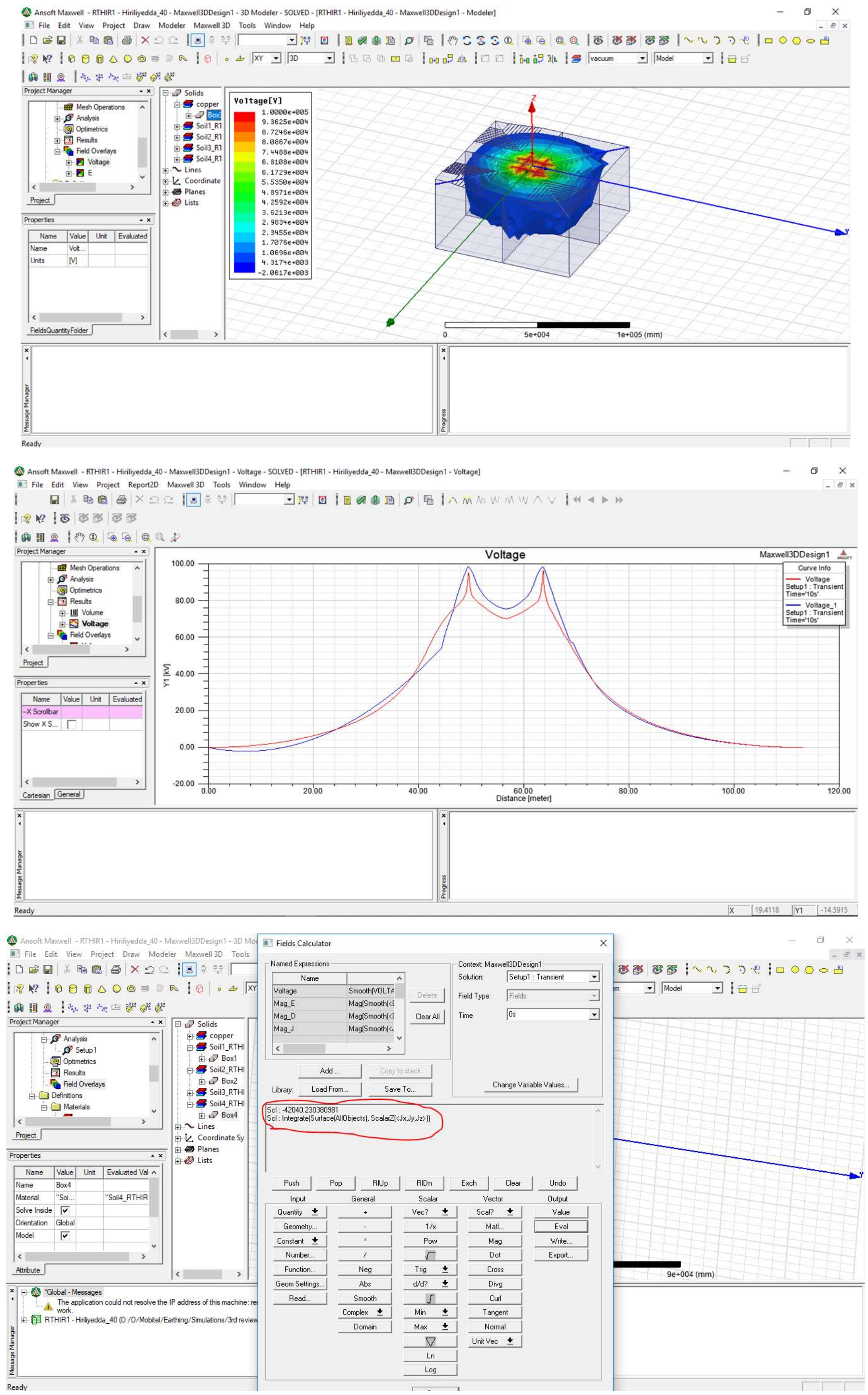


Figure 2-12 Modeling in Ansoft Maxwell - Results

2.2.7 Predictive model

For the classification and regression of mathematical models, machine learning algorithms are commonly used. Due to the fact of the efficiency with small data set, decision tree (DT) algorithms are adopting in many scenarios.

Decision tree is a representation of a flow-chart tree structure. And DT uses a branch off method to select distinct result of a decision. All specific nodes in the tree includes a test on a precise variable and branches are generated on such test.

The algorithm could be represented in such a way, assume X be a set that consist of x number of data samples. With these attributes, several n potentials values relating to n different type of Ci can be derived, where $i = 1, 2, 3 \ldots n$. The amount of information to classify a given data

The preprocessed dataset was partitioned into training data (85%) and 15% for testing as showing in Figure 2-13.

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}}$$

where x', the new value obtained after normalization; x, the value to be normalized, $x_{\min}$ and $x_{\max}$ are the minimum and maximum value of the dataset.

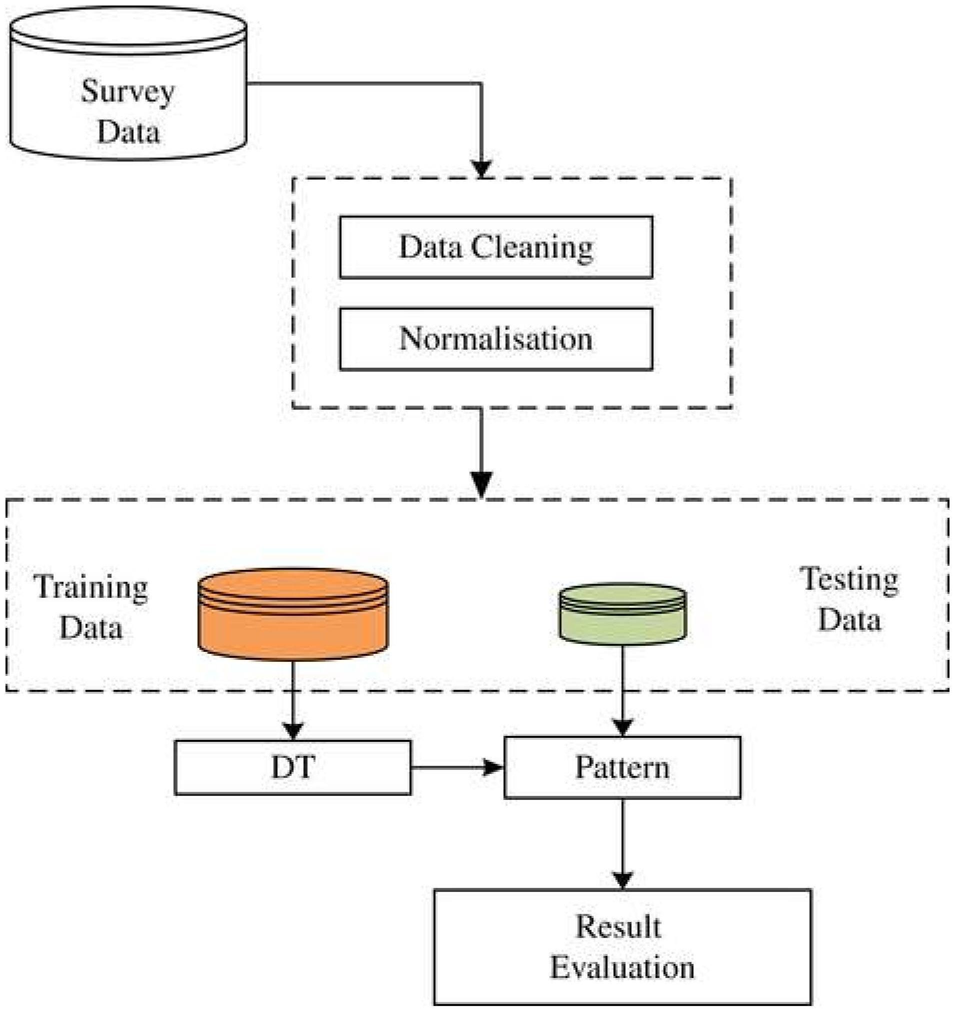


Figure 2-13 Predictive model – Data flow diagram

The root mean square error (RMSE) expressed in equation (8) and mean absolute percentage error (MAPE) as expressed in Equations (9) were used to evaluate the performance of the decision tree would be:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}}\left(\sum_{i=0}^{n}(\mathrm{m_i} - \mathrm{p}_i)\right) \qquad (8)$$

$$\mathrm{MAPE} = \frac{1}{n}\left(\sum_{i=0}^{n}\left|\frac{\mathrm{m_i} - \mathrm{p}_i}{\mathrm{m_i}}\right|\right) \qquad (9)$$

Where p_i is the predicted value, m_i is the measured value and n is the number of the predictions performed.

2.2.8 Variations in Theoretical and Practical Values in Earth Resistance

Variations may happen between practically measured values and the theoretical values due to serval reasons as follows,

1. Inadequacy of the analytical methods used in the calculations of the resistance.
2. As the soil condition varies, earth resistivities at measurement are differ than assumed in the design stage.
3. Non accurate or inadequate level of the resistivity study.
4. Substantial amount of the test current flow through buried conductive material in a site.
5. Measuring device errors.

3 METHODOLOGY

The research methodology will be elaborated from following steps as explained below. It was started from initial data collection in order to cotinine with theoretical modeling, analysis, comparison and reasons for deviations.

3.1 Collection of Earth Resistance Data

In a typical earthing installation, the direction earthing resistance was taken at the tower installation stage. This step is performed as a part of the preliminary acceptance test (PAT). As a planned maintenance practice, records of directional resistance values are maintained.

Sites which have significant variations were taken for the analysis.

Site ID	Resistance Reading (Ω)			
	R_1	R_2	R_3	R_4
KLMHG1	17.9	17.1	17.2	18.1
KLBUL4	31.8	22.2	50.8	28.2
GLNAR1	16.25	13.4	12.6	3.8
RTKAL1	17.2	25.3	35.4	28.4
RTHIR1	21	17.25	23.8	25.6
ZBAT04	18.8	19.4	15.56	15.2
ZHOM05	34.5	34.4	5.6	10.2
RTDAH1	35.5	33.8	40.5	32.8

Table 3-1 Earth Resistance Data of the selected sites

Above table shows sample earth resistance data of one of the operators in Sri Lanka.

Almost all the sites above are having deviated earth resistance values, which extracted from the earth resistance reports of telecom operator.

From the sites having deviated earth resistance values of each other for better comparison sites having similar earthing configuration were selected for further studies. Following figures illustrates earth configurations of the telecom sites.

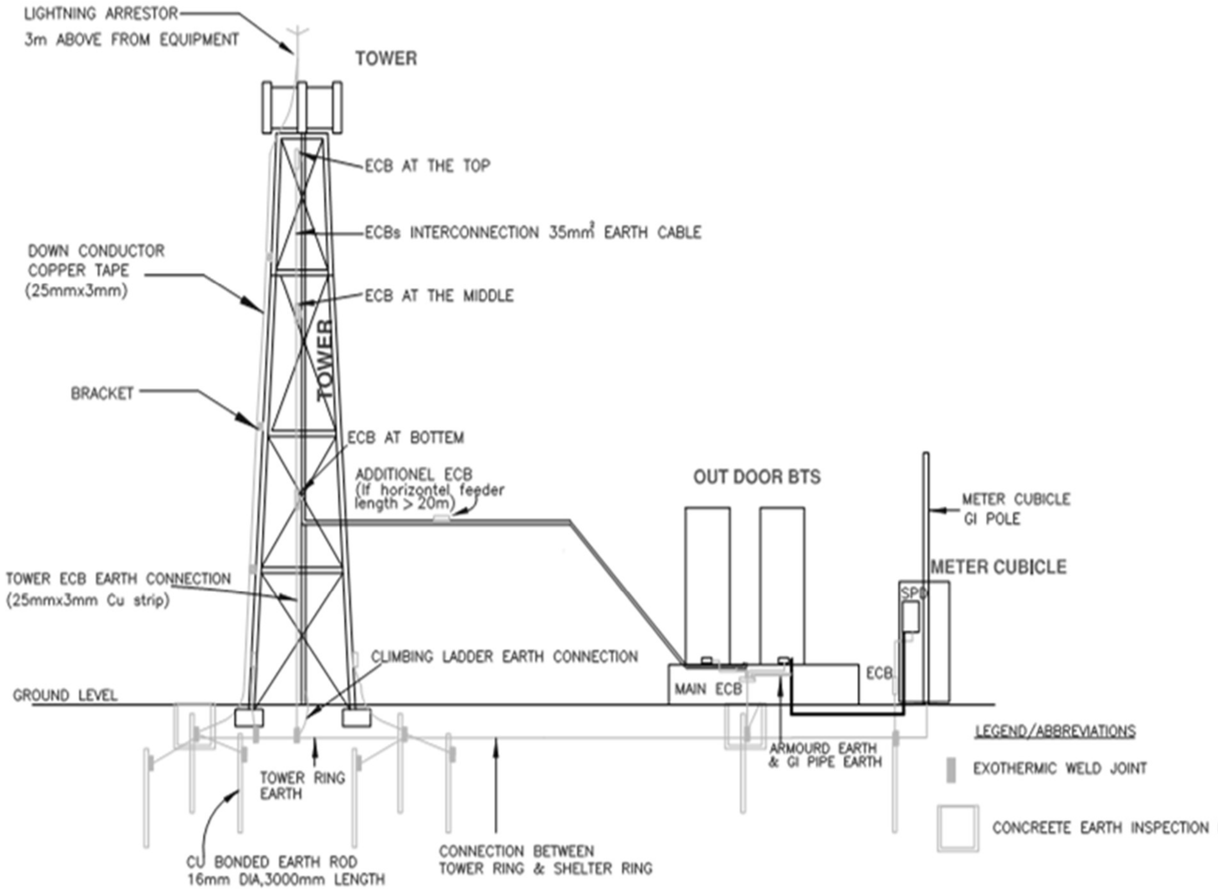


Figure 3-1 Typical Earth Configurations of Telecom Sites-1

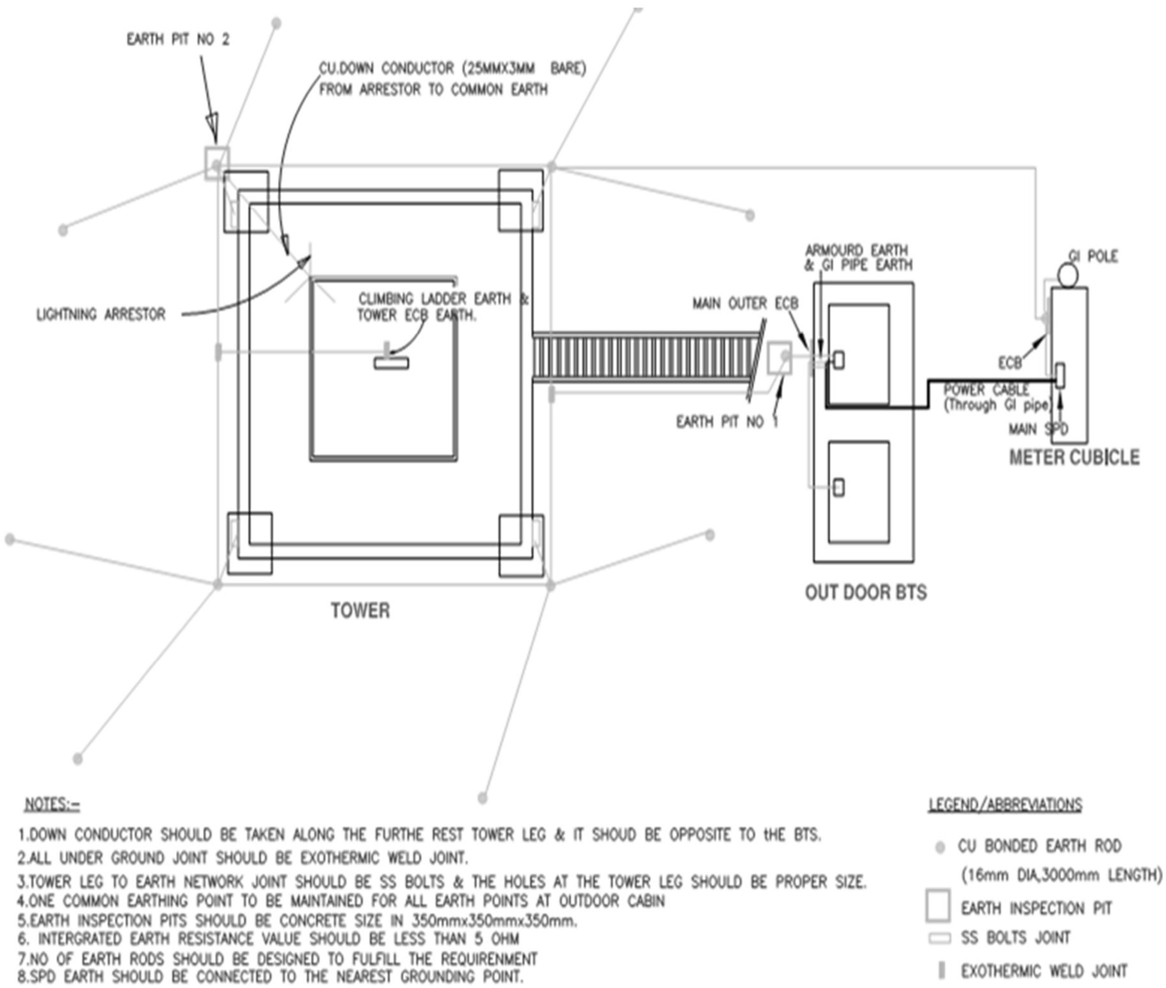


Figure 3-2 Typical Earth Configurations of Telecom Sites - 2

From the earth configurations existing in telecom sites, 4 leg towers are mostly common to each other. Earthing arrangements are also similar to each other in sites. It is noted the indoor and outdoor configurations have no significant changes in each site configurations related to the earthing network.

3.2 Gathering Earthing Data of Selected Sites

As 4 leg tower sites are selected for further study, earth network data were gathered for those types of sites. Sites were selected to represent different soil conditions from different parts of the country.

Following table shows measured data of sample telecom site and study will be done comparing sites located in different parts of the country.

Site Name	**KLMHG1**
Site Area	Western
Type of Tower	4 Leg
Earth Resistivity	1021 / 947.5 / 898.4 / 1257 Ωm
Earth Resistances	44.3 / 17.1 / 17.2 / 18.1 Ω

Table 3-2 Selected Site Earth Data

For selected sites earth network data were gathered and those were as follows.

Earth Grid Specifications	
Material	Cu
Earth Tapes	3x25 mm
Earth Rods	Cu bonded mild steel Diameter-16 mm Length – 3 m
Connections	Cad Welded

Table 3-3 Earth Network Specifications

Different lengths of Cu tape and rods were used as per the initial design of the earthing for each site.

3.3 Modeling Selected Sites

Modeling was done based on the measurements and modeling of the site was performed by using Ansys Electromagnetics Software. Site earth map was used for modeling of the earthing arrangement as per the actual dimensions and soil conditions. Buried earth ring was modeled including the conductor which connects the air terminal. Following is the site earth configuration.

3.3.1 Soil Modeling of Selected Telecom Site

Soil area was selected as per the site boundary and depth was selected in accordance to the soil resistivity measurement taken which was 20 m depth. Soil depth was considered as per maximum effectiveness towards earth resistance of the earth network of the telecom site.

3.3.2 Earth Network Modeling

Earth map of the telecom tower site was modeled inside the soil as it actually present. Typically, an earth network is under the soil for more than 300mm in depth. As per the drawing data earthing network is placed under the top soil surface according to the specified as built drawing. All the metal connections between copper tapes and earth rods are being made through it and for the simulation and it will act as one common continuous conductor without any open circuits.

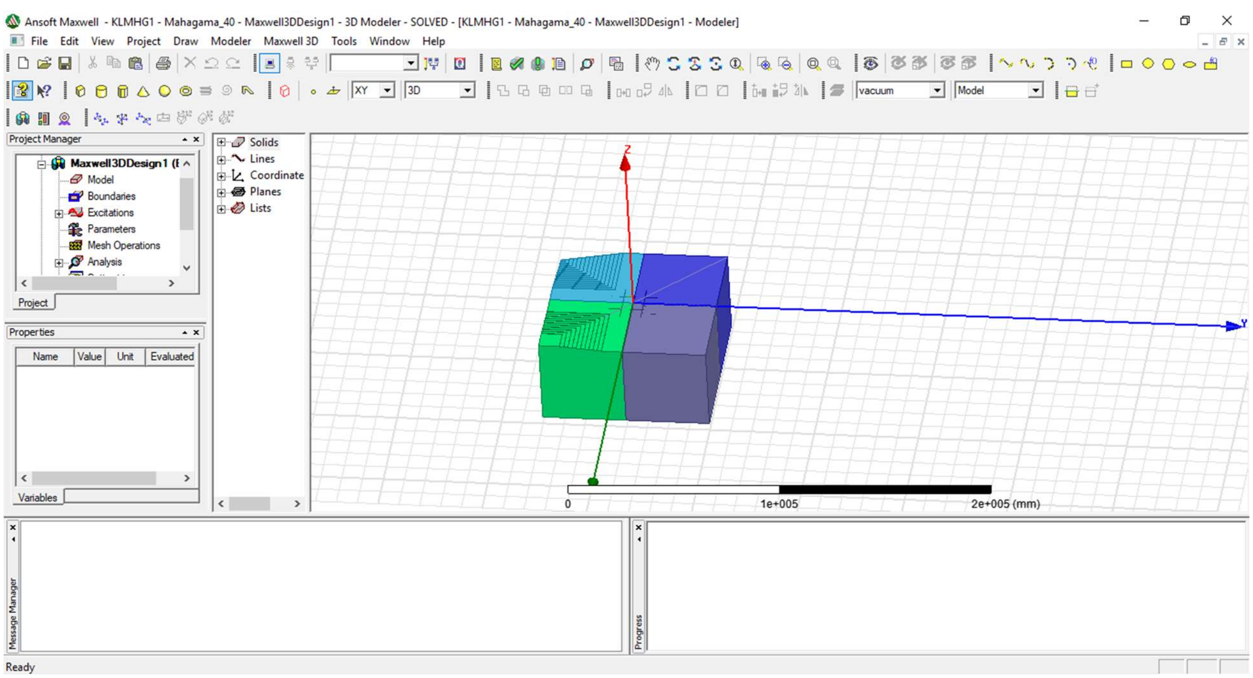


Figure 3-3 Modeled Earth Network with Soil

3.3.3 Electrical Modeling

Down conductor coming from the air termination is modeled from the earthing network to soil surface. It is needed for inject the current/voltage to the earth network for simulation and current carrying path of the earth network will commence through that. For the simulation purpose as it is considered only the soil depth of 20 m where resistivity is measured for that depth bottom layer of the soil is considered to be zero volts or the sink.

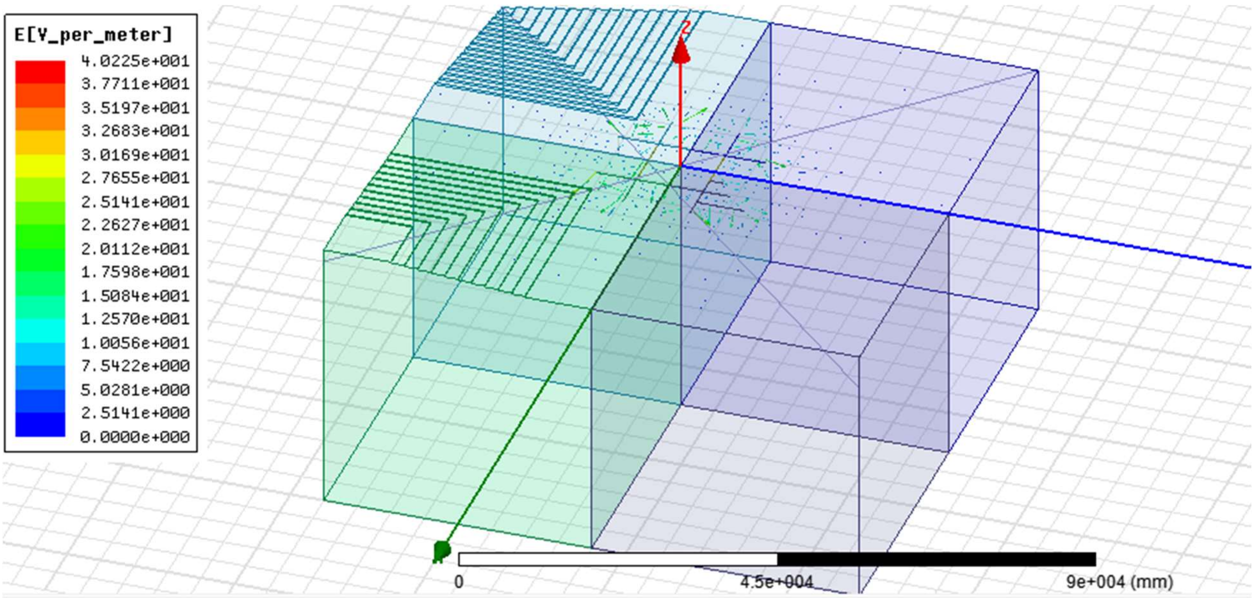


Figure 3-4 Modeled Earth Network with Boundary Conditions

3.3.4 Obtaining Voltage and Current Profiles

For the simulation purpose a test current of 100 kV was injected, and the simulation done to obtain the voltage and current profiles. Following figure illustrates the voltage profile at the soil volume after simulation.

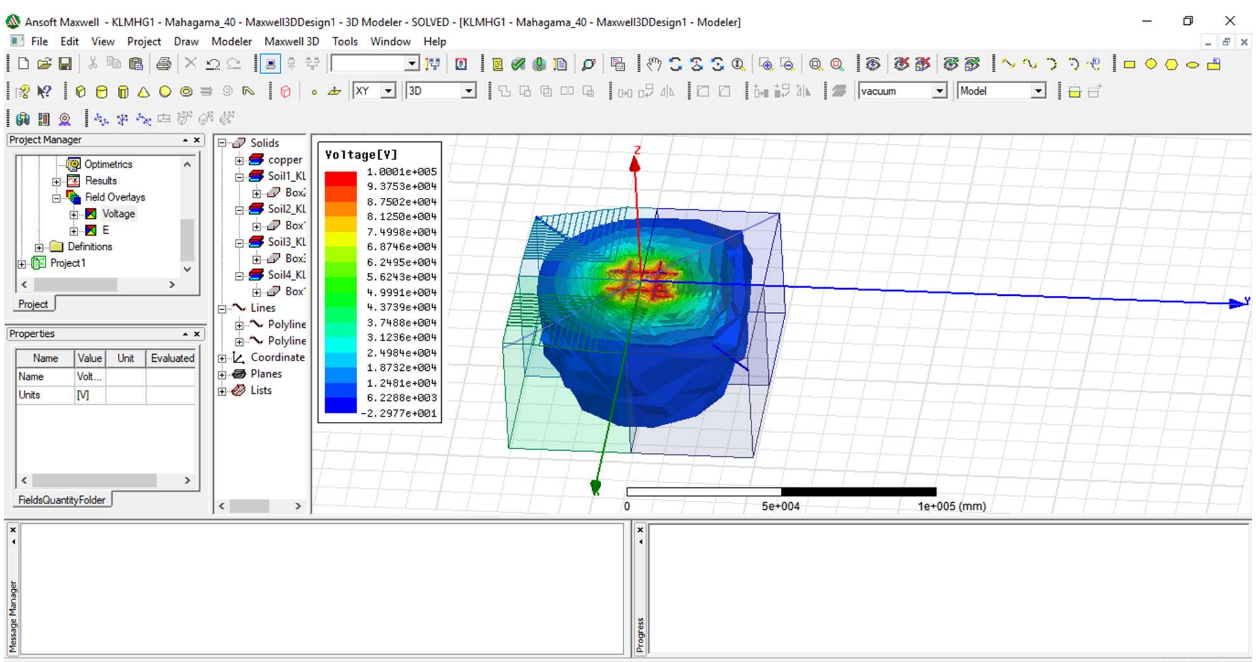


Figure 3-5 Simulated Voltage Profile of the Soil

Voltage at the earth network is at higher levels. With the distance outwards, voltage reduces in all directions on the surface and along the depth. To obtain voltage and current profiles along the directions where measurements being made, non-model lines were used and voltage and current densities were obtained.

The obtained voltage and current profiles were as follows.

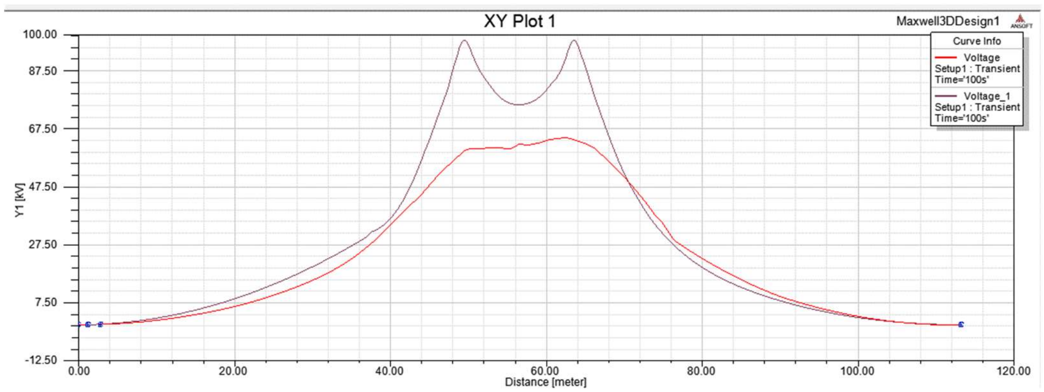


Figure 3-6 Modeled Earth Network - V,I Profile

3.3.5 Analyze the Behavior of the Profiles

Analysis is done based on the results received by the voltage profile of the telecom site and directional voltage and current profiles. The voltage profile is compared with similar telecom sites having similar earthing arrangement and different soil resistivity.

Further voltage profiles were compared from each direction of the site and between different sites having same earthing arrangement. It is to obtain a common simulated model for a typical telecom tower site and for reliable comparison between measurements and theoretical model.

3.3.6 Estimate the Earth Resistance Profiles

From the simulations as voltage profiles are being obtained, derivation of resistance profile is done from those voltage profiles. From a directional voltage profile, individual data points will be gathered from the simulator.

.

3.3.7 A Method to Estimate Actual Earth Resistance

To estimate the actual earth resistance from the complex earthing network directional voltage profiles or obtained resistance profiles has to be compared with measurements.

In order to that directional earth resistances has to be measured and comparison will be done for achieve relationships and through a validated model further comparison will be done to obtain a method for estimation.

The total current flow was taken from the simulation results and resistance value was derived considering the proportional properties of V and I

3.3.8 Reasons for Deviations

Reasons for deviations will be considered based on the literature and assumptions made. From the sites having equal configuration, directional profiles will be considered for sites having irregular behaviors on each other. Deviations from each other sites will be discussed.

4 THEORETICAL ANALYSIS

4.1 Introduction

The theoretical analysis is based on the ANSYS electromagnetics simulations on selected sites and obtained voltage and current profiles.

4.2 ANSYS Simulations on Selected sites

Sites were selected from different parts of the country considering the availability of earth maps on selected sites. Summary of sites data are as follows.

Earth resistances were measured and selected sites were having deviations from each other legs. These sites are to be modeled using ANSYS electromagnetics to obtain voltage and current profiles.

	Resistivity Readings (Ωm)			
Site ID	ρ_1	ρ_2	ρ_3	ρ_4
KLMHG1	1021	947.5	898.4	1257
KLKOL1	221.4	197.6	138.9	156.2
KLBUL4	980	498.2	2466	528
GLNAR1	647	236	274.4	73.5
RTKAL1	307.8	967.6	703.7	658.2
RTHIR1	277	307.8	307.8	358
ZBAT04	571.7	588.1	228.7	228.7
ZHOM05	155.1	294	130.6	140.3
RTDAH1	605.7	550	950.6	780.5

Table 4-1 Simulated Site Data

Earth network data was gathered as per the specifications of the material used in the sites. Almost all the sites had same earth grid specifications as follows.

Earth Grid Specifications	
Material	Cu
Earth Tapes	3x25 mm

Earth Rods	Cu bonded mild steel Diameter-16 mm Length – 3 m

Table 4-2 Earth Grid Specifications

4.2.1 Simulation of KLMHG1 Station Site

The site is at western Kaluthara District of Sri Lanka and the earth map was as follows.

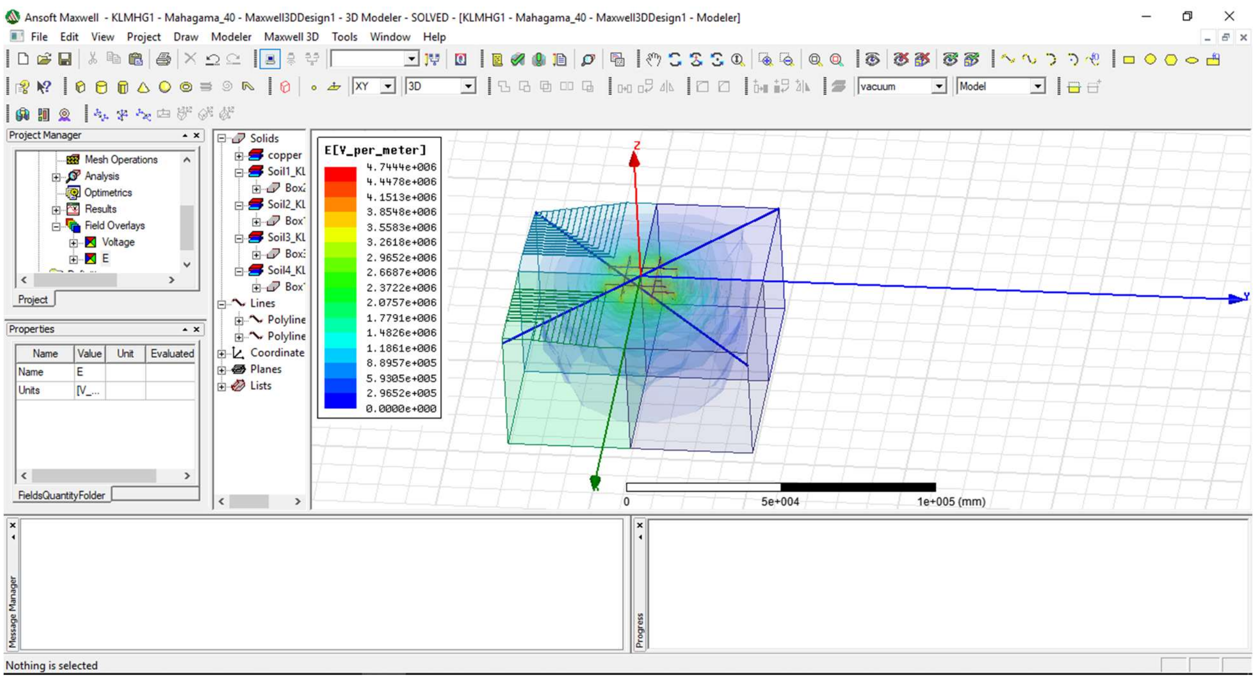


Figure 4-1 KLMHG1 Site Model

The site having earth rods, tapes and plates incorporated in the earthing network. Site modeling done using ANSYS by feeding soil data. Boundary conditions are selected as a cube formation 40m from the center of the voltage injection.

Initially a test voltage of 100 kV was used from the down conductor connecting point and below surface of the soil was assigned as the sink where voltage as zero in boundary conditions.

4.2.1.2 Results of KLMHG1 Station Site

Voltage distribution obtained was as follows.

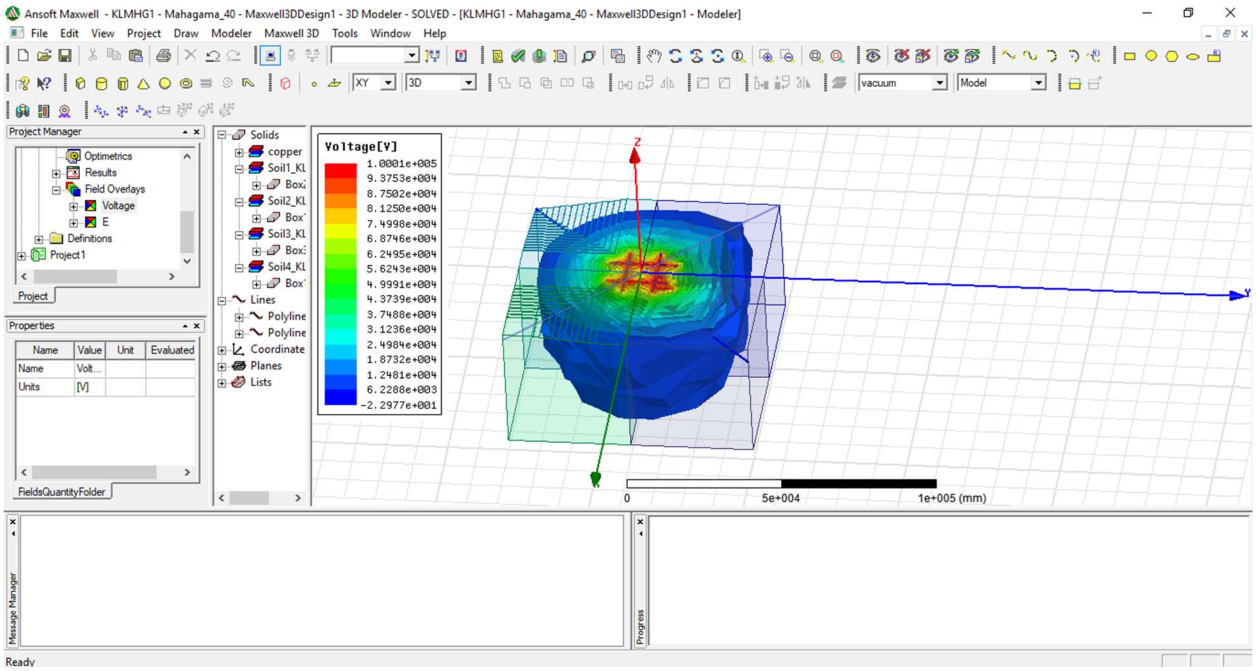


Figure 4-2 Voltage Distribution of KLMHG1Site

By analyzing the voltage distribution, it can be seen that higher voltage is built up near the earthing conductors. As the distance increases from the earth network, voltage drops as per the resistivity of the soil. For further comparison voltage and current profiles were taken along the distance of earth resistance measuring directions.

Obtained voltage profiles were as follows.

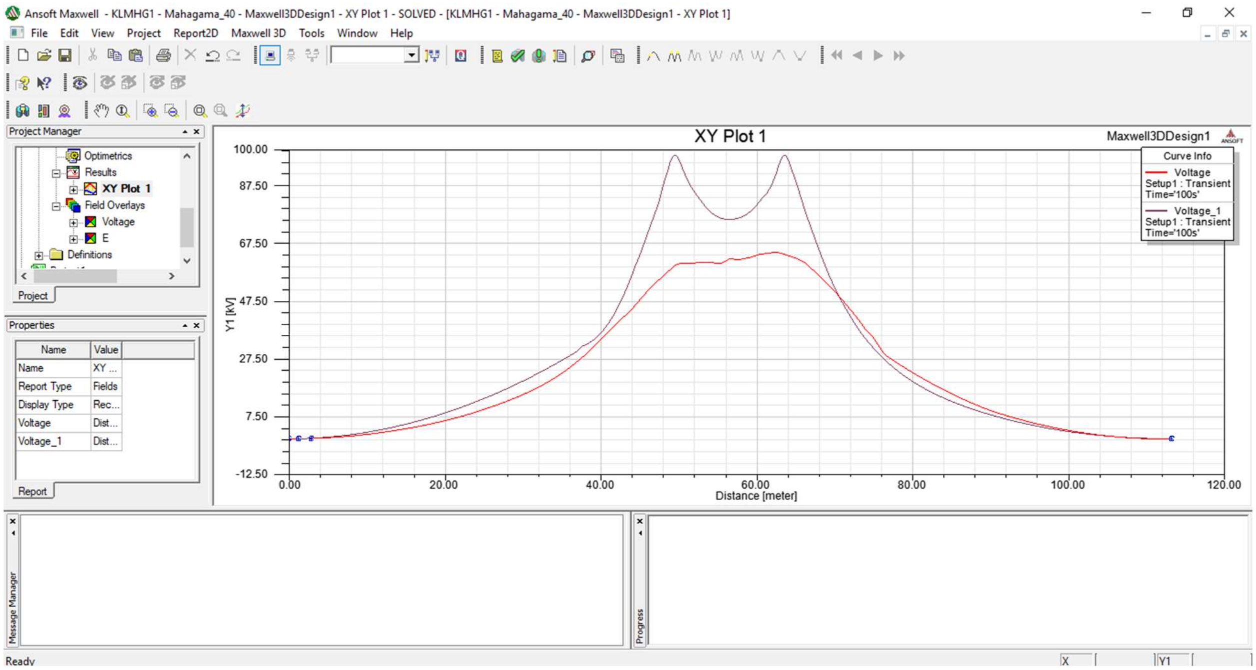


Figure 4-3 KLMHG1 Site - Voltage Profiles

Voltage pattern varied due to the tape formation and its effect eliminate once the measurement moving away from the center.

4.2.2 Simulation of RTKAL1 Site

This site is at north Sabaragamuwa province of Sri Lanka and having a higher soil resistivity at the site.

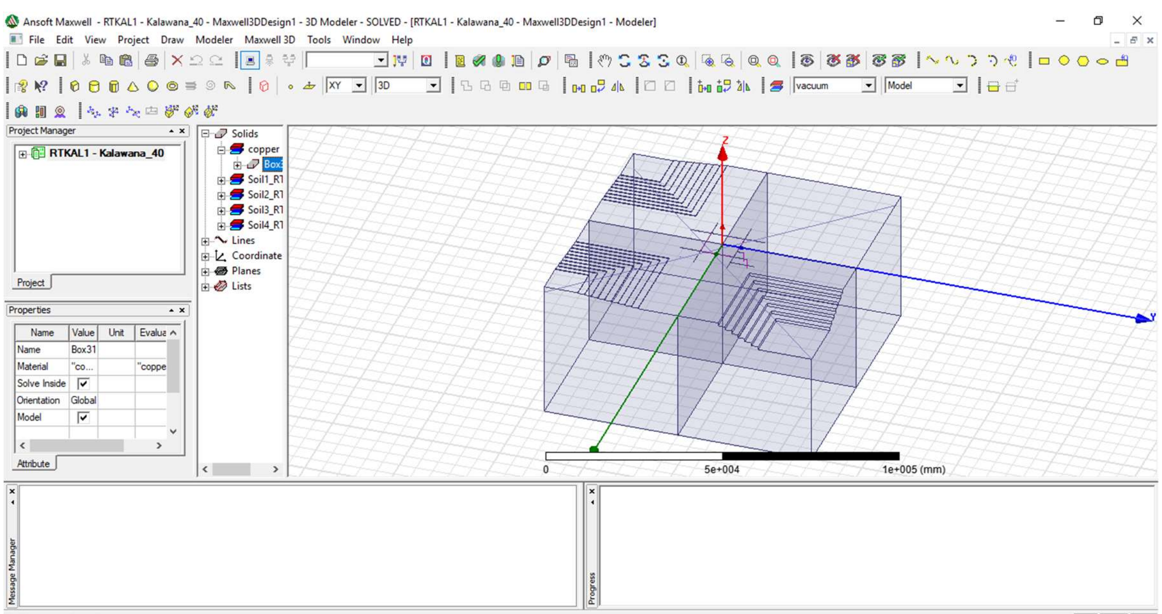


Figure 4-4 RTKAL1 Site Earth Map

4.2.2.1 Results of RTKAL1 Site

The voltage profile obtained was similar to the **RTKAL1** Station site and it is as follows.

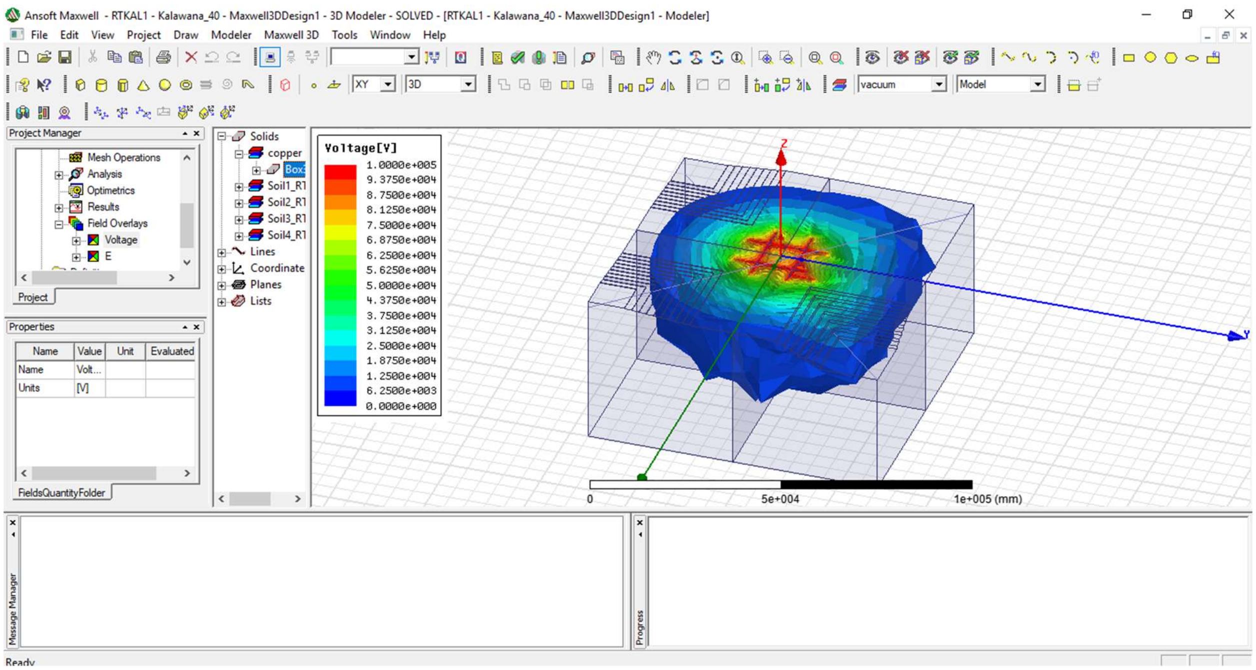


Figure 4-5 Voltage distribution of RTKAL1 Site

The higher voltage shown at the earth grid and its reducing with the distance increases from the earth network. Voltage profiles were obtained in the direction of the resistance measurements are taken.

Obtained voltage profiles were in similar pattern as in the RTKAL1 site and illustrated below.

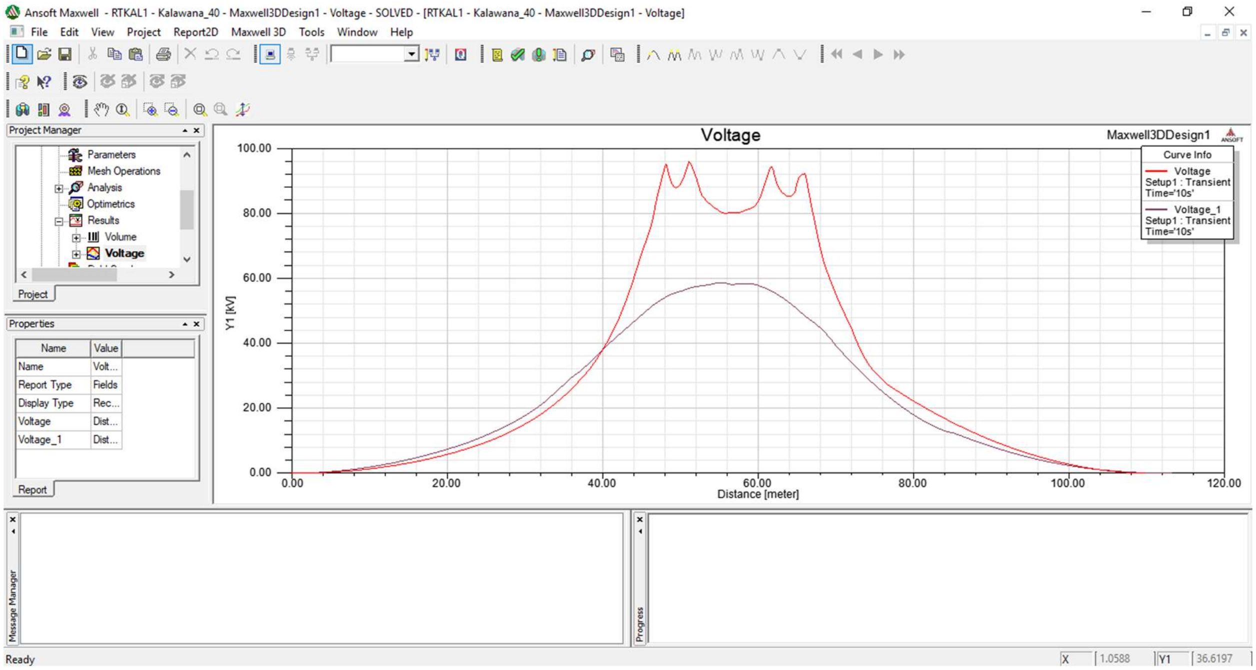


Figure 4-6 RTKAL1 Site - Voltage Profiles

4.2.3 Simulation of ZHOM05 Site

Being located at southern province of the country ZHOM05 site has lowest earth resistivity from the selected sites used for comparison.

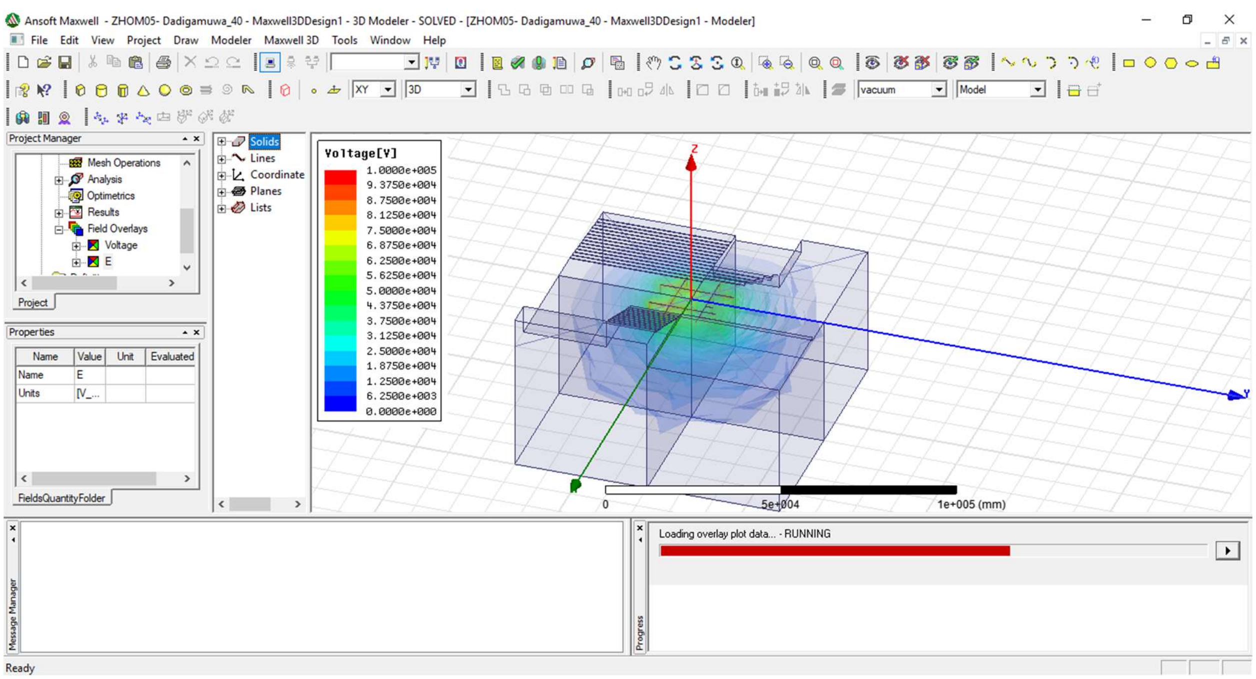


Figure 4-7 Voltage distribution of ZHOM05 Site

4.2.3.1 Results of GLNAR1 Site

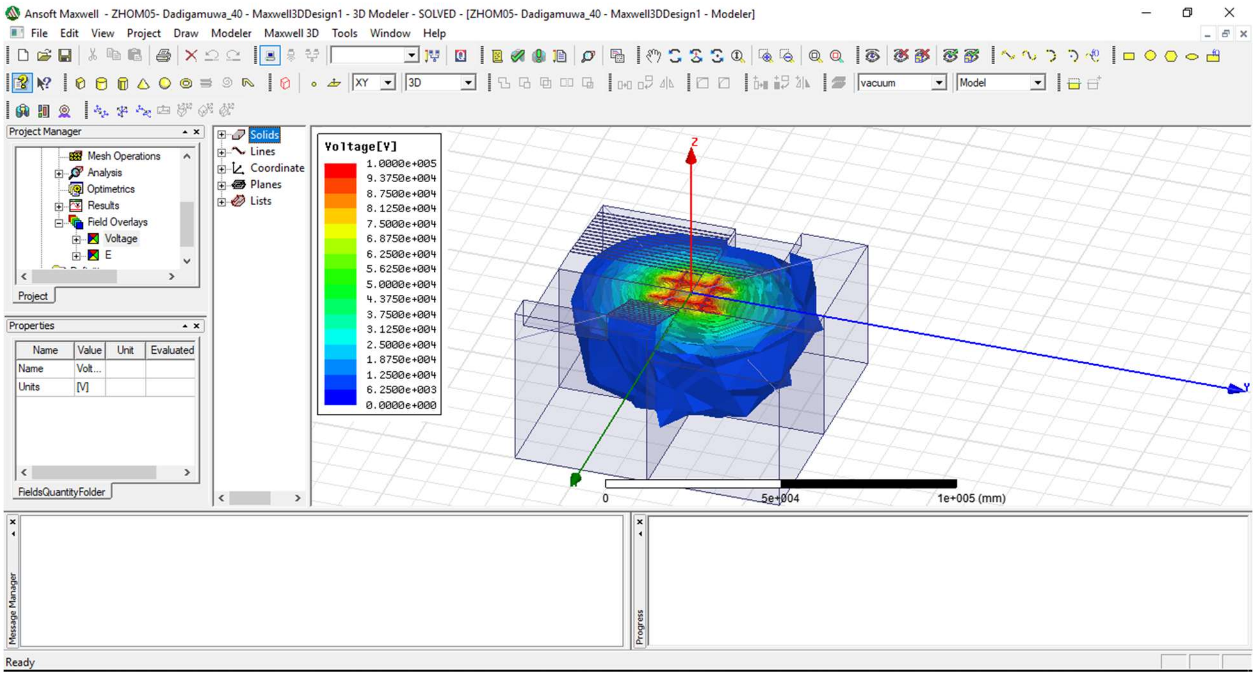


Figure 4-8 Voltage distribution of GLNAR1 Site

Directional voltage profile showing a similar pattern like in other two sites previously illustrated. The difference observed compared to other sites is voltage propagation to soil having longer distances as the resistivity is lower. Similar in other sites highest voltage was at the earth grid and reducing with the distance increases.

Directional voltage and current patterns along the corners were obtained as follows.

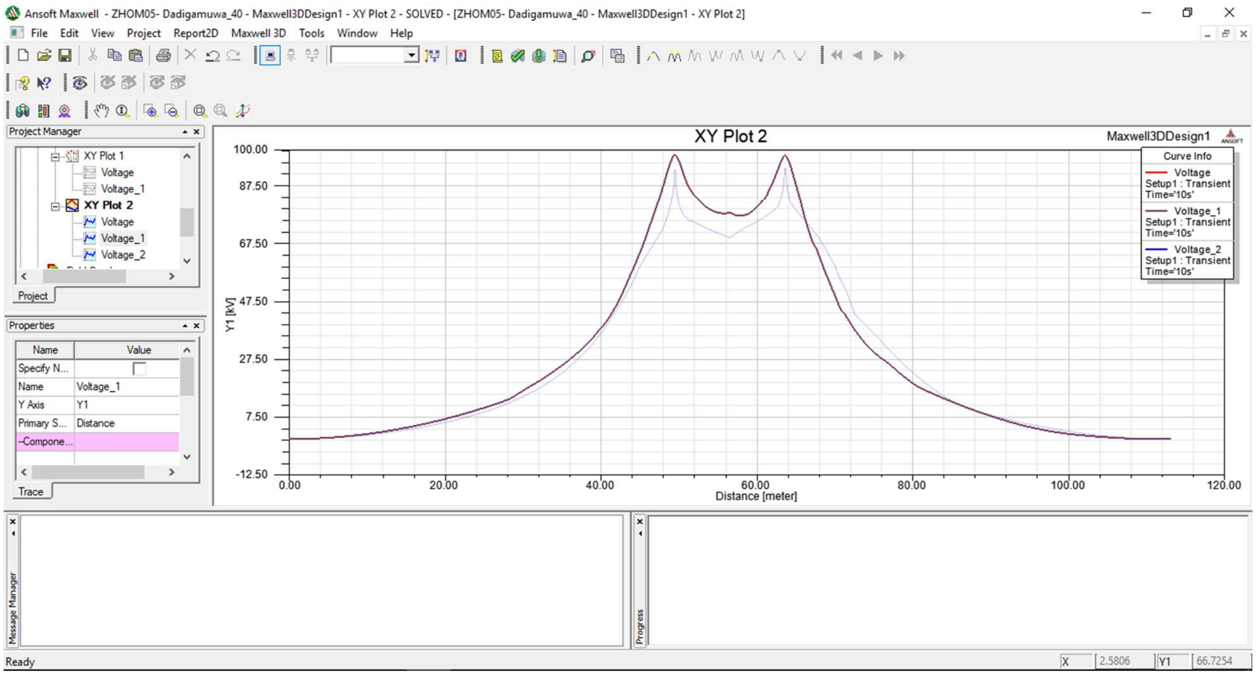


Figure 4-9 Voltage profile of GLNAR1 Site

4.3 Predictive Model Result

Main aim is to find a relationship between the simulated value and the Resultant field values

- Language selected : Python (Env: Conda / Editor : Jupiter Notepad)
- Used Python Libraries : numpy, seaborn, sklearn, pyplot

Performed both Linear regression, Polynomial regression

Key objectives of the modeling and analysis are

- Find an Estimation Model Site Resistance R
- Analyze the Model Accuracy/Validation
- RMSE (Root Mean Square Error)
- Find the behavior of the function on training and match predicted data vs the actual site reading
- 70% / 30% Population Train and Test the Model

Testing for the degree of the equation

Degree	Train RMSE	Test RMSE	Comment
1	9.41E-05	3.842399083	
2	9.41E-05	3.235870591	This is the most suitable degree.
3	9.41E-05	3.13829051	Only slight decline from here on RMSE. Model can be overfit to train data
4	9.41E-05	3.111705526	
5	9.41E-05	3.097850638	
6	9.41E-05	3.086334121	
7	9.41E-05	3.072825572	
8	9.41E-05	3.054940573	
9	9.41E-05	3.031968341	
10	9.41E-05	3.004448968	
11	9.41E-05	2.973601821	
12	9.41E-05	2.940851024	This is the best fit degree as per given training. But may overfit and give worst prediction due to "model overfit"
13	2.77E-04	852461409.6	From here not in graph as high RMSE
14	2.77E-04	632081237.2	

Table 4-3Testing results for the degree of the equation

Degree 2 has selected as per the above study.

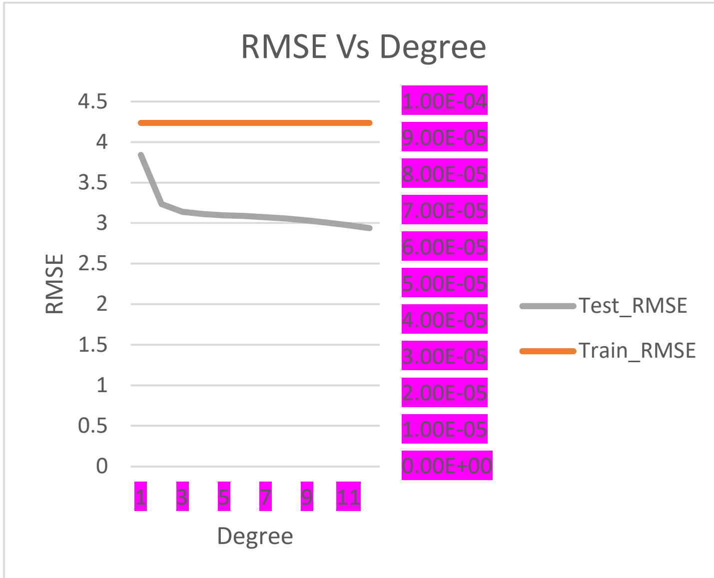


Figure 4-10 RMSE and Degree Comparison

Degree 2 has selected as per the above study.

Correlation - Heat Map for relationships

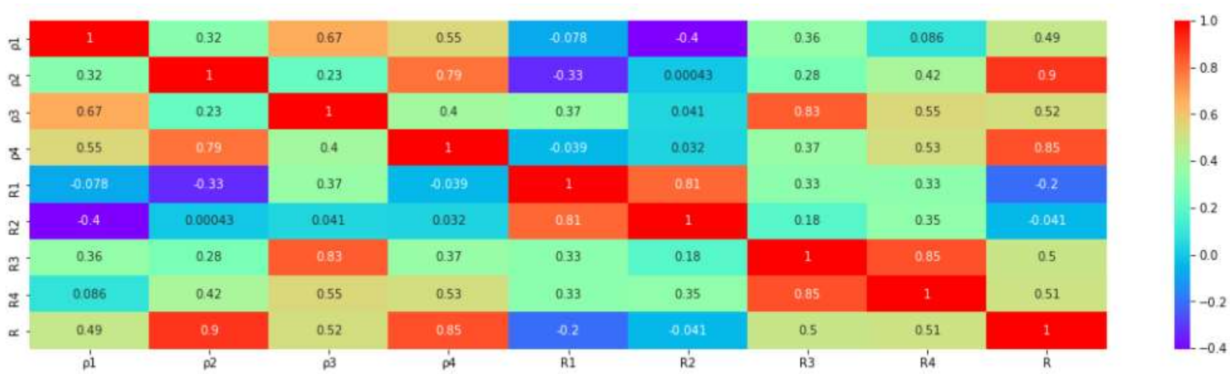


Figure 4-11 Correlation - Heat Map

Train and Predict Analysis

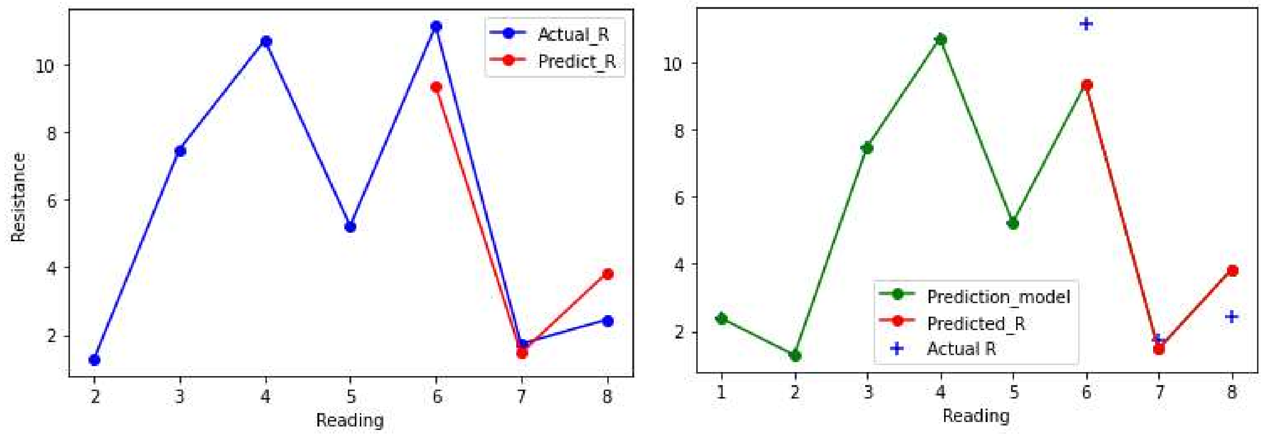


Figure 4-12Train and Predict Analysis

Results Test with a site out of the model data,

	Resistivity Readings (Ωm)				Resistance Reading ((Ω))				Simulated
Site ID	ρ_1	ρ_2	ρ_3	ρ_4	R_1	R_2	R_3	R_4	**Resistance (Ohm)**
KLKOL1	221.4	197.6	138.9	156.2	2.9	3.0	2.3	1.8	1.288

Table 4-4 Predictive Method Inputs

get R for new Xs

```
In [36]: # Get R for new data set (X1-X8) in excell data order
         new_x=[[221.4,197.6,138.9,156.2,29.3,30.2,23.6,18.3]]
         scaled_new_x_mm = scaler_mm.transform(new_x)
         model.predict(scaled_new_x_mm)

Out[36]: array([1.33195083])
```

Figure 4-13Predictive Method Test Result

Result,

Simulated R – 1.288 Ohms

Model R - 1.332 ohms

Error - 4.44 %

Defined Correlation is ,

(Simulated Resistance) = Correlation of [ρ_1 , ρ_2 ,ρ_3 ,ρ_4 ,R_1 ,R_2 ,R_3 ,R_4]

In the given matrix of ,

[1.08991487 0.14862681 1.85278518 0.63531181 0.32173443 -0.31417774
0.75348059 0.62200317 0.38718568 0.26666829 0.30297852 0.45015223
-0.02194201 -0.21940405 -0.21961632 0.27015422 0.03368588 2.08346532
0.57292057 0.83649996 -0.24706358 0.85579312 1.22802366 1.45982499
0.60291206 0.21871542 0.05547152 0.11268634 0.60672717 0.47281554
0.10538186 -0.56964698 -0.04637207 0.2532653 0.15378221 -0.33267339
-0.38375371 -0.55106424 -0.8663399 0.26021624 0.02893191 0.01624542
0.63495339 0.4146262 0.11182176]

* Degree 2 coefficient

5 EXPERIMENTAL RESULTS

Practical measurements on earth resistance and resistivity were taken in selected telecom sites using a selected method as per the literature survey.

5.1 Method of Earth Resistance Measurement

All the resistance measurements were done using fall of potential method as it has higher accuracy when correct probe spacings are used and due to most used technique in the telecom industry personals. The fall of potential method is done as per following figure.

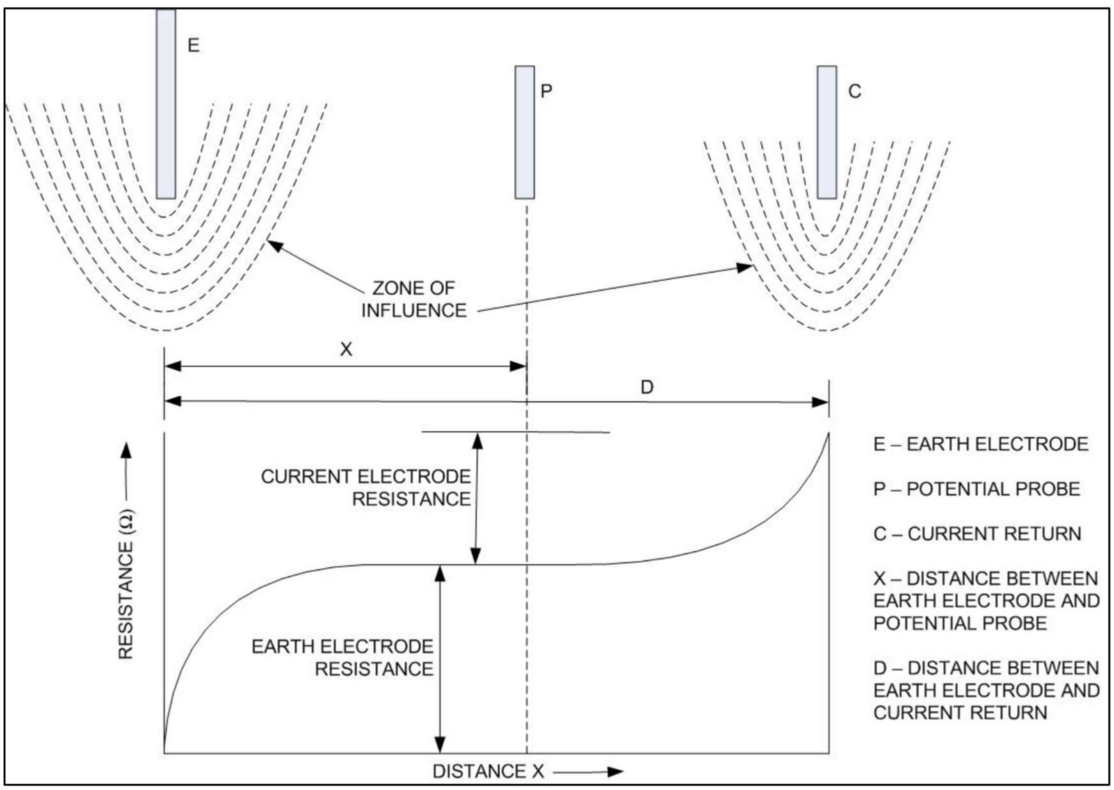


Figure 5-1 Fall of Potential Method [5]

There are 3 points connected to earth measuring equipment. Those are current and potential probes at predefined distance ratio of 62% = x/d and earth electrode. For accurate measurement correct spacing has to be placed and normally the earth electrode is at the earth grid, at which point the measurement need to be taken. Those points are typically the four corners of a 4-leg tower. The method used for earth resistance carries assumption where soil in which the earth network is build is having uniform soil resistivity.

5.2 Equipment Used for Measurement

5.3 Measurement Setup

When measuring the earth resistance at telecom tower sites initially only one measurement was taken, keeping current electrode in random distance and maintain the ratio with potential probe to be as per flat value formations method. But to get the directional variation of the earth resistance of the corner point of measurement total measurement length has to vary.

Site ID	Resistance Reading ((Ω))			
	R_1	R_2	R_3	R_4
KLMHG1	17.9	17.1	17.2	18.1
KLKOL1	2.9	3.0	2.3	1.8
KLBUL4	31.8	22.2	50.8	28.2
GLNAR1	16.25	13.4	12.6	3.8
RTKAL1	17.2	25.3	35.4	28.4
RTHIR1	21	17.25	23.8	25.6
ZBAT04	18.8	19.4	15.56	15.2
ZHOM05	34.5	34.4	5.6	10.2
RTDAH1	35.5	33.8	40.5	32.8

Table 5-1Site Measurements

The earth resistance measurement results obtained for variable measurement length were tabled against the measured distance and illustrated above.

6 RESULTS VALIDATION

Validation of simulation results were done by comparing the voltage results by achieved model of a particular telecom site and measured resistance value of the same site under the basic theory, where voltage is proportional to the resistance.

- Filed Analysis
- Literature Verification similar Modeling techniques

6.1 Selected Site Data

- For validation of results following sites was selected as per the results of theoretical modeling and Filed Analysis
- Literature Verification similar Modeling techniques

KLMHG1 site Sample measurement set for the verifying of the resistance from the distance, (20m)

Distance (20 m)	Resistance Reading (R ohms)
5	8.2
6	13.2
7	15.2
8	16.4
9	16.8
10	17.1
11	17.3
12	17.8
13	18.2
14	19.7
15	23.6
16	27.4
17	31.3
18	42.3
19	46.2
20	51.3

Table 6-1 On Site Measurements

Determine the resistance value from the flat are as detailed in the fall of potential resistance measurement process, estimated value is 17.9 Ohms.

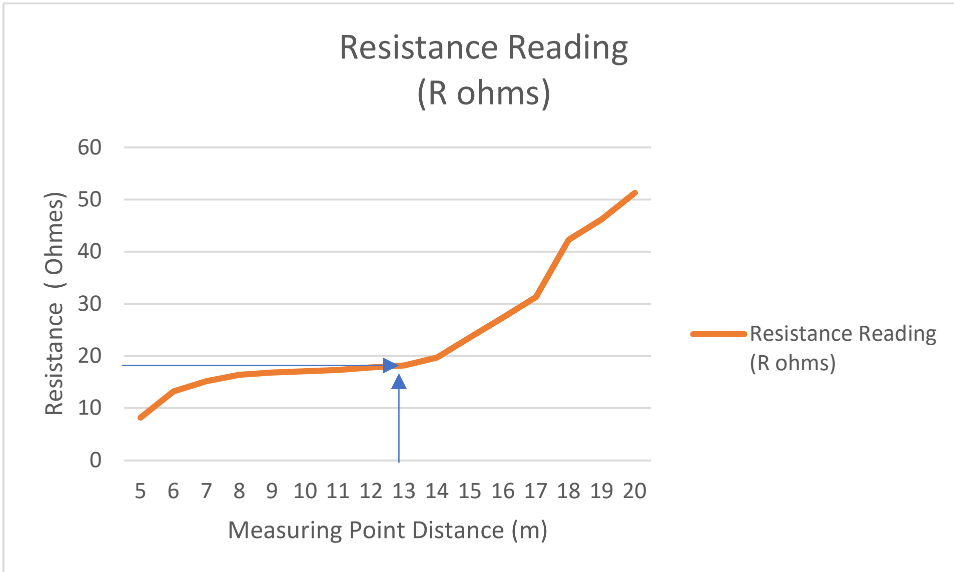


Figure 6-1Optimum point from the site measurements

Similar way the practice is processes for tabulated distances,

The resistance profile for the single direction.

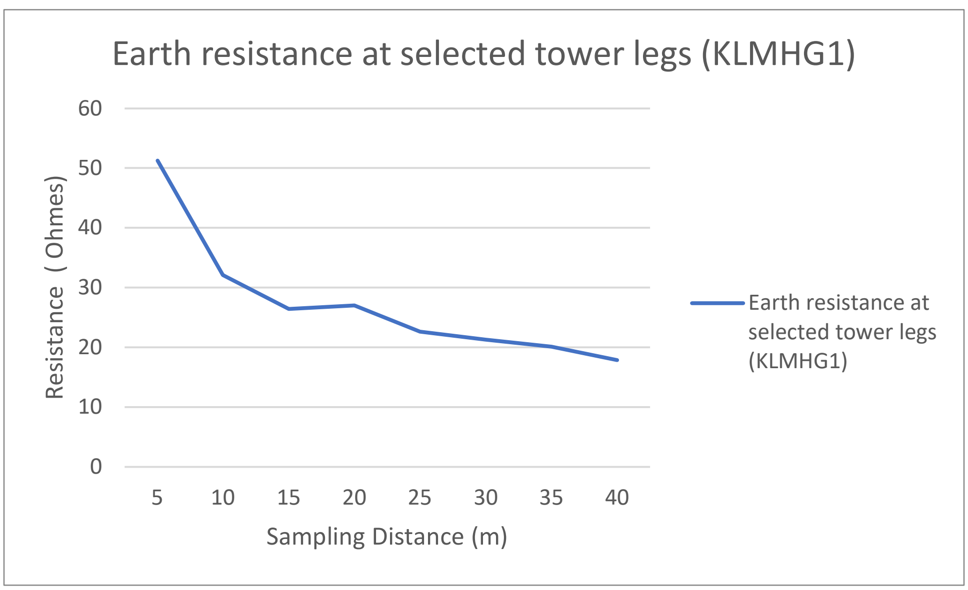


Figure 6-2 Site Resistance profile with distance

Further, the voltage profile of the same sites' simulation was compared with resistance profile

6.2 Comparison of Measured Values and Modeled Results

Measurements were taken in samples of measurement and earth resistance results were compared with the voltage results obtained by the calculation with equations. the soil was assumed to be homogeneous as the resistivity value represents the resultant resistive in the given direction.

Orientation	Number of Rods	Resistivity (Ohm.m)	a (Spacing factor)	Space (m)	Equation R (Ohm)	Simulation R (Ohm)	Error%	Field Results R (Ohm)	% Error
Rod	1	584	1		195.63	168.04	14.107	224.3	-14.65
Parallel	2	584	1.16	10	68.36	58.02	15.125	76.4	-11.76
Parallel	3	584	1.29	10	50.68	43.52	14.138	54.7	-7.93
Parallel	4	584	1.36	10	40.07	20.36	49.187	29.3	26.89
Star	3	584	1	10	25.42	17.31	31.921	23	9.54

Table 6-2 Comparison of results and measurements

The key reasons for the deviation of the observed results could be the none-homogeneity of the soil in the field results. The possible errors in the measuring device too could contribute to the error. the result may show a deviation due to the interference from a unidentified objects presence in the soil. Due to this reason the mutuel interferences each other rods may impact the deviation on the field result and the theoretical results.

By comparison of the simulated results and the filed values, it proves the error rate is drastically reduce while the rod count increases and there is an impact due to the distribution arrangement.

Comparison of a site measurement and simulation result,

Distance (m)	***Earth resistance at***	***Earth resistance at***

	selected tower legs	***selected tower legs***
1.5	95	95
2	61	61
2.5	31	31
3	27	27
3.5	25.8	25.8
4	23.5	23.5
4.5	18.6	18.6
5	25.8	25.8
5.5	17.5	17.5
6	11.6	11.6
6.5	8.8	8.8
7	8.4	8.4
7.5	6.1	6.1
8	5.3	5.3
8.5	5.1	5.1
9	5.2	5.2
9	5.2	5.2

Table 6-3Comparison of site measurement and simulation result

7 ANALYSIS OF RESULTS

Further analysis was done to find a method to estimate the actual earth electrode resistance of the earthing system. This comparisons and analysis continued for the telecom site used at the validation. Voltage drops and resistance drops along the measurement distance were in detailed compared for analysis.

Site ID	Resistivity Readings (Ωm)				Resistance Reading (Ω)				Simulated Resistance (Ω)	Predictive Model (Ω)
	ρ1	ρ2	ρ3	ρ4	R1	R2	R3	R4		
KLMHG1	1021	947.5	898.4	1257	17.9	17.1	17.2	18.1	11.15	11.89
KLKOL1	221.4	197.6	138.9	156.2	2.9	3.0	2.3	1.8	1.29	1.33
KLBUL4	980	498.2	2466	528	31.8	22.2	50.8	28.2	7.50	7.725
GLNAR1	647	236	274.4	73.5	16.25	13.4	12.6	3.8	1.73	1.54
RTKAL1	307.8	967.6	703.7	658.2	17.2	25.3	35.4	28.4	10.73	10.36
RTHIR1	277	307.8	307.8	358	21	17.25	23.8	25.6	2.38	2.51
ZBAT04	571.7	588.1	228.7	228.7	18.8	19.4	15.56	15.2	2.446	2.21
ZHOM05	155.1	294	130.6	140.3	34.5	34.4	5.6	10.2	1.28	1.23
RTDAH1	605.7	550	950.6	780.5	35.5	33.8	40.5	32.8	5.23	5.51

Table 7-1Result Analysis

7.2 Deviation analysis

Mean Resistance Reading	Simulated Resistance		Predictive Model	
Rm (Ω)	Rs (Ω)	% Deviation	Rp (Ω)	% Deviation
17.58	11.15	37%	11.89	32%
2.50	1.29	48%	1.33	47%
33.25	7.5	77%	7.72	77%
11.51	1.73	85%	1.54	87%
26.58	10.73	60%	10.36	61%
21.91	2.38	89%	2.51	89%
17.24	2.446	86%	2.21	87%
21.18	1.28	94%	1.23	94%
35.65	5.23	85%	5.51	85%

Table 7-2 Deviation Analysis

8 CONCLUSIONS AND RECOMMENDATION

8.1 Summary of Conclusions of the Study

In the conclusions of the study, a method realized by the analysis to measure earth resistance in a single figure with an error percentage and limitations of the study are discussed.

The key objective of the research is to present a sites earth resistance value in a single figure considering the directional measured values of earth resistance and resistivity using finite element analysis and predictive modelling.

This research work has achieved the objective by presenting the earth resistance of the sites through the predictive model using the site's directional resistance and resistivity readings measured from the fall of potential method.

8.2 Recommendation for Earth Resistance Measurement

The study has shown that, when measuring earth resistance by commonly used measurement methods such as fall of potential method, placement of electrodes in the ground has to do with extensive care and it too has its own limitation in the context of tower earth resistance measurements. The correct factors of measurement to be maintained, if the measurement is done by fall of potential method.

Once measurement distance is increased , the results are convergent towards each other. Practical constraints are evidence to achieve this task of getting large distance readings. The model present in the research bring a novel approach to represent direction reading to a single value. The rich data set will lead to better accuracy with less error percentage.

The measurements have to be less effected from interference from the earthing network elements. Further standard practices have to be incorporated when taking measurements such as placing of electrodes in the line of perpendicular to the earth network.

8.3 Limitations of the Study

As ANSYS Electromagnetics is electromagnetics simulator has its own constrains to do a straightforward earthing network analysis and voltage variation along the directions is used to calculate the resistance. It was hard to find a simulator for complex earthing networks which uses finite element method for analysis.

The prediction model accuracy depends on the data set provided and higher the date count provides a higher accuracy. Most of the operators do not have the earthing reading along.

8.4 Recommendations for future work

The theoretical analysis on why the earth resistance gets different in different directions were examined in this research. As the future study, this shall be extended to develop a model to incorporate the effect of multi-layer formation to address none homogeny soil layers in site. Further this action could use to reduce the boundary conditions of the modeling. This will help to incorporate the lesser distanced measurement of the actual resistance and resistivity in the studding directions which is more practical in the current land availability in a telecom site.

The data model could be evaluated with a better sample of site readings with the help of the other operators in the business and this tool could be use as the benchmarking tool for the conformity of the earthing system acceptance with the approval from regulatory bodies such as TRCSL.

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