

**THE EFFECTS OF INCREASED FAULT CURRENT ON THE EXISTING
SUBSTATION GROUNDING SYSTEM – a Case Study**

Research Project

By

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ABSTRACT

The aim of this research is to investigate the effect of increased fault current on an existing substation grounding system. Increased load demands because of the new customers connecting on the existing network or reconfigured network, power flows on the transmission and distribution assets will increase, which will in turn trigger the increase in fault current levels, both three-phase and phase-to-ground, throughout the power system. The protection that ground grids provide against step- and touch potentials is only good up to the expected level and duration of ground fault currents, as originally communicated in the design phase. A case study is presented in this research project to investigate the effects of increased fault current on the existing Ruighoek distribution substation grid. It is found that, the ground potential rise and touch potential are aggravated by the increased fault currents. And by increasing the area occupied by the ground grid and decreasing the horizontal spacing of parallel conductors, step- and touch potentials are improved to safe limit as per IEEE Std. 80-2000.

DECLARATION

Although much literature was consulted during the preparation of this research project, absolute caution was taken within the bounds of human accuracy to ensure that all works were properly referenced. I therefore declare that this research project is my own work and that it has not been submitted (prior to this submission) to any academic institution or body of academics for examination.

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Dr JM Van Coller (Supervisor)
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DEDICATION

‘Unto my Heavenly Father, the ultimate source of all power, wisdom and life, be all the glory, honour and praise’.

TABLE OF CONTENTS

Abstract.....	2
Declaration.....	3
Dedication.....	4
Table of Contents.....	5
Table of Figures.....	8
List of Tables.....	9
List of Symbols.....	10
Chapter 1 – Introduction.....	13
1.1 Background.....	13
1.2 Research Scope.....	15
1.3 Research Approach.....	16
1.3.1 Chapter 1 (Background).....	16
1.3.2 Chapter 2 (Literature Study).....	16
1.3.3 Chapter 3 (Grid Design Mathematical Model).....	17
1.3.4 Chapter 4 (Research Case Study).....	17
1.3.5 Chapter 5 (Possible Design Improvements).....	17
1.3.6 Chapter 6 (Conclusion).....	17
1.3.7 Chapter 7 (References).....	17
1.4 Conclusion.....	17
Chapter 2 – Literature Review.....	18
2.1 Introduction to Substation Grounding System.....	18
2.1.1 Ground Potential Rise.....	19
2.1.2 Touch Voltage.....	20
2.1.3 Step Voltage.....	21
2.1.4 Transferred Voltage.....	21
2.1.5 Mesh Voltage.....	22
2.1.6 Metal to Metal Touch Voltage.....	22

2.2 Determination of Maximum Grid Current.....	23
2.2.1 Effect of Future Network Changes	25
2.3 Soil Characteristics	26
2.3.1 Measurement of Soil Resistivity.....	27
2.3.2 Measurement of Earth Resistance.....	30
2.4 Designing of Grounding System.....	32
2.4.1 Grounding System Design Critical Parameters	34
2.4.1.1 Maximum Grid Current	34
2.4.1.2 Fault Duration and Shock Duration	34
2.4.1.3 Soil Resistivity.....	34
2.4.1.4 Resistivity of Surface Layer.....	35
2.4.1.5 Grid Geometry	35
2.5 Design Procedure of a Grounding System.....	35
2.5.1 Design Modification	38
2.6 Types of Grounding	40
2.7 Conclusion	43
Chapter 3 – Grid Design Mathematical Model.....	44
3.1 Introduction.....	44
3.2 Tolerable Step- and touch Voltage	44
3.3 Conductor Sizing	45
3.4 Asymmetrical Currents	47
3.5 Soil Resistivity Measurements.....	48
3.6 Ground Resistance	48
3.7 Maximum Grid Current	50
3.8 Fault Currents.....	52
3.9 Ground Potential Rise.....	53
3.10 Mesh Potential	54
3.11 Step Potential	58
3.12 Conclusion	59

Chapter 4 – Research Case Study	60
4.1 Introduction.....	60
4.2 Eskom Policy for Neutral Earthing of Electrical Networks.....	61
4.2.1 Earthing of Transformer HV Neutrals	62
4.2.2 Earthing of Transformer MV Neutrals	63
4.2.2.1 Fault Current Contribution per Neutral Earthing Point	63
4.2.2.2 Neutral Earthing Points Provided from a Common Earth mat	64
4.2.2.3 Neutral Earthing Points Provided from a Separate Earth mat	64
4.3 Ruighoek Substation	65
4.4 Existing Grounding System Design.....	69
4.4.1 Visual Inspection.....	69
4.4.2 Earth Electrodes Resistance Measurement.....	70
4.4.3 Soil Resistivity Measurement.....	72
4.4.4 Existing Substation Earth Grid Analysis.....	78
4.5 Grounding System Design with Increased Faults Current.....	82
4.5.1 Ground Potential Rise Analysis.....	85
4.5.2 Mesh Potential Analysis.....	86
4.5.3 Step Potential Analysis.....	87
4.6 Conclusion	88
Chapter 5 – Possible Design Improvements	90
5.1 Grid Design Improvement	90
5.2 Conclusion	95
Chapter 6 – Conclusion	96
Chapter 7 – References	97
Appendix	98

TABLE OF FIGURES

Figure 1.1: Proposed Network Expansion.....	14
Figure 1.2: Research Methodology.....	16
Figure 2.1: An illustration of GPR.....	20
Figure 2.2: Basic Shock Situation.....	21
Figure 2.3: Extended Transferred Potential.....	22
Figure 2.4: Soil Model.....	26
Figure 2.5: Wenner Four-pin Method.....	28
Figure 2.6: Circuit Diagram for Three-pin or Driven Ground Rod Method.....	29
Figure 2.7: Fall of Potential Method of Measuring Earth Resistance.....	31
Figure 2.8: Tagg Method of Measuring Earth Resistance of a Large Grid Electrode.....	32
Figure 2.9: Design Procedure Block Diagram.....	37
Figure 2.10: Ungrounded System with a Line-to-Ground fault.....	40
Figure 2.11: Solidly Grounded System.....	41
Figure 3.1: An illustration of distribution line.....	51
Figure 4.1: Ararat 88kV and 132kV Network.....	60
Figure 4.2: Case Study 88kV Network Diagram.....	61
Figure 4.3: Existing Ruighoek Substation Single Electric.....	66
Figure 4.4: Existing Ruighoek Substation Earth mat Configuration.....	67
Figure 4.5: Existing Earth Electrodes.....	70
Figure 4.6: Fall of potential method of measuring earth resistance.....	70
Figure 4.7: Earth Resistance Curve.....	71
Figure 4.8: Wenner Four Pin Method.....	72

Figure 4.9: Wenner Arrangement.....	73
Figure 4.10: Direction of Soil Resistivity Measurement on site.....	74
Figure 4.11: Two Layer Earth Model.....	75
Figure 4.12: An Illustration of Transferred GPR.....	81
Figure 4.13: New 132kV Network Diagram.....	83
Figure 4.14: New Ruighoek Substation Single Electric Diagram.....	84
Figure 5.1: Illustration of Touch Potential.....	90
Figure 5.2: Illustration of Mesh Potential.....	91
Figure 5.3: An Improved Ruighoek Substation Earth mat Configuration	94

LIST OF TABLES

Table 2.1: Typical ratio of corner to corner mesh voltage.....	33
Table 2.2: Characteristics of Grounding Methods.....	42
Table 3.1: Typical Values for D_f	47
Table 3.2: Empirical Resistance Values.....	52
Table 4.1: Substation Parameters.....	68
Table 4.2: Measured Resistances.....	71
Table 4.3: Soil Resistivity Survey Measurement Results.....	75
Table 4.4: Auto grid Pro Results.....	76
Table 4.5: Existing Ground Grid Results.....	81
Table 4.6: New Substation Parameters.....	83
Table 4.7: Summary of Results.....	87
Table 5.1: Grid Parameters.....	92
Table 5.2: Summary of Results.....	93

LIST OF SYMBOLS

Symbol	Description	Clause number
ρ	Soil resistivity	$\Omega.m$
ρ_s	Surface layer resistivity	$\Omega.m$
$3I_0$	Symmetrical fault current	A
A	Total area enclosed by ground grid	m^2
C_s	Surface layer derating factor	-
d	Diameter of grid conductor	m
D	Spacing between parallel conductor	m
D_f	Decrement factor for determining I_G	-
D_m	Maximum distance between any two points On the grid.	m
E_m	Mesh voltage at the centre of the corner mesh For the simplified method	V
E_s	Step voltage between points above the outer Corner of the grid and a point 1m diagonally outside The grid for the simplified method	V

h	Depth of grid conductors	m
h_s	Surface layer thickness	m
I_G	Maximum grid current that flows between Ground grid and surrounding earth (including DC offset)	A
K	Reflection factor between different resistivities	-
K_h	Corrective weighting factor that emphasizes the effects Of grid depth, simplified method	-
K_i	Correction factor for grid geometry, simplified method	-
K_{ii}	Corrective weighting factor that adjusts for the effects of inner Conductors on the corner mesh, simplified method	-
K_S	Spacing factor for step voltage, simplified method	-
L_C	Total length of grid conductor	m
L_M	Effective length of L_C+L_R for mesh voltage	m
L_R	Total length of ground rods	m
L_S	Effective length of L_C+L_R for step voltage	m
L_T	Total effective length of grounding system Conductor, including grid and ground rods	m

L_x	Maximum length of grid conductor in x direction	m
L_y	Maximum length of grid conductor in y direction	m
n	Geometric factor composed of factors n_a , n_b , n_c and n_d	-
R_g	Resistance of grounding system	Ω
S_f	Fault current division factor	-
t_c	Duration of fault current for sizing ground conductors	s
t_f	Duration of fault current for determining decrement factor	s
t_s	Duration of shock for determining allowable body current	s

CHAPTER 1 – INTRODUCTION

The aim of this research is to investigate the effects of increased fault currents on the existing substation grounding system and suggest possible design improvements.

1.1 Background

After an investigation of **Ararat 88kV** network, challenges from both transmission and distribution networks were compiled. From the transmission network side, the Ararat - Spitskop 275kV lines are thermally constrained and the 275/88kV 3x315MVA transformers at Ararat main transmission substation (MTS) have exceeded firm capacity. Expansion space for 88kV and 275kV bays is not possible. The challenge on the distribution network is the new load growth within the Ararat network, which is currently limited to 30MVA. This is due to the N-1 thermal and voltage constraints, as well as the ageing Ararat distribution network. There is a new load growth of more than 150MVA that cannot be supplied from Ararat MTS, due to the growth limitation on the network. The proposed solution for this problem is to establish a new **Ngwedi main transmission station (MTS)** and convert some of the Ararat 88kV substations to 132kV (see figure 1.1). The new Ngwedi 400/132kV MTS will initially have 2x500MVA transformers. The decision was made to convert *Ruighoek, Mogwase Industries, SA Chrome, Boschkoppie and Manyane* substations to 132kV [2].

Due to increased load demands as a result of new customers connecting on the existing network or reconfigured network, power flow on the transmission and distribution assets will increase. This will, in turn, trigger an increase in fault current levels throughout the power system, both three-phase and phase-to-ground. New generation sources to be added to the transmission and distribution networks increase fault current intensities. It is crucial for the user of a distribution facility to be aware of the magnitude of increased ground-fault current at the service entrance, as well as of the actual condition of the grid.

The protection that ground grids provide against step- and touch potential is only good up to the expected level and duration of ground fault currents, as originally communicated in the design phase.

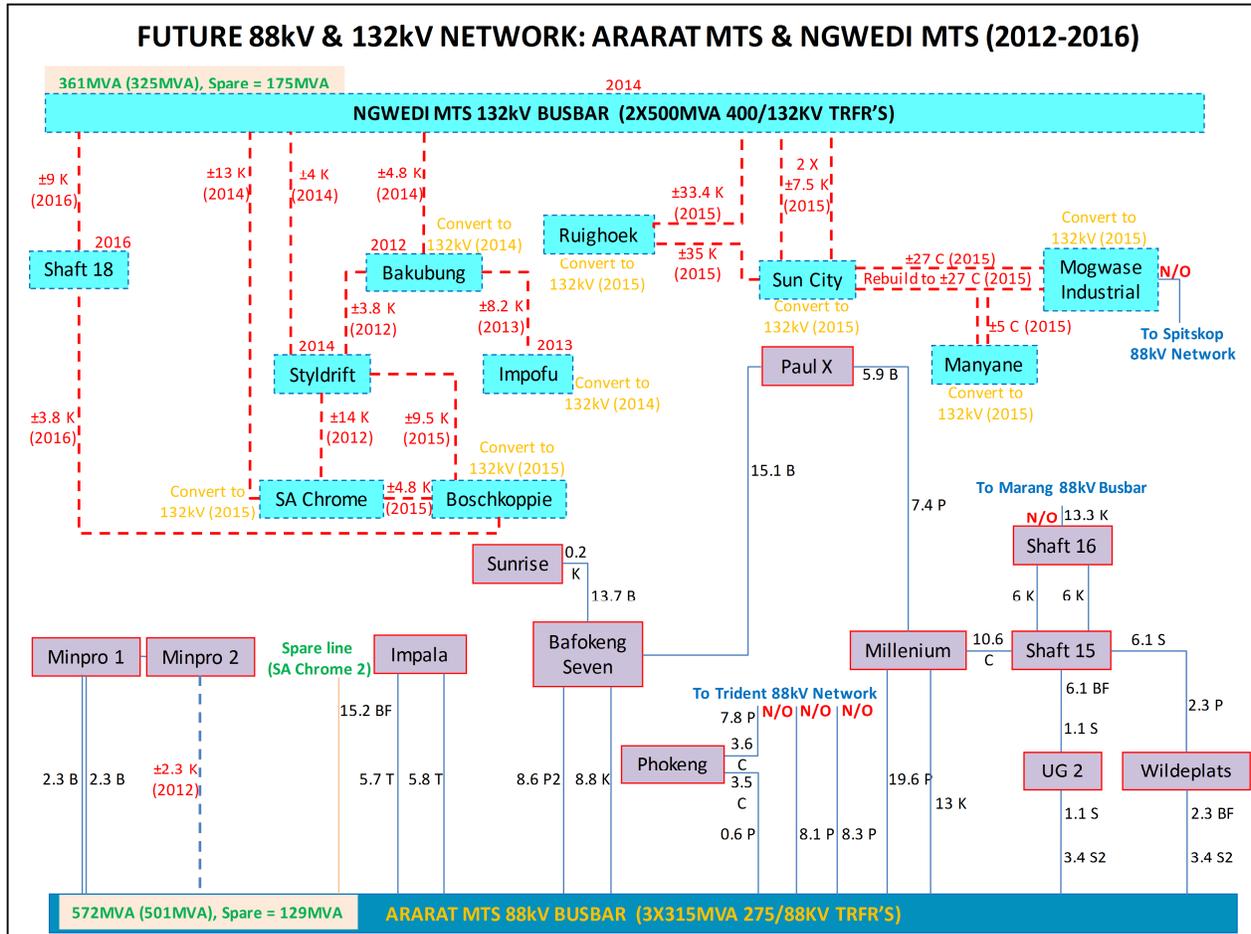


Figure 1.1: Proposed network expansion [2].

It is necessary in all types of substations to install a system that effectively connects all metallic structures and non-energised parts of the power system equipment together and to earth, in order to limit unsafe values of potential differences between them. This system is referred to as the “grounding system”, and is an essential component of the power transmission system. The grounding system typically consists of a grid of conductors, grounding electrodes (rods, grounding wells, etc.), equipment connections to the grid (risers), external connections (distribution neutrals, overhead shield wires, etc.), and may also include a thin layer of high resistivity surfacing material [1, 4].

The potential differences in a substation are the result of lightning discharges, ground currents caused by fault conditions, phase imbalance, switching, or inrush currents caused by normal system operations. The path of these currents through the soil and metallic conductors cause voltages that can, if not properly controlled, be dangerous to human life, damage system equipment, or cause it to malfunction [1, 4]. The grounding system is designed and installed to provide a means to safely discharge lightning strokes to earth, reduce step- and touch potential to safe levels and limit dangerous soil currents. It allows the detection of ground faults by protective relaying systems, provides low impedance paths through the earth for load and ground currents, and provides a common ground reference which assists in the coordination of insulation throughout the power system [1, 3]. It is important to undertake an assessment and refurbishment of substation grounding systems, since the physical and electrical properties or requirements of the substation grounding system can change overtime. This is due to the available fault current magnitude at a substation that may have increased substantially due to new generation or network expansion/reconfiguration.

1.2 Research Scope/Limitations

This research will only deal with the effects of the increased fault current on the existing substation grounding systems, focusing mainly on the ground potential rise, safe step- and touch potentials. The short circuit calculations will not be covered in this research. The possible design improvements will also be investigated as part of the research. Ruighoek substation will be used as a case study for the research.

1.3 Research Approach

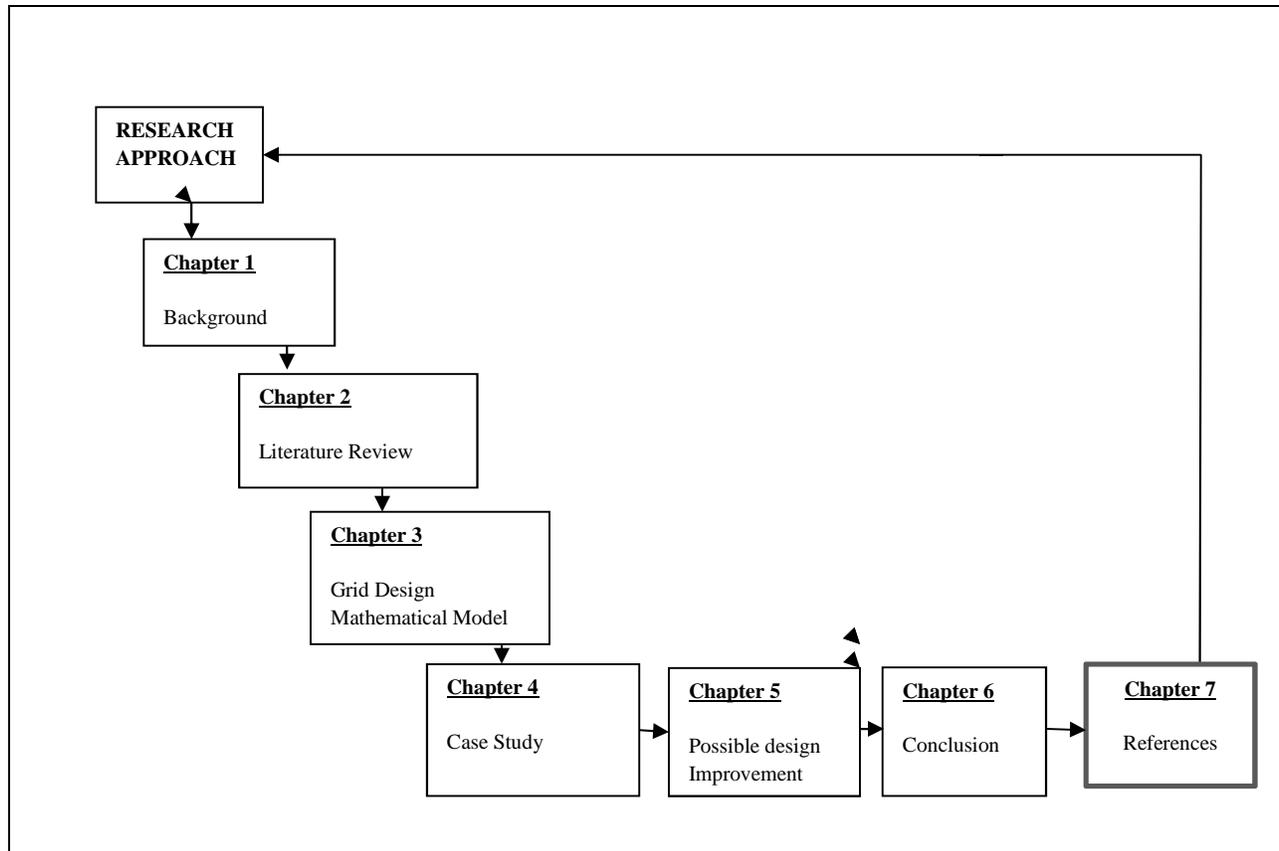


Figure 1.2: Research methodology

1.3.1 Chapter 1: Background

This chapter deals with research background relating to substation grounding system and increased fault current in transmission and distribution networks.

1.3.2 Chapter 2: Literature review

This chapter deals with a literature review related to substation grounding system design, as well as types of grounding. It presents an overview of relevant academic theories in the various areas applicable to this research study, and provides the basis for analysis and improvement of existing substation grounding system.

1.3.3 Chapter 3: Grid design mathematical model

This chapter presents the mathematical model for the grounding system design, which provides the basis for analysis and design of substation earth mat.

1.3.4 Chapter 4: Research case study

Chapter 4 presents the case study that will be used to investigate the effects of increased fault currents on the existing substation grounding system. Grid resistance measurements and calculations are included in this chapter. The research for the case study is done at Ruighoek substation.

1.3.5 Chapter 5: Possible design improvement

In this chapter the insight gained from previous chapters is analysed and interpreted in order to provide possible grid design improvements.

1.3.6 Chapter 6: Conclusion

A comprehensive conclusion of the research objectives is provided in this chapter.

1.3.7 Chapter 7: References

This chapter provides all references used in the research report.

1.4 Conclusion

The background of the research purpose, objectives, approach and methodology is provided. The articulation of the research aim provides the focus required to gather information/knowledge to arrive at research objectives.

CHAPTER 2 - LITERATURE REVIEW

This chapter presents the literature study about grounding system designs, in order to gather an insight that will assist in the analysis, to derive possible design improvements. Research variables or constraints will also be discussed in order to set a benchmarking platform for the proposed solutions to the research problem statement. Lastly, a brief discussion with regards to the methodology to be used to measure soil resistivity and resistance is presented.

2.1 Introduction to substation grounding system

A substation grounding system is an underground, regular mesh conductor network that serves the purpose of providing the path of least resistance to the traversing current so that, in the case of a fault, it is distributed in all directions in the underlying earth. If efficient, the resulting ground potential due to a fault and the ensuing step- and touch potential will be low enough to guarantee the safety of personnel working on the substation, as well as to the safety of the installed equipment [3].

Absence of a safe and effective grounding system can result in maloperation or non-operation of control and protective devices, thereby disturbing the operation of a complete power system. Great care should therefore be taken when designing the grounding system of any substation, primarily to ensure electrical safety of persons working within or near substations [4]. The main functions of any grounding system are to provide a passage for electrical current to earth without exceeding operating limits of equipment, and to provide a safe environment for the protection of personnel in the vicinity of grounded facilities against the danger of electrical shock, particularly under fault conditions. A grounding system consists of all of the interconnected grounding facilities in the substation area, including ground grid, overhead ground wires, neutral conductors, underground cables, etc, of which ground grid is the main component. The ground grid comprises of horizontal interconnected conductors, often supplemented by vertical ground rods [4].

Being a major component of the overall grounding system, the design of the grounding grid should be such that the total grounding system is safe and, at the same time, cost-effective. A good grounding system should be able to maintain the actual mesh- and step voltages within a substation well below tolerable step- and touch voltages. These tolerable safety criteria have been established based on the fibrillation discharge limit of the body current. To obtain this safety, the equivalent electrical resistance of the grounding system must be low enough to ensure that fault currents dissipate mainly through the grounding grid into the earth [6, 7].

The main performance parameters of the grounding system are grid resistance, step voltage, touch voltage and ground potential rise (GPR). The main thing to be taken care of in the design of any substation grounding system is that actual step- and touch voltages must not exceed those described as tolerable values [4]. Tolerable step- and touch voltages for a person weighing 50 and 70 kg are described in IEEE Std. 80-2000 [7].

2.1.1 Ground potential rise

The ground potential rise is the product of the ground resistance R_g , which is a function of the number of grid conductors, its area, its depth and the resistivity of the surrounding soil multiplied by the current I_G entering the grid during a fault [3]. This is the maximum electrical potential that a substation grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. Under normal conditions, the grounded electrical equipment operates at near zero ground potential. That is, the potential of a grounded neutral conductor is nearly identical to the potential of remote earth. During a ground fault, the portion of fault current that is conducted by the substation grounding grid into the earth causes the rise of the grid potential with respect to remote earth [7].

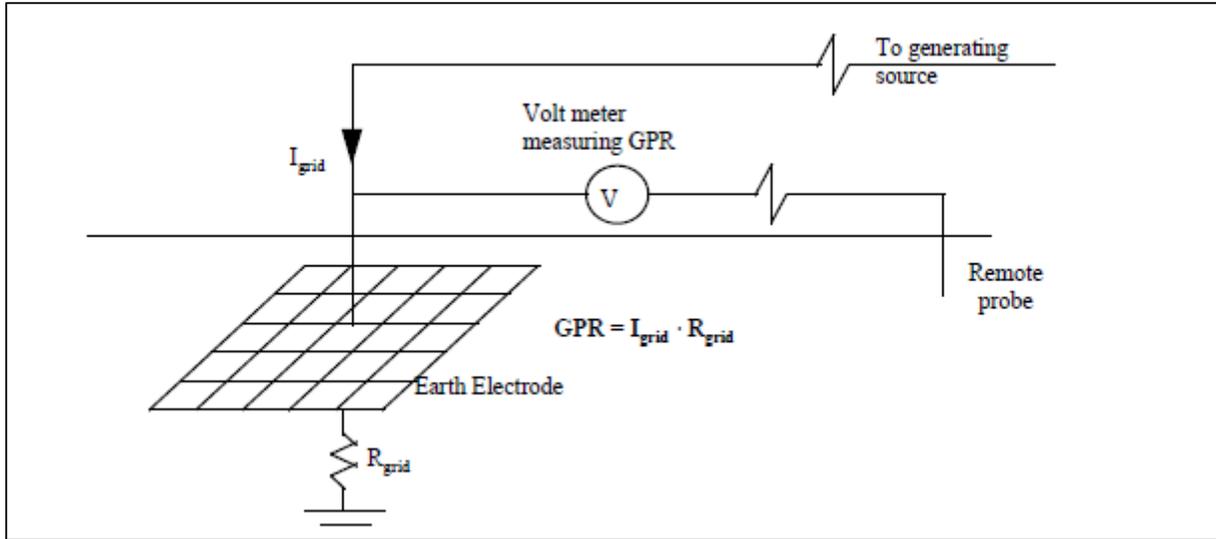


Figure 2.1: An illustration of GPR [6].

In order to protect communication equipment, i.e. telephones, faxes etc., the GPR must be limited to about 5000 V [6]. The maximum allowable grid resistance is therefore:

$$R_{grid} = \frac{5000}{I_{grid}} \Omega \quad 2.1$$

2.1.2 Touch voltage

At the instant of a fault, the potentials that occur at the surface of the earth are such that voltage spikes appear above the grid conductors, while depressions occur above the mesh areas. At typical operational frequencies, this potential distribution is relatively equal, regardless of the point of current injection [7].

Touch voltage is the potential difference between the GPR and the surface potential at the point where a person is standing, while at the same time having a hand in contact with a grounded structure, as shown in figure 2.2.

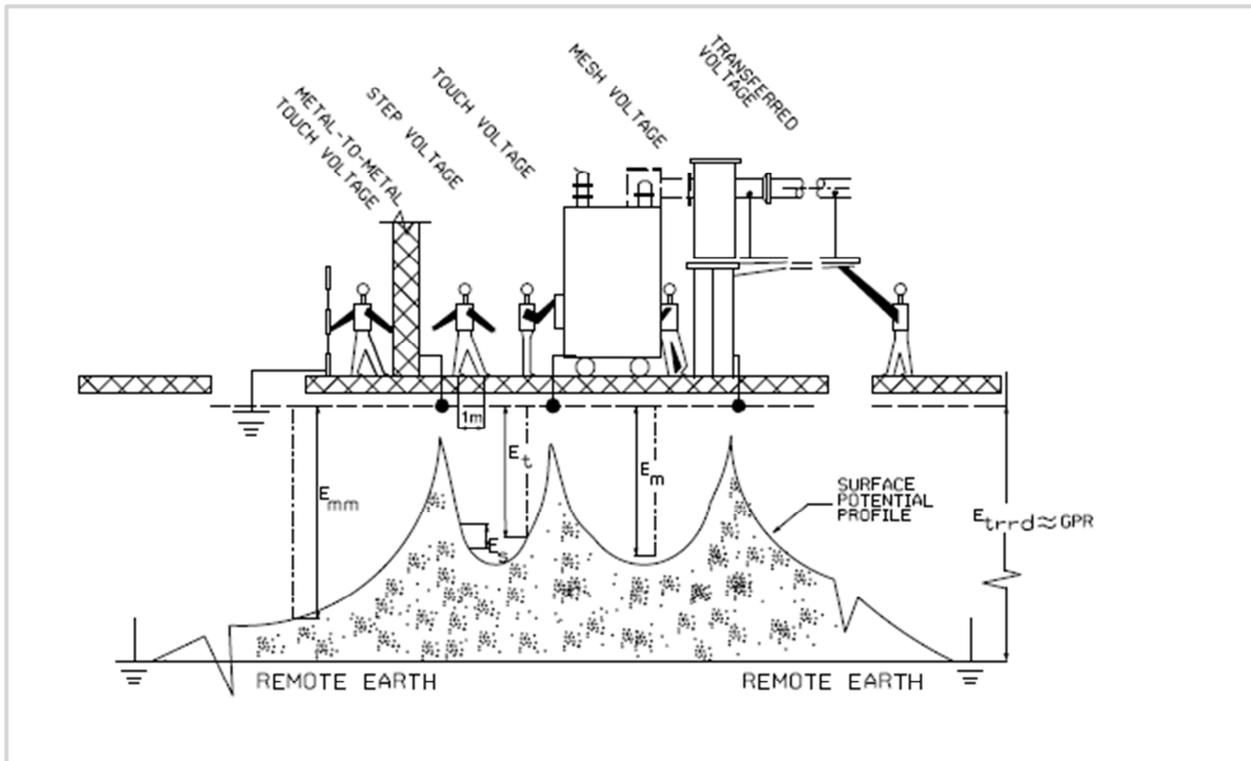


Figure 2.2: Basic shock situation [7].

2.1.3 Step voltage

Step voltage is the difference in surface potential experienced by a person bridging a distance of 1m with the feet without coming into contact with any grounded object, as shown in figure 2.2. It is equal to the difference in voltage given by the voltage distribution curve between two points at different distances from the earth electrode. A person could be at risk of injury during a fault simply by standing near the earthing system point [6, 7].

2.1.4 Transferred voltage

Transferred voltage is a special case of touch voltage, where voltage is transferred into or out of the substation from or to a remote point external to the substation site (see figure 2.2). Typically, the case of transferred voltage occurs when a person stands within the substation area and touches a conductor grounded at a remote point, or stands at a remote point and touches a conductor connected to the substation grounding grid [6, 7]. During fault conditions, the resulting potential to ground may equal or exceed the full GPR of a grounding grid discharging the fault current, rather than the fraction of this total voltage encountered in the ordinary touch

contact situations. The transferred voltage may exceed the sum of the GPRs of both substations, due to induced voltages on communication circuits, static or neutral wires, pipes, etc. It is impractical, and often impossible, to design a ground grid based on the touch voltage caused by the external transferred voltages. Hazards from these external transferred voltages are best avoided by using isolating or neutralising devices, and by treating and clearly labelling these circuits, pipes, etc. as being equivalent to energised lines [7].

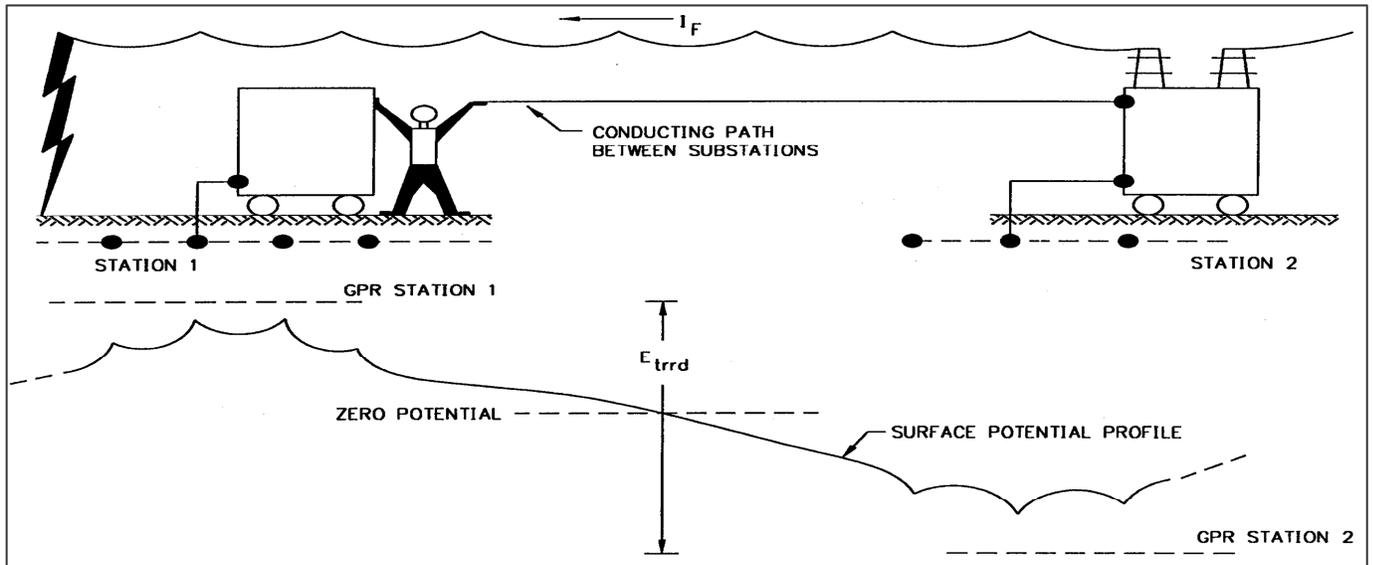


Figure 2.3: Extended transferred potential [7].

2.1.5 Mesh voltage

Mesh voltage is the maximum touch voltage within a mesh of a ground grid. Mesh voltage represents the highest possible touch voltage that may be encountered within a substation grounding system. Thus, voltage across a man standing in the centre of the mesh and touching a structure bonded to the earth grid some distance away [6].

2.1.6 Metal - to - metal touch voltage

Metal-to-metal touch voltage is the difference in potential between metallic objects or structures within the substation site that could be bridged by direct hand-to-hand or hand-to-feet contact. The metal-to-metal touch voltage between metallic objects or structures bonded to the ground grid is assumed to be negligible in conventional substations [7].

However, the metal-to-metal touch voltage between metallic objects or structures bonded to the ground grid and metallic objects internal to the substation site, such as an isolated fence, but not bonded to the ground grid, may be substantial. In a conventional substation, the worst touch voltage is usually found to be the potential difference between a hand and the feet at a point of maximum reach distance [7].

The typical case of metal-to-metal touch voltage occurs when metallic objects or structures within the substation site are not bonded to the ground grid. Objects such as pipes, rails, or fences that are located within or near the substation ground grid area, and not bonded to the ground grid, meet this criteria. Substantial metal-to-metal touch voltages may be present when a person standing on or touching a grounded object or structure comes into contact with a metallic object or structure within the substation site that is not bonded to the ground grid [7].

2.2 Determination of maximum grid current

A design value of the maximum grid current is defined as follows:

$$I_G = D_f \times I_g, \quad 2.2$$

Where:

I_G is the maximum grid current in A,

D_f is the decrement factor for the entire duration of the fault t_f

I_g is the rms symmetrical grid current in A

The symmetrical grid current is that portion of the symmetrical ground fault current that flows between the grounding grid and surrounding earth [7].

It may be expressed as

$$I_g = I_f \times S_f \quad 2.3$$

Where:

I_g is the rms symmetrical grid current in A,

I_f is the rms value of symmetrical ground fault current in A

S_f is the fault current division factor.

In most cases, the largest value of grid current will result in the most hazardous condition. For these cases, the following steps are involved in determining the correct design value of maximum grid current I_G for use in substation grounding calculations:

- a) Assess the type and location of those ground faults that are likely to produce the greatest flow of current between the grounding grid and surrounding earth, and hence the greatest GPR and largest local surface potential gradients in the substation area.
- b) Determine, by computation, the fault current division factor S_f for the faults selected in establishing the corresponding values of symmetrical grid current I_g
- c) For each fault, determine the value of decrement factor D_f , based on its duration time, t_f , to allow for the effects of asymmetry of the fault current wave.
- d) Select the largest product $D_f \times I_g$ and hence the worst fault condition.

The current division factor would change during the fault duration, based on the varying decay rates of the fault contributions and the sequence of interrupting device operations. However, for the purposes of calculating the design value of maximum grid current and symmetrical grid current per definitions of symmetrical grid current and maximum grid current, the ratio is assumed to be constant during the entire duration of a given fault [7]. Where transmission line overhead ground wires or neutral conductors are connected to the substation ground, a substantial portion of the ground fault current is diverted away from the substation ground grid. Where this situation exists, the overhead ground wires or neutral conductors should be taken into account in the design of the grid. Connecting the substation grid to overhead ground wires or neutral conductors, or both, and through them to transmission line structures or distribution poles, will usually have the overall effect of increasing the GPR at tower bases, while lessening it at the substation [7].

This is because each of the nearby towers will share in each voltage rise of the substation ground mat, whatever the cause, instead of being affected only by a local insulation failure or flashover at one of the towers. Conversely, when such a tower fault does occur, the effect of the connected substation ground system should decrease the magnitude of gradients near the tower bases [7].

2.2.1 Effect of future network changes

It is a common experience for maximum fault currents at a given location to increase as system capacity is added, or new connections are made to the grid. While an increase in system capacity will increase the maximum expected fault current I_f , new connections may increase or decrease the maximum grid current I_G . One case in which the grid current may decrease with new connections is when new transmission lines are added with ground or neutral wires, or both [7].

In general, if no margin for increase in I_G is included in the original ground system design, the design may become unsafe. Subsequent additions will also usually be less convenient and more expensive to install. It is a widely accepted practice to assume the total fault current, I_f , between the grid and surrounding earth in an attempt to allow for system growth. While this assumption would be overly pessimistic for present-year conditions, it may not exceed the computed current I_G , considering current division and system growth [7].

If the system growth is taken into account and current division is ignored, the resulting grid will be oversized. An estimate of the future system conditions can be obtained by including all system additions forecasted. Caution should be exercised when future changes involve such design changes as disconnection of overhead ground wires coming into the substations. Such changes may have an effect on ground fault currents and may result in an inadequate grounding system. However, future changes such as additions of incoming overhead ground wires, may decrease the current division ratio, resulting in the existing ground system being oversized [7].

When fault currents that are in excess of design values enter a grounding system, the following effects may occur [15]:

1. Reduction in electrical safety, increased step- and touch potentials.
2. Damage or failure of grounding equipment:
 - a) Thermal damage due to excessive short circuit currents
 - b) Mechanical damage due to excessive short-circuit stresses
 - c) Drying of the soil, resulting in increased soil resistivity (IEEE 2000 Sec.12.3)
 - d) Insulation failure due to high-induced voltages (IEEE. 1996.)
3. Possible effects of grounding grid degradation on the electrical power system:
 - a) Reduced lightning protection
 - b) Misoperation of ground fault protection
 - c) Increased zero-sequence impedance for unbalanced load currents
 - d) Reduced electromagnetic compatibility [15].

2.3 Soil characteristics

The behaviour of a ground electrode buried in soil can be analysed by means of the circuit in figure 2.4. Most soils behave both as a conductor of resistance, r , and as a dielectric. Except for high-frequency and steep-front waves penetrating very resistive soil material, the charging current is negligible in comparison to the leakage current, and the earth can be represented by pure resistance [6, 7].

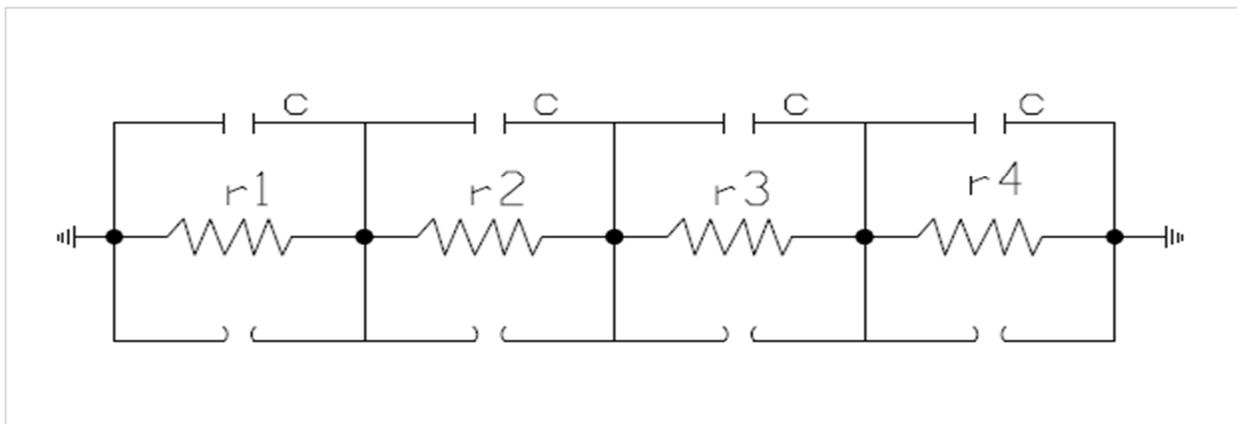


Figure 2.4: Soil model [7].

Soil resistivity is not affected by a voltage gradient, unless the latter exceeds a certain critical value. The value somewhat varies with the soil material, but it usually has the magnitude of several kilovolts per centimetre. Once exceeded, arcs would develop at the electrode surface and progress into the earth so as to increase the effective size of the electrode, until gradients are reduced to values that the soil material can withstand [7].

This condition is illustrated in figure 2.4 by the presence of gaps. Because the substation grounding system is normally designed to comply with far more stringent criteria of step- and touch voltage limits, the gradient can always be assumed to be below the critical range. Soil resistivity in the vicinity of ground electrodes may be affected by current flowing from the electrodes into the surrounding soil. The thermal characteristics and the moisture content of the soil will determine if a current of a given magnitude and duration will cause significant drying, and thus increase the effective soil resistivity [7].

2.3.1 Measurement of soil resistivity

Resistivity investigations of a substation site are essential for determining both the general soil composition and degree of homogeneity. Test samples and other geological investigations often provide useful information on the presence of various layers and the nature of soil material, leading at least to some ideas regarding the range of resistivity at the site [13].

Actual resistivity tests should be made at a number of places within the site. Substation sites where the soil may possess uniform resistivity throughout the entire area and to a considerable depth are seldom found. There are typically several layers, each with a different resistivity. Lateral changes also occur after, but in comparison to the vertical ones, these changes are usually more gradual. Soil resistivity tests should be made to determine if there are any important variations of resistivity with depth. The number of such readings should be greater where the variations are large, especially if some readings are so high as to suggest a possible safety problem [13].

If the resistivity varies appreciably with depth, it is often desirable to use an increased range of probe spacing in order to obtain an estimate of the resistivity of deeper layers. This is possible because, as the probe spacing is increased, the test source current penetrates more and more distant areas, in both vertical and horizontal directions, regardless of how much the current path is distorted due to the varying soil conditions [13]. A number of measuring techniques can be used to measure the resistivity of the soil. The Wenner four-pin method, as shown in figure 2.5, is the most commonly used technique. In brief, four probes are driven into the earth along a straight line, at equal distances a apart, driven to a depth b . The voltage between the two inner (potential) electrodes is then measured and divided by the current between the two outer (current) electrodes to give a value of resistance R .

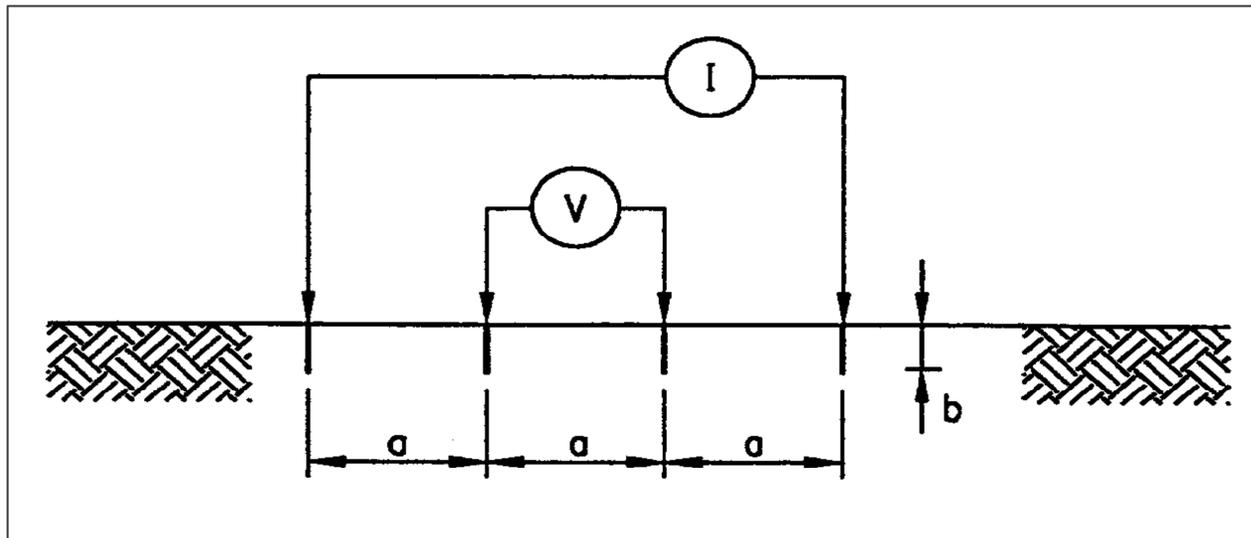


Figure 2.5: Wenner four-pin method [7].

Another method of measuring soil resistivity, shown in figure 2.6, is the driven-rod method based on the three-pin or fall-of-potential method. In this method, the depth L_r of the driven-rod located in the soil to be tested is varied. The other two rods, known as reference rods, are driven to a shallow depth in a straight line. The location of the voltage rod is varied between the test rod and the current rod. Alternatively, the voltage rod may be placed on the side opposite the current rod [7].

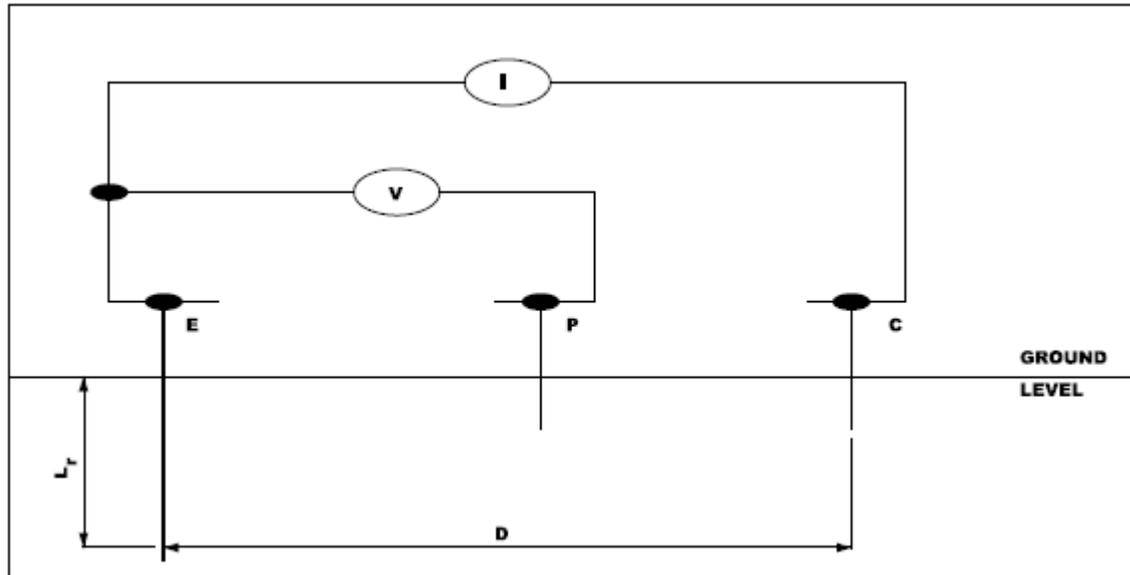


Figure 2.6: Circuit diagram for three-pin or driven-ground rod method [7].

Tests conducted by the Ohio State University [7] demonstrated that either the Wenner four-pin method or the driven-rod three-pin method can provide the information needed to develop a soil model. The Wenner four-pin method is the most popular method in use. There are a number of reasons for this popularity. The four-pin method obtains the soil resistivity data for deeper layers without driving the test pins to those layers. No heavy equipment is needed to perform the four-pin test. The results are not greatly affected by the resistance of the test pins or the holes created in driving the test pins into the soil [7].

An advantage of the driven-rod method, although not related necessarily to the measurements, is the ability to determine to what depth the ground rods can be driven. Knowing if and how deep rods can be driven into the earth can save the need to redesign the ground grid. Often, because of hard layers in the soil such as rock, hard clay, etc., it becomes practically impossible to drive the test rod any further, resulting in insufficient data. A disadvantage of the driven-rod method is that when the test rod is driven deep in the ground, it usually loses contact with the soil due to the vibration and the larger diameter couplers, resulting in higher measured resistance values. A ground grid designed with these higher soil resistivity values may be unnecessarily conservative. The driven-rod method presents an uncertainty in the resistance value [7].

2.3.2 Measurement of earth resistance

A good grounding system provides a low resistance to remote earth in order to minimise the GPR. For most transmission and other large substations, the ground resistance is usually about 1 Ω or less. In smaller distribution substations, the usually acceptable range is from 1 Ω to 5 Ω , depending on the local conditions as per design requirement [7].

In order to measure the earth resistance of an electrode, a test current has to be circulated between the electrode and an auxiliary current electrode. It is important, however, that the resistance volumes of the electrode to be measured and the auxiliary electrode do not overlap to an extent that serious errors in the measurement are introduced. For this reason, the distance between the geometrical centres of the earth electrode and the auxiliary current electrode has to be made as large as possible (e.g. 100 m or more), but at least five times the largest diagonal width, or depth, of the electrode, whichever is the greater. In some cases, an existing electrode of known resistance could be used as an auxiliary electrode, provided that its resistance is not much greater than that of the electrode to be measured. However, the resistance volume of the auxiliary current electrode could be large and could seriously overlap that of the electrode to be measured [7]. As in the case of the measurement of earth resistivity in areas where the resistivity is high, it could be necessary to measure the current injected into the current probe that is being used as auxiliary electrode. If the current is low (e.g. less than 5 mA) it could be necessary to reduce the earth resistance of both the potential and current probes by “watering” the area immediately around the probe [7].

The same instrument used for the measurement of soil resistivities can be used for earth resistance measurement, and to connect C_1 and P_1 to the auxiliary current and potential electrodes respectively. Connect C_2 and P_2 to the earth lead of the electrode to be measured. Drive the auxiliary current and potential electrodes into the earth along a straight line from the geometric centre of the earth electrode (see figure 2.7), with due regard given to the presence of other buried structures [7].

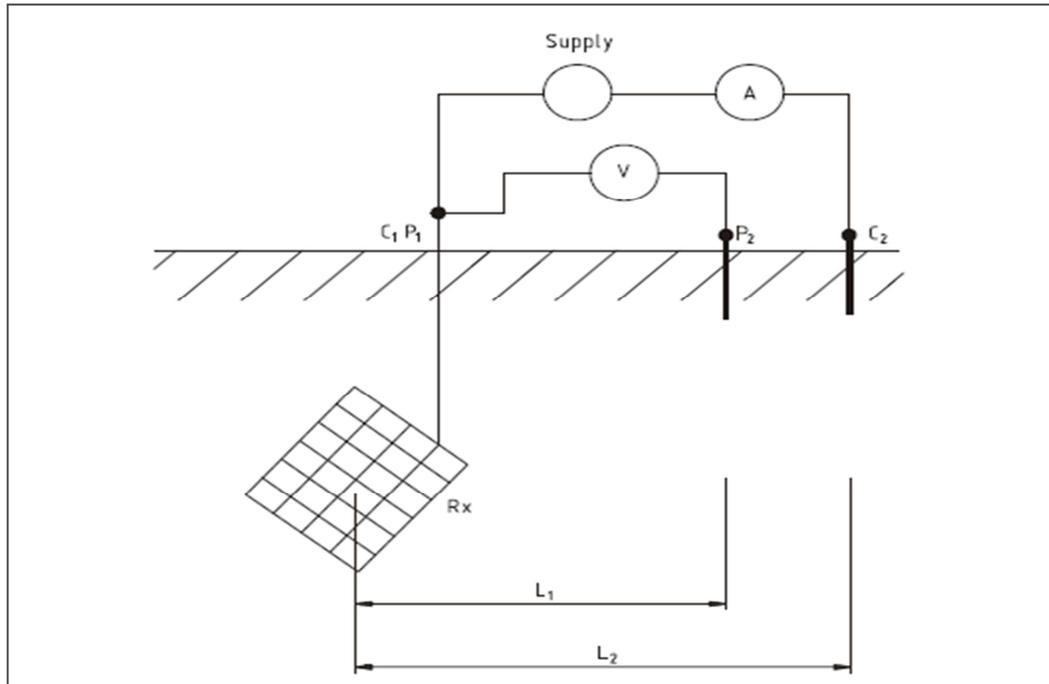


Figure 2.7: Fall of potential method for measuring earth resistance [7].

Because of the dimensions of larger grid electrodes, it could be difficult or impractical to reach a distance L_2 of at least five times the largest diagonal width or depth of the electrode, whichever is greater, owing to the presence of other buried structures. The coupling between the voltage and current leads should be large enough to negate the accuracy of the measurement obtained by increasing the distance L_2 . A further problem is in deciding where the centre of the equivalent hemisphere is, and from which point the measurements of L_2 are taken.

This method has several variations and is applicable to all types of ground resistance measurements. The ground resistance measurement basically consists of measuring the resistance of the grounding system with respect to a remote ground electrode. The remote electrode is theoretically at an infinite distance from the grounding system where the earth current density approaches zero. Although the fall-of-potential method is universally used, it presents many difficulties and sources of error when used to measure the resistance of large grounding systems usually encountered in practice. These difficulties occur mainly because of the size and configuration of the grounding system and soil heterogeneity [7].

When measurements are conducted on a large electrode, the electrical centre of the grid tends to move from the geometric centre to a point on the grid nearer to the current and potential electrodes. The Tagg method shown in figure 2.8 is a practical and relatively simple method of finding the earth resistance of large grid electrodes, taking the above constraints into account [13].

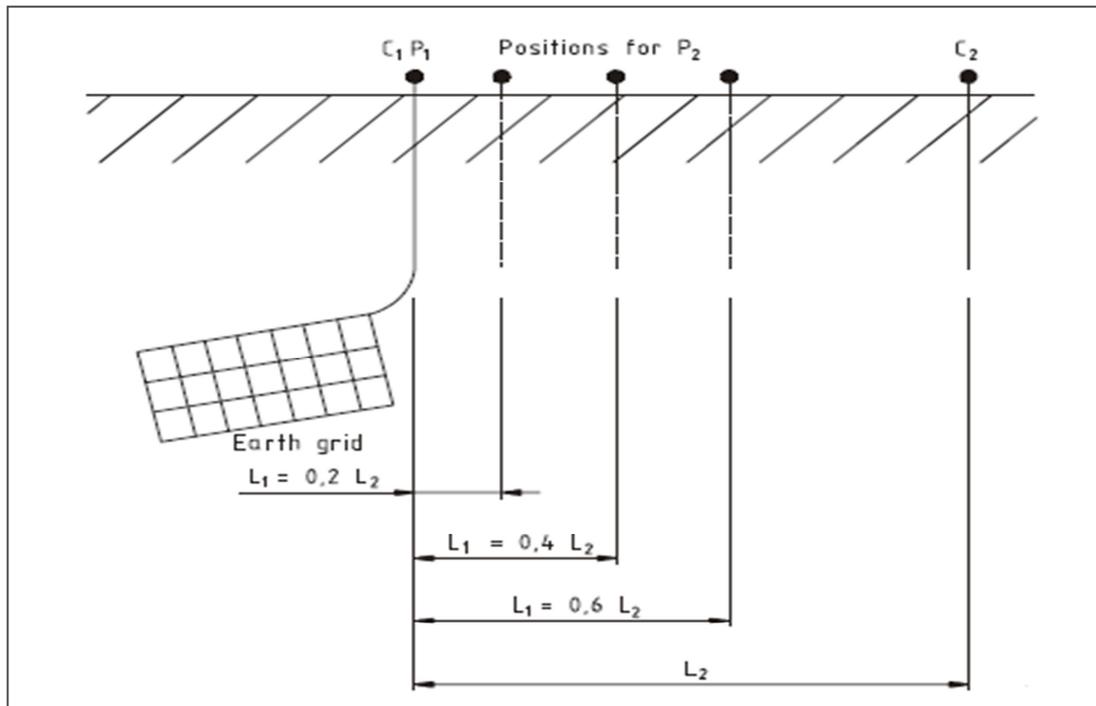


Figure 2.8: Tagg method of measuring earth resistance of a large grid electrode [13].

2.4 Designing of grounding system

As already stated in this chapter, there are two main design goals to be achieved by any substation ground system under normal and fault conditions. These goals are:

- a) To provide means to dissipate electric currents into the earth without exceeding any operating and equipment limits.
- b) To ensure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.

The design procedure described here is based on assuring safety from dangerous step- and touch voltages within, and immediately outside, the fenced substation area. Because the mesh voltage is usually the worst possible touch voltage inside the substation (excluding transferred potentials), the mesh voltage will be used as the basis of this design procedure. Step voltages are inherently less dangerous than mesh voltages. If, however, safety within the grounded area is achieved with the assistance of a high resistivity surface layer (surface material), which does not extend outside the fence, step voltages may be dangerous. In any event, the computed step voltages should be compared with the permissible step voltage after a grid that satisfies the touch voltage criterion has been designed. For equally spaced ground grids, the mesh voltage will increase along meshes from the centre to the corner of the grid. The rate of this increase will depend on the size of the grid, number and location of ground rods, spacing of parallel conductors, diameter and depth of the conductors, and the resistivity profile of the soil [7].

As indicated in table 2.1, the corner mesh voltage is generally much higher than that in the centre mesh. This will be true unless the grid is unsymmetrical (has projections, is L-shaped, etc.), has ground rods located on or near the perimeter, or has extremely non-uniform conductor spacings.

Thus, in the equations for the mesh voltage $E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_G}{L_M}$, only the mesh voltage at the centre of the corner mesh is used as the basis of the design procedure [7].

Table 2.1: Typical ratio of corner-to-corner mesh voltage [7].

Grid number	Number of meshes	E_m corner/centre
1	10 x 10	2.71
2	20 x 20	5.55
3	30 x 30	8.85

2.4.1 Grounding system design critical parameters

The following site-dependent parameters have been found to have substantial impact on the grid design: maximum grid current I_G , fault duration t_f , shock duration t_s , soil resistivity ρ , surface material resistivity (ρ_s) and grid geometry. Several parameters define the geometry of the grid, but the area of the grounding system, the conductor spacing and the depth of the ground grid have the most impact on the mesh voltage, while parameters such as the conductor diameter and the thickness of the surfacing material have less impact [7].

2.4.1.1 Maximum grid current (I_G)

In determining the maximum current I_G , consideration should be given to the resistance of the ground grid, division of the ground fault current between the alternate return paths and the grid and the decrement factor.

2.4.1.2 Fault duration (t_f) and shock duration (t_s)

The fault duration and shock duration are normally assumed equal, unless the fault duration is the sum of successive shocks, such as from reclosings. The selection of t_f should reflect fast clearing time for transmission substations and slow clearing times for distribution and industrial substations [7]. The choices t_f and t_s should result in the most pessimistic combination of fault current decrement factor and allowable body current. Typical values for t_f and t_s range from 0.25 s to 1.0 s [7].

2.4.1.3 Soil resistivity (ρ)

The grid resistance and the voltage gradients within a substation are directly dependent on the soil resistivity. Because soil resistivity will in reality vary horizontally as well as vertically, sufficient data must be gathered for a substation yard. The Wenner method already described in this chapter is widely used for this application [7, 6].

2.4.1.4 Resistivity of surface layer (ρ_s)

A layer of surface material helps in limiting the body current by adding resistance to the equivalent body resistance [7].

2.4.1.5 Grid geometry

The area of the grounding system is the single most important geometrical factor in determining the resistance of the grid. The larger the area grounded, the lower the grid resistance and, thus, the lower the GPR [7].

2.5 Design Procedure of a grounding system

The block diagram in figure 2.9 illustrates the sequence of steps to design the ground grid that were established by the IEEE Standard 80-2000 for the design of the ground grid. The parameters shown in the block diagram are identified in the index presented in the list of symbols. The following describes each step of the procedure:

- Step 1: The property map and general location plan of the substation should provide good estimates of the area to be grounded. A soil resistivity test will determine the soil resistivity profile and the soil model needed (that is, uniform or two-layer model).
- Step 2: The conductor size is determined. The fault current $3I_0$ should be the maximum expected future fault current that will be conducted by any conductor in the grounding system, and the time, t_c should reflect the maximum possible clearing time (including backup).
- Step 3: The tolerable step- and touch voltages are determined by $E_{touch} = \left(R_B + \frac{R_f}{2} \right) I_B$ and $E_{step} = (R_B + 2R_f) I_B$. The choice of time, t_s , is based on the judgment of the design engineer, with guidance from applicable standards.

- Step 4: The preliminary design should include a conductor loop surrounding the entire grounded area, plus adequate cross conductors to provide convenient access for equipment grounds, etc. The initial estimates of conductor spacing and ground rod locations should be based on the current I_G and the area being grounded.
- Step 5: Estimates of the preliminary resistance of the grounding system in uniform soil. For the final design, more accurate estimates of the resistance may be desired. Computer analysis based on modelling the components of the grounding system in detail can compute the resistance with a high degree of accuracy, assuming the soil model is chosen correctly.
- Step 6: Determine the grid current I_G . To prevent overdesign of the grounding system, only that portion of the total fault current, $3I_0$, that flows through the grid to remote earth should be used in designing the grid. The current I_G should, however, reflect the worst fault type and location, the decrement factor and any future system expansion.
- Step 7: If the GPR of the preliminary design is below the tolerable touch voltage, no further analysis is necessary. Only additional conductor, required to provide access to equipment grounds is necessary.
- Step 8: The calculation of the mesh- and step voltages for the grid as designed can be done by the approximate analysis techniques, or by the more accurate computer analysis techniques.
- Step 9: If the computed mesh voltage is below the tolerable touch voltage, the design may be complete (see Step 10). If the computed mesh voltage is greater than the tolerable touch voltage, the preliminary design should be revised (see Step 11).
- Step 10: If both the computed step- and touch voltages are below the tolerable voltages, the design needs only the refinements required to provide access to equipment grounds. If not, the preliminary design must be revised (see Step 11).
- Step 11: If either the step or touch tolerable limits are exceeded, revision of the grid design is required. These revisions may include smaller conductor spacings, additional ground rods, etc.
- Step 12: After satisfying the step- and touch voltage requirements, additional grid and ground rods may be required [7].

The additional grid conductors may be required if the grid design does not include conductors near equipment to be grounded. Additional ground rods may be required at the base of surge arresters, transformer neutrals, etc.

- The final design should also be reviewed to eliminate hazards due to transferred potential and hazards associated with special areas of concern [7].

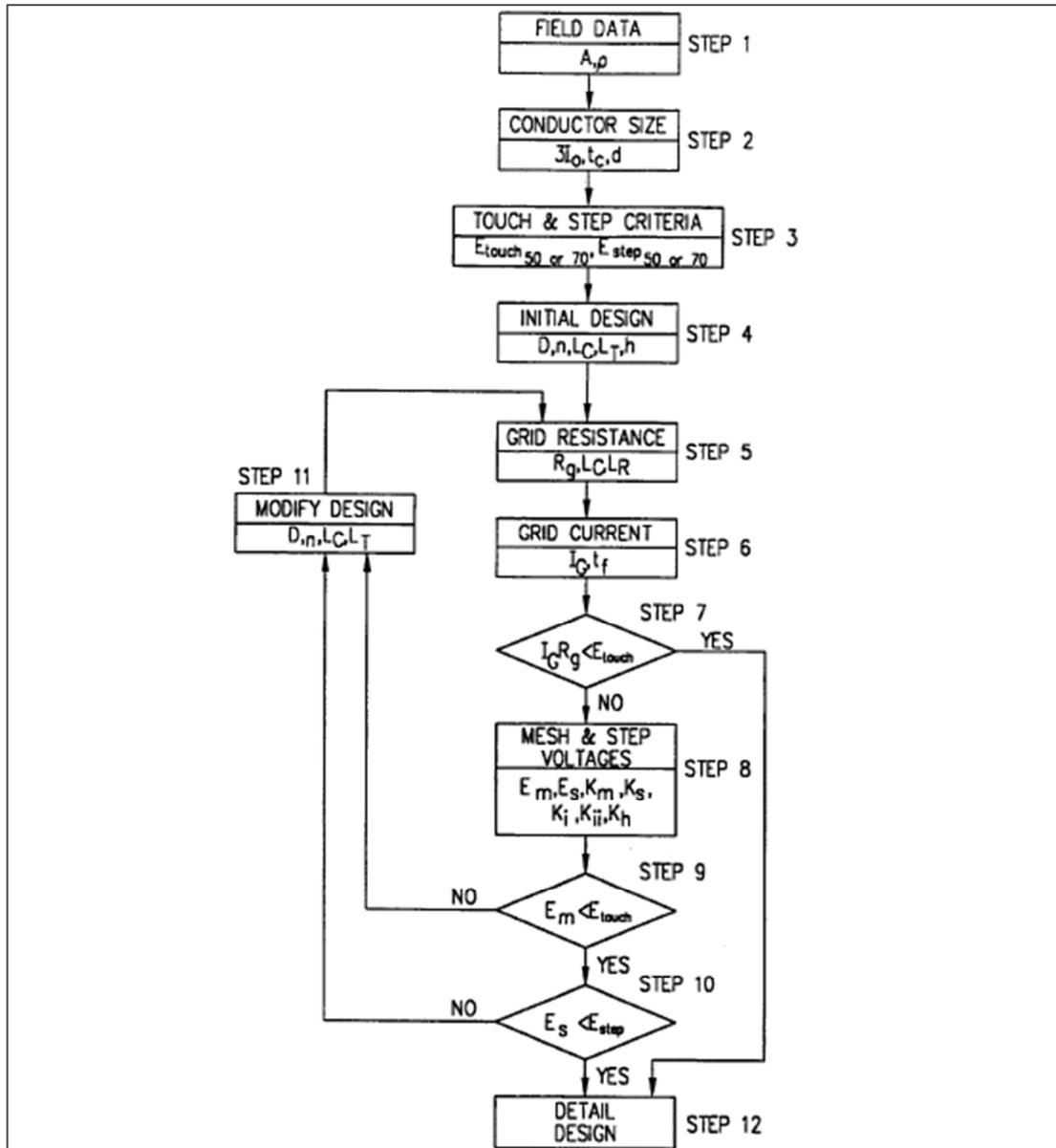


Figure 2.9: Design procedure block diagram [7].

2.5.1 Design modification

If the calculated grid mesh- and step voltages are greater than the tolerable step- and touch voltages, the preliminary design needs to be modified. The following are possible remedies:

- a) Decrease the total grid resistance. This will decrease the maximum grid potential rise (GPR). The most effective way to decrease the grid resistance is by increasing the area occupied by the grid. Deep driven rods along the grid perimeter may be used if the area is limited. The latter technique is especially practical for two soil layer models representing a “hi on lo” resistivity profile.
- b) Improvement of gradient control (closer grid spacings). By employing closer spacing of grid conductors (minimum 2.5m), dangerous potentials within the station can thus be eliminated at a cost. The problem at the perimeter may be more difficult, especially at a small station where earth resistivity may be high. However, it is usually possible by burying the grid perimeter earth conductor outside the fence line, to ensure that the steeper gradients immediately outside the grid perimeter do not contribute to more dangerous touch contacts. Another effective and economical way to control perimeter gradients is to increase the density of ground rods at the perimeter.
- c) Increase the thickness of the surface layer.
- d) Diverting a greater part of the fault current to other paths. By connecting overhead ground wires of sub-transmission HV lines, or by decreasing the tower footing resistances in the vicinity of the substation, part of the fault current will be diverted from the grid. With regard to the latter, however, the effect of fault gradients near tower footings should be weighed. Accurate calculations of the grid current must be done, taking connected transmission line shield wires into account.
- e) Limit the earth fault current flowing into the earth grid. Other factors, will, usually make this impractical. Moreover, if accomplished at the expense of greater fault clearing time, the danger may be increased, rather than diminished [1, 7].

- f) Barring access to limited areas. Barring access to certain areas, will, where practical, reduce the probability of hazards to personnel.
- g) Step- and touch voltage within limit, but GPR too high. A serious hazard may result during a ground fault from the transfer of potential between the substation ground grid area and outside locations ($GPR > 5kV$). This transferred potential may be transmitted by communication circuits, conduit, pipes, metallic fences, low voltage neutral wires, etc.

A transferred potential problem generally occurs when a person standing at a remote location away from the substation area touches a conductor connected to the substation grounding grid. The importance of the problem results from the high magnitude of potential difference, which is often possible. This potential difference may be equal to or exceed (due to induced voltage on unshielded communications circuits, pipes, etc.) the GPR of the substation during a fault condition. Various means can be taken to protect against the danger of transferred potentials. Methods have been developed for communication circuits involving optic isolating devices, thereby eliminating the transfer of high potentials from substation communication terminal to the remote terminal. The use of insulating panels to isolate the substation fence from any nearby connecting fences will also eliminate the dangers pertaining to transfer of high potential via fences.

- h) Effective use of the surface layer material (yard stone) to reduce high step- and touch potentials. The resistivity of the crushed stone layer helps to increase the impedance of the path through a person's body for step- and touch voltages. Increasing this value results in higher safe step- and touch voltages.
- i) Use of the soil treatment to lower resistivity [1, 7].

2.6 Types of Grounding

Grounding is divided into two parts, namely equipment grounding and system grounding. Equipment grounding, also referred to as protective grounding, is mainly for prevention from dangerously high shock that may occur when there is an earth fault current between an energised electrical conductor and the structure that might either enclose it, or is nearby. The system grounding is an intentional electrical interconnection between the electrical system conductors and ground, and forms part of the operating system. The main difference between equipment grounding and system grounding is that system grounding is the part of the electrical operating circuit under normal operating conditions, while equipment grounding is not. System grounding fixes the potential at any part of the network with respect to earth, and provides sufficient fault current so that protection equipment can operate. System grounding can be of four different types, namely ungrounded systems, resistance grounding, reactance grounding and solid grounding [10, 14].

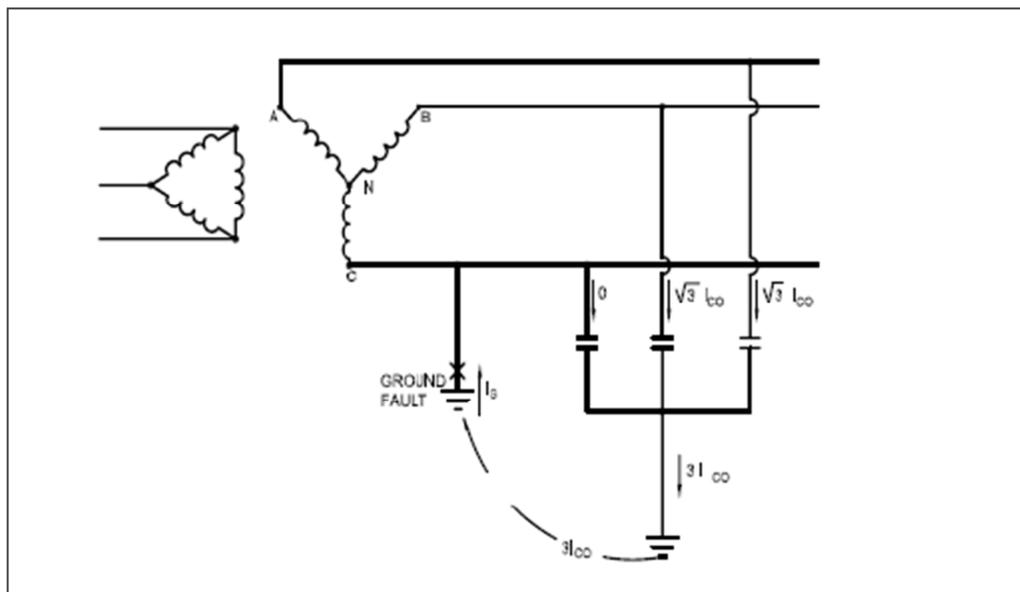


Figure 2.10: Ungrounded system with a line-to-ground fault [10, 14].

There is no connection between earth and the system neutral, except for very high impedance devices in ungrounded systems. Even if the system is not grounded, the system is still coupled to ground through the distributed capacitances [9].

The system fixes the neutral point and the voltages are not floating. The problem with this system is that there is only the ground capacitance current, which makes detection by over current relays impossible in case of the line-to-ground fault and potential of the other healthy phases raise to line-to-line voltage levels. This will overstress the insulation of healthy phases so that the likelihood of a second line-to-ground fault is increased. These are the main disadvantages of this type of system. It has, on the other hand, an advantage: the system continues to operate in case of a line-to-ground fault.

Resistance and reactance to grounded systems employ an intentional resistance or impedance connection between the neutral of the system and ground [9, 12].

Although these systems provide fault current, high voltage is still experienced on healthy phases in case of a ground fault. Fault current can be limited to acceptable levels 1-1000A in case of low resistance grounding, as it has better reduction on ground fault current, compared to reactance grounded systems [9, 10].

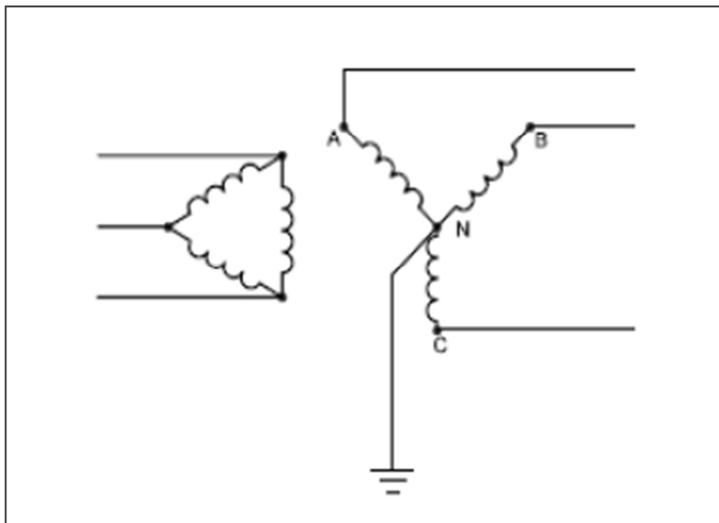


Figure 2.11: Solidly grounded system [9, 14].

High voltage systems are usually solidly-grounded (figure 2.11). In this case there is no intentional impedance between the system neutral and the ground. Under these circumstances the ground fault current can reach very high levels [9].

These systems are normally made up of overhead lines. There is no problem with the stress of high fault currents. Insulation is, however, a problem in high voltage systems. The voltages across the healthy phases in solidly grounded systems do not increase with the occurrence of a line-to-ground fault [4].

When such high currents flow into the earth, the potential at the point of contact to earth will increase to dangerous levels. For example, a ground fault current of 20kA going through a ground resistance of 1Ω will raise the potential to 20kV at the grounded point, which is harmful to both human and equipment in a grounding region. This voltage is known as the GPR, which is the most important parameter for designing grounding systems. This potential has to be limited to a value which is not hazardous to system operation [5].

Table 2.2: Characteristics of grounding methods [14].

	Ungrounded	Solid grounding	Reactance grounding		Ground-fault neutralizer	Resistance grounding	
			Low value reactor	High value reactor		Low resistance	High resistance
Current for phase-to-ground fault in percent of three-phase fault current	Less than 1%	Varies, may be 100% or greater	Usually designed to produce 25% to 100%	5% to 25%	Nearly zero fault current	20% and downward to 100A to 1000A	Less than 1% but not less than system charging, $3I_{C0}$
Transient over-voltage	Very high	Not excessive	Not excessive	Not excessive	Not excessive	Not excessive	Not excessive
Surge arresters	Ungrounded-neutral type	Grounded-neutral type	Grounded-neutral type if current 60% or greater	Ungrounded neutral type	Ungrounded-neutral type	Ungrounded-neutral type	Ungrounded-neutral type
Remarks	Not recommended due to overvoltage and non-segregation of fault	Generally used on systems (1) 600V and below and (2) Over 15kV		Not used due to excessive overvoltages	Best suited for application in most medium-voltage industrial and commercial systems that are isolated from their electric utility system by transformers.	Generally used on systems of 2.4kV to 15kV particularly where large rotating machines are connected.	Used on systems 600V and below where service continuity is desired.

2.7 Conclusion

In this chapter, literature relating to the research is investigated. The areas of review included substation grounding system design, GPR, step potential, touch potential, effects of increased fault currents on earth grid and possible grid design improvement. Different methods of grounding are discussed.

CHAPTER 3: GRID DESIGN MATHEMATICAL MODEL

3.1 Introduction

In order to design a proper and safe substation grounding system, various safety parameters must be found, such as the ground potential rise, touch potential and step potential levels. Each grounding system must be uniquely designed in order to have the mesh- and step voltages below the tolerable step- and touch voltages of the personnel who might be working at the substation when a fault occurs. This chapter provides the process and equations to safely design a substation grounding system (*according to IEEE Std 80-2000*).

3.2 Tolerable step- and touch voltage

When designing a substation grounding system, the maximum tolerable voltages must be calculated in order to create a proper ground grid. These voltages depend on the soil resistivity, soil layer and the duration of the shock current. The maximum driving voltage of any accidental circuit should not exceed the step voltage and touch voltage limits [7].

For step potential the limit is:

$$E_{step} = (R_B + 2 \cdot R_f) \cdot I_B \quad 3.1$$

For a body weighing 50 kg,

$$E_{step} = (1000 + 6 \cdot C_s \cdot \rho_s) \frac{0.116}{\sqrt{t_s}} \quad 3.2$$

Where

C_s : surface layer derating factor

ρ_s : resistivity of surface layer material ($\Omega \cdot m$)

ρ : resistivity of the earth ($\Omega \cdot m$)

h_s : thickness of surface material (m)

For touch potential, the limit is

$$E_{touch} = \left(R_B + \frac{R_f}{2} \right) \cdot I_B \quad 3.3$$

For a body weighing 50kg

$$E_{touch50} = (1000 + 1.5 \cdot C_s \cdot \rho_s) \frac{0.116}{\sqrt{t_s}} \quad 3.4$$

For a body weighing 70kg

$$E_{touch70} = (1000 + 1.5 \cdot C_s \cdot \rho_s) \frac{0.157}{\sqrt{t_s}} \quad 3.5$$

If no protective surface layer is used in the substation, $C_s = 1$ and $\rho_s = \rho$.

3.3 Conductor sizing

The symmetrical current can be calculated based on the material and the size of the conductor used as [7]:

$$I = A_{mm^2} \sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_c \alpha_r \rho_r} \right) \ln \left(\frac{K_0 + T_m}{K_0 + T_a} \right)} \quad 3.6$$

If the conductor size is given in kcmil, the equation becomes:

$$I = 5.07 \times 10^{-3} A_{kcmil} \sqrt{\left(\frac{TCAP}{t_c \alpha_r \rho_r} \right) \ln \left(\frac{K_0 + T_m}{K_0 + T_a} \right)} \quad 3.7$$

Where

- I : rms current (kA)
- A_{mm^2} : conductor cross section (mm^2)
- A_{kCmil} : conductor cross section ($kcmil$)
- T_m : maximum allowable temperature ($^{\circ}C$)
- T_a : ambient temperature ($^{\circ}C$)
- α_r : thermal coefficient of resistivity at reference temperature T_r ($1/^{\circ}C$)
- ρ_r : resistivity of the ground conductor at reference temperature T_r ($\mu\Omega - cm$)
- t_c : duration of current (s)
- K_0 : equals $1/\alpha_0$ or $(1/\alpha_r) - T_r$ ($^{\circ}C$)
- $TCAP$: thermal capacity per unit volume ($J/cm^2 \cdot ^{\circ}C$)

The required area for a conductor given a current can be calculated as:

$$A_{mm^2} = I \frac{1}{\sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_c \alpha_r \rho_r}\right) \ln\left(\frac{K_0 + T_m}{K_0 + T_a}\right)}} \quad 3.8$$

Equation (3.8) can be simplified as:

$$A_{kcmil} = I \cdot K_f \cdot \sqrt{t_c} \quad 3.9$$

The diameter of a conductor can be calculated as:

$$d_{c(mm)} = 2\sqrt{\frac{A_{mm^2}}{\pi}} \quad 3.10$$

3.4 Asymmetrical currents

If the effect of the dc offset is needed to be included in the fault current, the values of the symmetrical current is found by [7]:

$$I_F = I_f \cdot D_f \quad 3.11$$

The decremental factor, D_f , can be calculated as:

$$D_f = \sqrt{1 + \frac{T_a}{t_f} \left(1 - e^{-\frac{2t_f}{T_a}} \right)} \quad 3.12$$

Where

t_f : time duration of the fault (s)

$$T_a = \frac{X}{\omega R} \quad 3.13$$

The decrement factor is used to determine the effective current during a given time interval after inception of a fault.

Table 3.1: Typical values for D_f

Cycles at 50 Hz	Seconds	X/R=2	X/R=3	X/R=4	X/R=5	X/R=10	X/R=20	X/R=30	X/R=40
0.4	0.00833	1.323	1.389	1.437	1.474	1.576	1.648	1.675	1.688
2.5	0.05	1.014	1.050	1.082	1.113	1.232	1.378	1.462	1.515
5.0	0.10	1.023	1.037	1.050	1.063	1.125	1.232	1.316	1.378
10.0	0.20	1.012	1.018	1.025	1.032	1.064	1.125	1.181	1.232
15.0	0.30	1.006	1.011	1.016	1.020	1.043	1.085	1.125	1.163
20.0	0.40	1.007	1.010	1.014	1.017	1.033	1.064	1.095	1.125
25.0	0.50	1.004	1.007	1.010	1.013	1.026	1.052	1.077	1.101
37.5	0.75	1.004	1.006	1.007	1.009	1.018	1.035	1.052	1.068
50.0	1.00	1.002	1.004	1.005	1.006	1.013	1.026	1.039	1.052

3.5 Soil resistivity measurements

The methods for soil resistivity measurements are discussed in 2.3. Since Wenner's four-pin method is the most common, only calculations for this method will be discussed.

The mutual resistance R is determined by dividing the voltage between the two inner probes by the current of the two outer probes. Using the mutual resistance R , the soil resistivity can be calculated as follows [7]:

$$\rho = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \quad 3.14$$

Where

ρ : soil resistivity ($\Omega \cdot m$)

R : measured resistance (Ω)

a : distance between adjacent electrodes (m)

b : depth of the electrodes (m)

If $b \ll a$, the above equation (3.14) can be simplified to

$$\rho = 2\pi a R \quad 3.15$$

For small probe spacing, the current tends to flow near the surface, but for large spacing, more of the current penetrates deeper soils. It is therefore reasonable to assume that the resistivity measure for a probe of spacing a represents the apparent soil resistivity of depth a .

3.6 Ground resistance

One of the first steps in determining the size and layout of the grounding system is the estimation of the total resistance to remote earth. Resistance primarily depends on the area of the grounding system.

In the early stages of the design, the area to be occupied is usually known. As an approximation, the minimum value of the substation grounding resistance in uniform soil can be estimated as [7]:

$$R_g = \frac{\rho}{4} \sqrt{\frac{\pi}{A}} \quad 3.16$$

Where

R_g : substation ground resistance (Ω)

ρ : soil resistivity ($\Omega.m$)

A : area occupied by the ground grid (m^2)

Laurent and Niemann proposed a method of calculating the substation ground resistance by adding a second term. This equation gives an upper limit of the substation ground resistance. This proposed equation is:

$$R_g = \frac{\rho}{4} \sqrt{\frac{\pi}{A}} + \frac{\rho}{L_T} \quad 3.17$$

Where

L_T : total burial length of conductors (m)

The total burial length is the combination of the horizontal and vertical conductors in the grid as well as the ground rods. L_T can be calculated as:

$$L_T = L_C + L_R \quad 3.18$$

Where

L_C : total length of grid conductor (m)

L_R : total length of ground rods (m)

A better approximation was determined to include the grid depth

$$R_g = \rho \left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h\sqrt{20/A}} \right) \right] \quad 3.19$$

Where

h : depth of the grid (m)

This equations shows that the larger the area and the greater the total length of the grounding conductor used would result in a lower ground grid resistance.

3.7 Maximum grid current

A portion of the fault current will flow through the grounding grid to the earth. This is called the grid current and must be calculated. The maximum grid current, I_G , can be calculated as [7]:

$$I_G = D_f \cdot I_g \quad 3.20$$

Where

I_G : maximum grid current (A)

D_f : decrement factor for the duration of the fault

I_g : rms symmetrical grid current (A)

The symmetrical grid current, I_g , is the portion of the symmetrical ground fault current that flows between the grid and surrounding earth. It is expressed as:

$$I_g = S_f \times I_f \quad 3.21$$

Where

I_g : rms symmetrical grid current (A)

I_f : rms symmetrical grid fault current (A)

S_f : fault current division factor

High voltage distribution lines are provided with overhead shield wires that are earthed at each tower along the line. Where these shield wires are connected to the substation earth grid they divert a substantial portion of the fault current away from the station earth grid and can be taken into consideration in the design of the substation earth grid [6, 7].

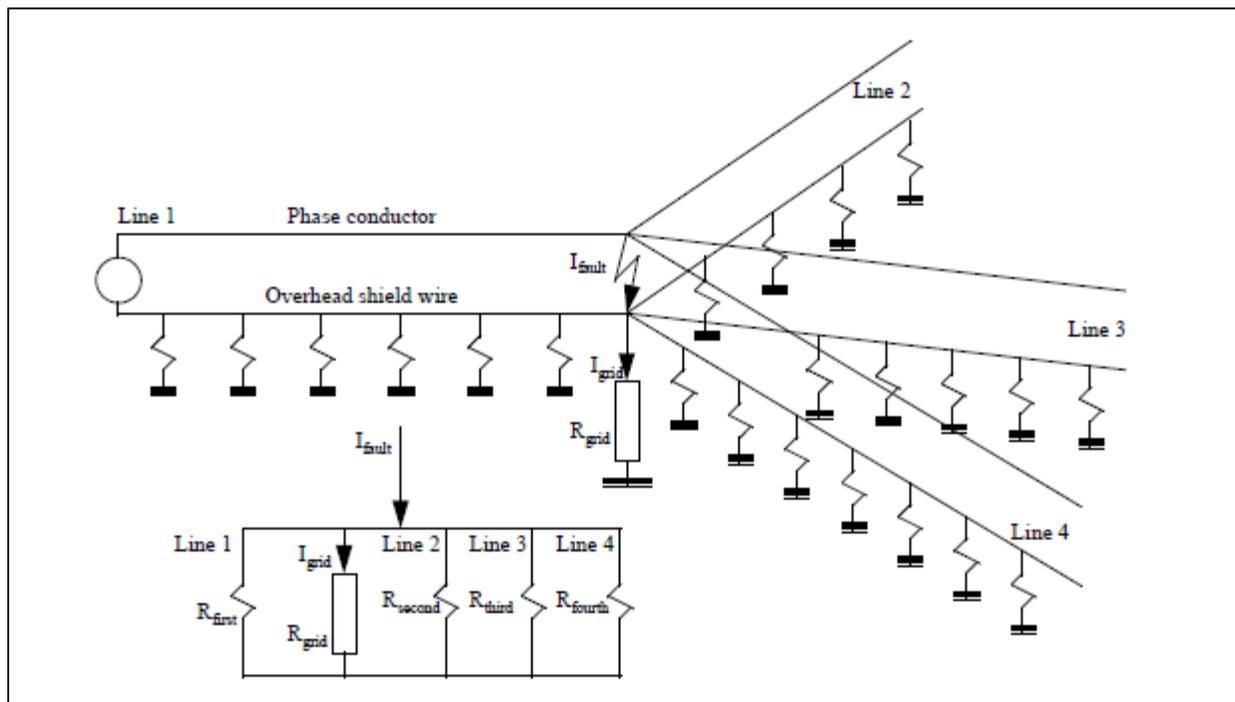


Figure 3.1: An illustration of distribution line [6].

The effect of connected overhead shield wires can be calculated by regarding them as parallel resistances to the grid resistance, as shown in figure 3.1. Empirical values of these resistances are given in the accompanying table 3.2.

Table 3.2: Empirical Resistance values

	Distribution line fitted with one shield wire	Distribution line fitted with two shield wires
First line with shield wires connected	7.3Ω	3.5Ω
All subsequent lines with shield wires connected	10.6Ω	5.2Ω

3.8 Fault currents

Many different faults can occur in a system. It is difficult to determine the fault type and location that would result in the greatest current flow between the ground grid and the surrounding earth. When determining the applicable faults types, the probability of occurrence needs to be considered. It is recommended to consider single line-to-ground and double-line-to-ground faults [7].

In the case of a double line-to-ground fault, the zero-sequence fault current is:

$$I_0 = \frac{E.(R_2 + jX_2)}{(R_1 + jX_1) \cdot [(R_0 + R_1 + 3R_f + j(X_0 + X_2))] + (R_2 + jX_2).(R_0 + 3R_f + jX_0)} \quad 3.22$$

Where

I_0 : symmetrical rms value of zero sequence fault current (A)

E : phase -to-neutral voltage (V)

R_f : estimated resistance of the fault in Ω (normally it is assumed $R_f = 0$)

R_1 : positive sequence equivalent system resistance (Ω)

R_2 : negative sequence equivalent system resistance (Ω)

R_0 : zero sequence equivalent system resistance (Ω)

X_1 : positive sequence equivalent system reactance (Ω)

X_2 : negative sequence equivalent system reactance (Ω)

X_0 : zero sequence equivalent system reactance (Ω)

In the case of a single line-to-ground fault, the zero-sequence fault current is:

$$I_0 = \frac{E}{3R_f + R_1 + R_2 + R_0 + j(X_1 + X_2 + X_0)} \quad 3.23$$

$R_1, R_2, R_0, X_1, X_2,$ and X_0 are computed looking into the system from the point of fault.

In most cases, the resistances are ignored, thus the zero-sequence fault current equations are simplified.

The simplified double line-to-ground zero-sequence fault current becomes:

$$I_0 = \frac{E \cdot X_2}{X_1 \cdot (X_0 + X_2) + (X_2 + X_0)} \quad 3.24$$

The simplified single line-to-ground zero-sequence fault current becomes:

$$I_0 = \frac{E}{X_1 + X_2 + X_0} \quad 3.25$$

3.9 Ground potential rise (GPR)

Ground potential rise (GPR) is defined as: “the maximum electrical potential that a substation grounding grid may attain relative to a distant grounding point, assumed to be at the potential of remote earth. The GPR is calculated as [7]:

$$GPR = I_G \cdot R_g \quad 3.26$$

Where

R_g : substation ground resistance (Ω)

I_G : maximum grid current (A)

3.10 Mesh potential (E_m)

Mesh potential is a form of touch potential. Mesh potential represents the highest possible touch potential that may be encountered within a substation's grounding system. Mesh potential is the basis for designing a safe grounding system inside and immediately outside the substation. In order for the grounding system to be safe, the mesh potential has to be less than the tolerable touch potential, otherwise the substation ground grid design needs modification [7].

The mesh potential can be calculated as:

$$E_m = \frac{\rho \cdot I_G \cdot K_m \cdot K_i}{L_M} \quad 3.27$$

Where

ρ : resistivity of the earth ($\Omega \cdot m$)

L_M : effective burial length (m)

K_m : geometrical spacing factor

K_i : irregularity factor

The geometrical spacing factor, K_m , for mesh potential is:

$$K_m = \frac{1}{2 \cdot \pi} \cdot \left[\ln \left[\frac{D^2}{16 \cdot h \cdot d} + \frac{(D + 2 \cdot h)}{8 \cdot D \cdot d} - \frac{h}{4 \cdot d} \right] + \frac{K_{ii}}{K_h} \cdot \ln \left[\frac{8}{\pi(2 \cdot n - 1)} \right] \right] \quad 3.28$$

Where

D : spacing between parallel conductors (m)

d : diameter of grid conductors (m)

h : depth of ground grid conductors (m)

K_{ii} : corrective weighting factor adjusting for the effects of inner conductors on the corner mesh

K_h : corrective weighting factor adjusting for the effects of grid depth

The corrective weighted factor, K_h is:

$$K_h = \sqrt{1 + \frac{h}{h_0}} \quad 3.29$$

Where

h_0 : grid reference depth ($h_0 = 1$)

For ground grids with ground rods along the perimeter and throughout the grid as well as in the corners, the corrective weighting factor, K_{ii} , is:

$$K_{ii} = 1 \quad 3.30$$

For grids with no ground rods, or a few ground rods scattered throughout the grid, but none located along the perimeter or in the corners, the corrective weighting factor, K_{ii} , is:

$$K_{ii} = \frac{1}{(2 \cdot n)^{\frac{2}{n}}} \quad 3.31$$

Where the geometric factor, n , is composed of factors n_a, n_b, n_c , and n_d . The geometric factor, n , is:

$$n = n_a \cdot n_b \cdot n_c \cdot n_d \quad 3.32$$

Where

$$n_a = \frac{2 \cdot L_C}{L_P} \quad 3.33$$

$$n_b = 1 \text{ for square grids} \quad 3.34$$

$$n_c = 1 \text{ for square and rectangular grids} \quad 3.35$$

$$n_d = 1 \text{ for square, rectangular and L-shaped grids} \quad 3.36$$

Otherwise:

$$n_b = \sqrt{\frac{L_P}{4 \cdot \sqrt{A}}} \quad 3.37$$

$$n_c = \left[\frac{L_x \cdot L_y}{A} \right]^{\frac{0.7 \cdot A}{L_x \cdot L_y}} \quad 3.38$$

$$n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}} \quad 3.39$$

Where

L_C : total length of conductor in the horizontal grid (m)

L_P : peripheral length of grid (m)

D : spacing between parallel conductors (m)

d : diameter of grid conductors (m)

h : depth of ground grid conductors (m)

A : area of grid (m^2)

L_x : maximum length of grid in the x-direction (m)

L_y : maximum length of grid in the y-direction (m)

D_m : maximum distance between any two points on the grid (m)

The irregularity factor, K_i , is used in conjunction with n . It is calculated as:

$$K_i = 0.644 + 0.148 \cdot n \quad 3.40$$

For grids with no ground rods, or a few ground rods scattered throughout the grid, but none located along the perimeter or in the corners, the effective buried length, L_M , is:

$$L_M = L_C + L_R \quad 3.41$$

Where

L_R : total length of all ground rods (m)

For ground grids with ground rods along the perimeter and throughout the grid, as well as in the corners, the effective buried length, L_M , is:

$$L_M = L_C + \left[1.55 + 1.22 \left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}} \right) \right] L_R \quad 3.42$$

Where

L_r : total length of each ground rods (m)

3.11 Step potential (E_s)

If a grid system is designed for safe mesh potential, the step potential will be within tolerable limits. Step potential is usually smaller than touch potential, because both feet are in series rather than parallel. The body can also tolerate higher currents through a foot-to-foot path, because it does not pass through vital organs such as the heart. For the ground system to be safe, the step potential has to be less than the tolerable step potential [7].

The mesh potential can be calculated as:

$$E_s = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_s} \quad 3.43$$

The effective buried conductor length L_s is:

$$L_s = 0.75 \cdot L_C + 0.85 \cdot L_R \quad 3.44$$

The step factor K_s for the step voltage is given by

$$K_s = \frac{1}{\pi} \left[\frac{1}{2 \cdot h} + \frac{1}{D + h} + \frac{1}{D} (1 - 0.5^{n-2}) \right] \quad 3.45$$

Where

D : spacing between parallel conductors (m)

h : depth of ground grid conductors (m)

n : geometric factor composed of factors n_a, n_b, n_c and n_d

3.12 Conclusion

The grounding system design mathematical model presented in this chapter is used to analyse, design and improve Ruighoek substation's grounding system.

CHAPTER 4: RESEARCH CASE STUDY

4.1 Introduction

Substations take in power from the grid connections and transform this down to the required voltages for utilisation. Ruighoek substation is used as a case study because this substation will have a fault current increase once Medupi power station and Ngwedi transmission station come onto the grid, and will be converted from 88kV to 132kV. Figure 4.1, below, shows the single line diagram of the Ararat 88kV network. The shaded area depicts the network that will be converted from 88kV to 132kV. The 132kV network will be supplied from Ngwedi MTS, as discussed in chapter 1.

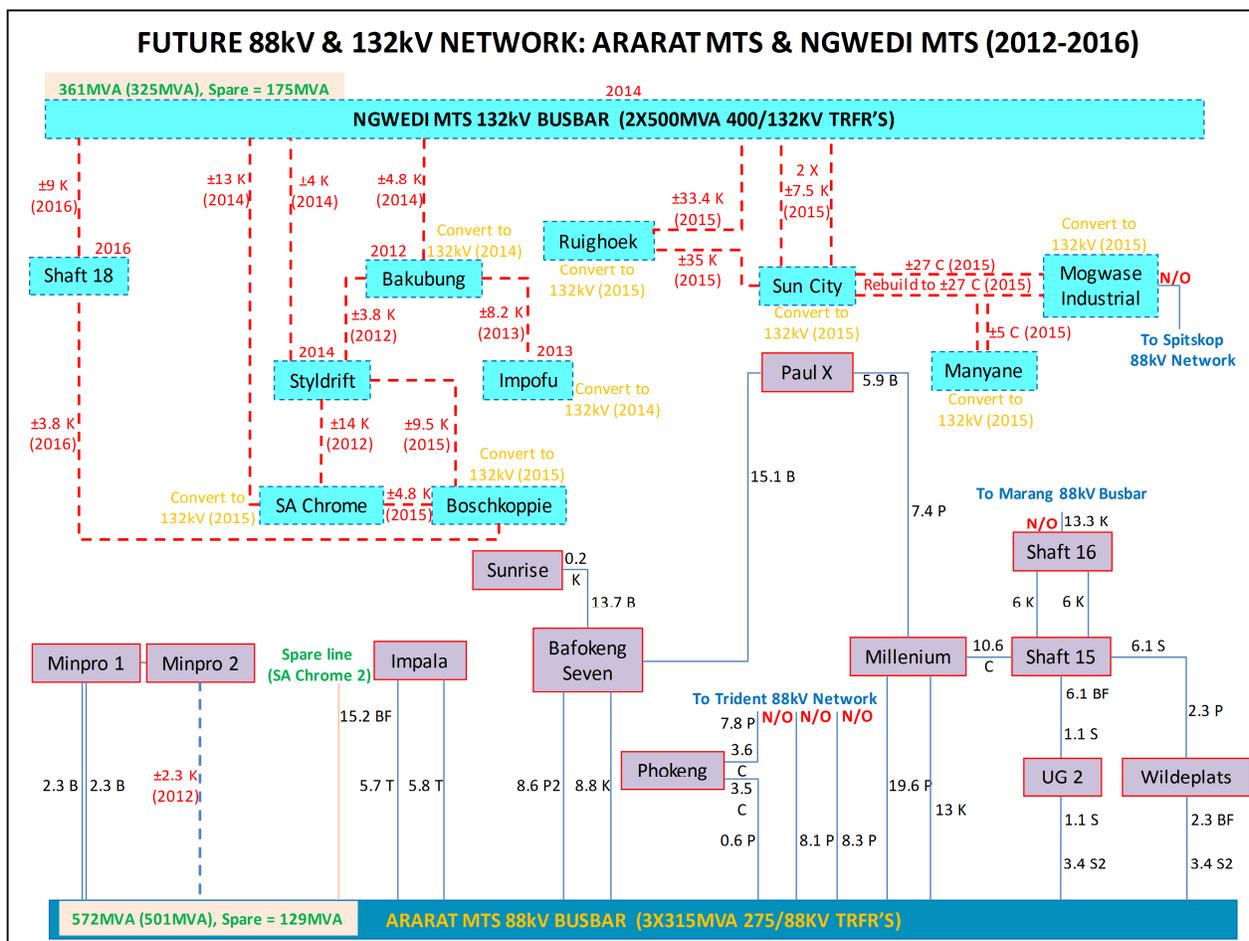


Figure 4.1: Ararat 88kV and Ngwedi 132kV network [2].

Ruighoek substation is situated in North West province, 30km from Sun City and 150km from Rustenburg. Figure 4.2, depicts the Sun City substation, which is a source station. Ruighoek substation is a load station and an 88kV Hare conductor line radial feed interconnects the two substations.

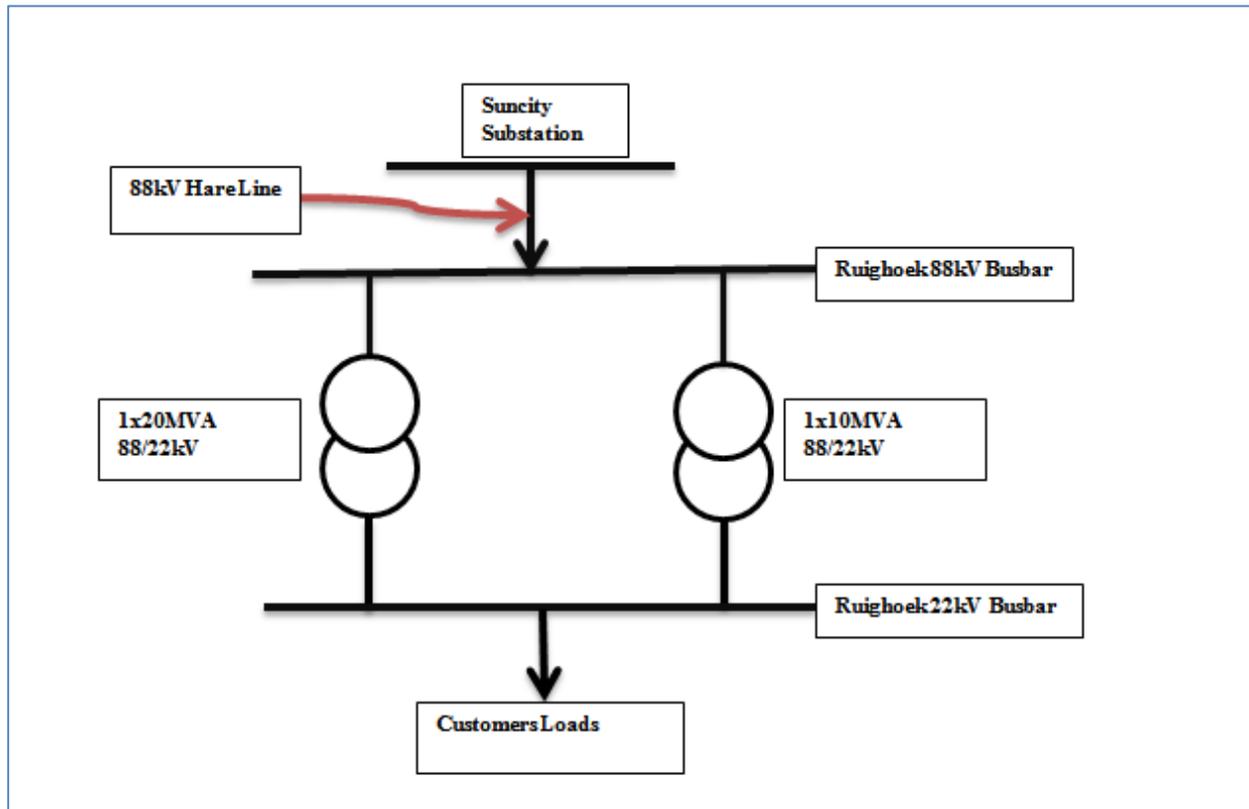


Figure 4.2: Case study 88kV network diagram [2].

Ruighoek substation has 1x20MVA, 1x10MVA 88/22kV transformers installed, and 1x88kV Hare line with a shield wire installed.

4.2 Eskom policy for neutral earthing of electrical networks

Sections 4.2.1 and 4.2.2 present Eskom's adopted policy for neutral earthing of electrical network.

4.2.1 Earthing of transformer HV neutrals

High voltage networks shall be effectively earthed at the source substation. That is, the HV neutral of the EHV/HV transformers, or the secondary (load-side) neutral of HV/HV source transformers, shall be solidly earthed. In many cases, source substation transformers are autotransformers. The neutral is then common to both the primary and secondary windings, and shall be solidly earthed [12]. The HV neutrals of load transformers (e.g. HV/MV transformers, or the primary-side winding of HV/HV transformers) shall be operated unearthed, except where [12]:

- a) The transformer winding has fully graded insulation. The affected transformer's HV neutral shall be solidly earthed. Historically, 132kV transformer windings have been specified with fully graded insulation (i.e. the basic insulation level (BIL) of the neutral terminal was 110kV). This was amended to partially graded insulation (i.e. the BIL of the neutral terminal was increased to 250kV). All other transformer HV windings have historically been specified with partially graded insulation [12].
- b) The transformer is an autotransformer. The transformer neutral shall be solidly earthed.
- c) Single pole tripping is applied on the network. All transformer HV neutrals on the affected network shall be solidly earthed.
- d) Network studies determine that, by not earthing some or all load transformer HV neutrals, the healthy phase voltages exceed 80% of the nominal phase-to-phase voltage under the condition of a bolted single phase-to-earth or phase-to-phase-to-earth fault on the network. The results of the studies shall be used to determine which transformer's HV neutrals shall be earthed to avoid overvoltage conditions [12].
- e) Network studies determine that certain load transformer HV neutrals must be earthed in order for the network earth fault protection to function adequately (i.e. with adequate sensitivity and selectivity). The results of the studies shall be used to determine which transformer's HV neutrals shall be earthed in this case [12].
- f) The transformer is supplied via a radial feed and there is a high risk of single phasing of the HV line (e.g. in an area prone to conductor theft). The affected transformer's HV neutral shall be solidly earthed.

In this case, earthing of the transformer HV neutral serves to avoid the risk of high transient overvoltages caused by ferro-resonance under the condition of one or two broken conductors on the supply feeder [12].

Where transformer HV neutrals are left unearthed, the neutral terminal shall be protected by a suitable surge arrester:

- a) For a 66kV, 88kV or 132kV partially graded winding, the neutral surge arrester's maximum continuous over-voltage (MCOV) shall be 48kV, with a protective level/maximum residual voltage of 165kV.
- b) For a 44kV partially-graded winding, the neutral surge arrester MCOV shall be 36kV, with a protective level/maximum residual voltage of 125kV.

The neutral surge arrester is provided so as to protect the neutral terminal (which has a lower BIL than the line terminals) from damage in the case of simultaneous voltage surges entering the star windings from two or more HV line terminals [12].

4.2.2 Earthing of transformer MV neutrals

The neutral point of an MV network shall be resistively earthed under all operating conditions. This requires that the neutral point be earthed via a suitable neutral earthing resistor (NER). In the case of a HV/MV power transformer featuring a delta-connected MV winding, the neutral point of the MV network shall be provided and earthed by means of a neutral electromagnetic coupler (NEC) with internal NER, known as a neutral electromagnetic coupler with resistor (NECR). It is common practice to include an auxiliary MV/LV transformer in the same tank as the NECR, giving rise to the designation NECRT [12].

4.2.2.1 Fault current contribution per neutral earthing point

In new installations, the NER or NECR for each point of MV neutral earthing shall be specified, such as to limit the earth fault current contribution per neutral earthing point as follows:

- a) In overhead (typically rural) distribution networks: 360A; and
- b) In underground (typically urban) distribution networks: 960A.

4.2.2.2 Neutral earthing points provided from a common earth mat

In an effort to limit the total earth fault current and the associated touch potentials imposed at the structures of faulted equipment, a maximum of three NEC/NECRs shall be applied per overhead or underground distribution network. Networks, including sections of both overhead and underground feeders, shall be treated as overhead networks for this purpose. In cases where each HV/MV or MV/MV power transformer provides its own point of MV neutral earthing, this requirement effectively limits the maximum number of paralleled supply transformers to three. This requirement is derived from the calculated touch potentials appearing on the MV earth electrode at MV/LV distribution transformers in the event of a phase-to-tank fault. Medium voltage industrial supply networks may be provided with more than three points of MV neutral earthing, subject to agreement between Eskom and the affected customer(s) [12].

Except where agreed otherwise by Eskom and the customer, the standard shall be to use 360A NEC/NECRs in these applications. Neutral earthing of MV industrial supplies shall be in accordance with SANS 10200. Except in the cases outlined in Section 4.2.2.3 below, the neutral of each MV network shall be earthed from a common earth mat, usually from the source substation. This requires that the MV neutrals of load transformers (e.g. MV/LV transformers, or the primary-side winding of MV/MV transformers) shall be operated unearthed [12].

4.2.2.3 Neutral earthing points provided from separate earth mats

Customers (including embedded generators) requiring the provision of an additional point of neutral earthing to an Eskom MV network (for example, to facilitate islanded operation of his plant), and which will not be provided from the same earth mat as the network's neutral earth connection, shall do so only with written permission from Eskom. Two alternative earthing arrangements may be permitted in this case [12]:

- a) The customer operates a switched neutral earth such that the customer's neutral earthing point is earthed no more than 200ms prior to disconnecting the supply (and the earthing point) from the Eskom network, and disconnected from earth within 200ms upon re-connection of the customer network to the Eskom MV network [12].

- b) The customer provides a permanent point of neutral earthing, but the NER is sized such that the total earth fault current contribution from the customer earth(s) is less than or equal to 10% of the total earth fault current contribution from the Eskom source, but no more than 72A [12].

In case (a), provision shall be made for the detection of a failed neutral earthing switch, either in the open or closed positions. The control system shall isolate the customer supply point from the Eskom network within 500ms in the event that the neutral earthing switch fails in the closed position [12]. In case (b), provision shall be made for suitably sensitive earth fault protection for both islanded and grid connected operating modes of the customer's facility. Additional network earths may not be installed downstream of an open-delta connected voltage regulator, as the regulator causes a neutral voltage shift which establishes circulating current between the distant earths, dependent on the regulator tap number. The application of three single-phase regulators avoids this problem [12].

4.3 Ruighoek substation

Ruighoek substation is an 88kV Eskom Distribution substation. The substation has two star/delta transformers, 88/22kV 1 x 20MVA and 1 x 10MVA. The substation serves a semi-rural area with mixed load, comprising farmers and a few light and large industries. Ruighoek substation is currently supplied through 30km 88kV Hare line from the Sun City substation. The power transformers installed in this substation have **star-delta** connection and their HV neutrals are solidly earthed. Earthing of the transformer HV neutral serves to avoid the risk of high transient overvoltages caused by ferro-resonance under the condition of one or two broken conductors on the supply feeder. Solid grounding refers to the connection of the HV neutral transformer directly to the earth mat [12]. The installed transformers at Ruighoek substation are partially graded insulated, and the neutrals are solidly earthed. When the neutral is kept unearthed, a surge arrester must be connected between the neutral and earth mat. The idea of installing a surge arrester in the neutral is that it is assumed when a lightning strike hits the line, the surge will be equal and in phase on all three phases and below the insulation level of the surge arrester mounted on the phase terminals of the transformer.

When the surge reaches the neutral it will add up and double when reflected back to the neutral point. The surge arrester is thus installed to clamp the voltage to a safe level in order to protect the neutral from internal flashing [12].

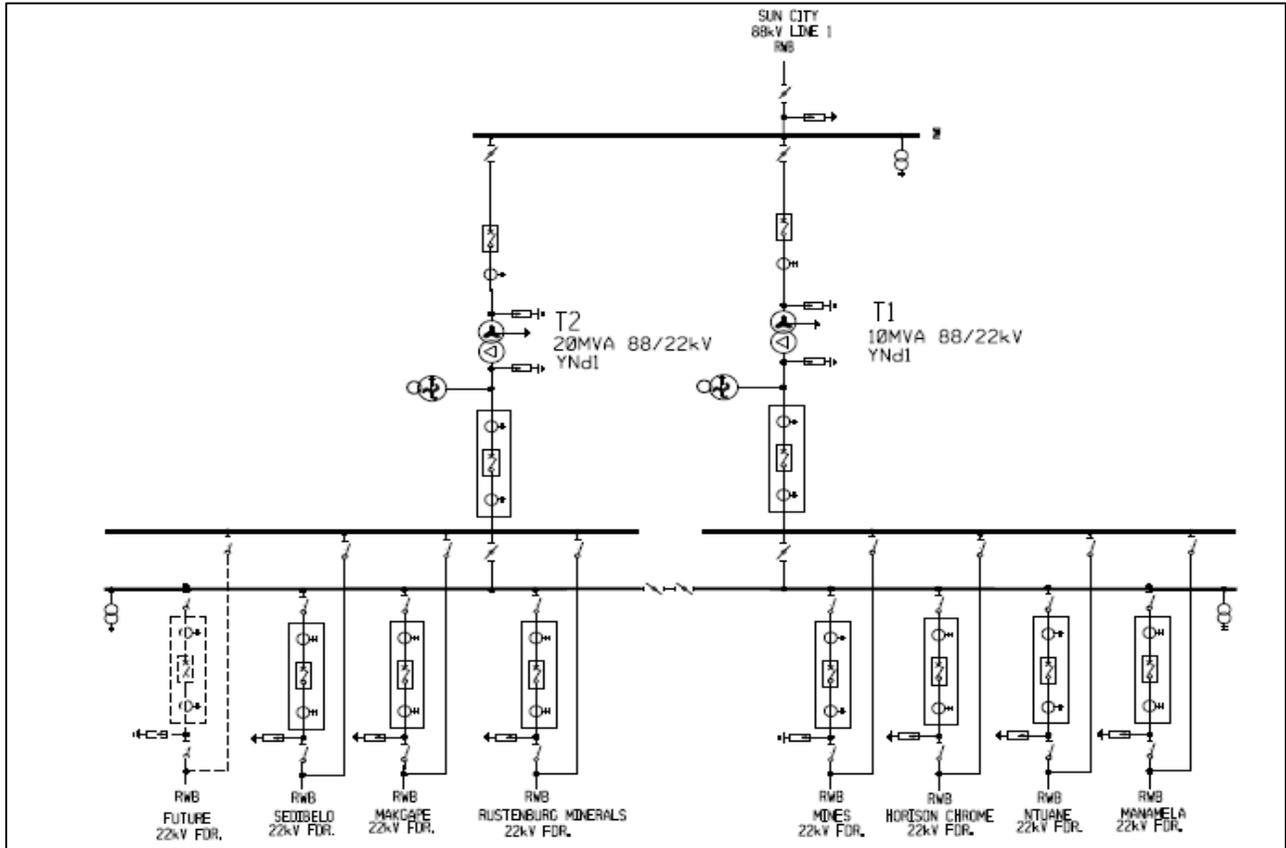


Figure 4.3: Existing Ruighoek substation single electric diagram [2].

In this case the HV/MV transformers feature a delta-connection MV winding. The neutral point of the MV network is provided and earthed by means of an NEC with internal NER, known as a NECR. The auxiliary MV/LV transformer is included in the same tank as the NECR, giving rise to the designation NECRT [12].

The NECRT for each point of MV neutral earthing is specified such as to limit the earth fault current contribution per neutral earthing point as follows [12]:

1. In overhead (typically rural) distribution networks: 360A; and
2. In underground (typically urban) distribution networks: 960A.

The NECRT is a ZN-connected winding used for artificially providing a neutral point in a system where a system neutral point is not otherwise available, and capable of passing a specified zero sequence earth fault current for a specified duration of time when connected to a system of specified rated voltage [11,12].

The principal objectives of the system neutral earthing are as follows [12]:

- a. To stabilise the phase-to-earth voltages;
- b. To limit transient overvoltages and to reduce arcing damage at the point of a fault; and
- c. To enable the operation of protection equipment for the isolation of faulty equipment and circuits by allowing an earth fault current of adequate magnitude to flow to the point of intentional earthing during the occurrence of an earth fault.

The applied resistive earthing in this substation reduced earth fault current magnitude (typically 300-900A), lowered the degree of damage at fault point and caused no damage to feeder equipment and, most importantly, reduced the step- and touch potentials [12].

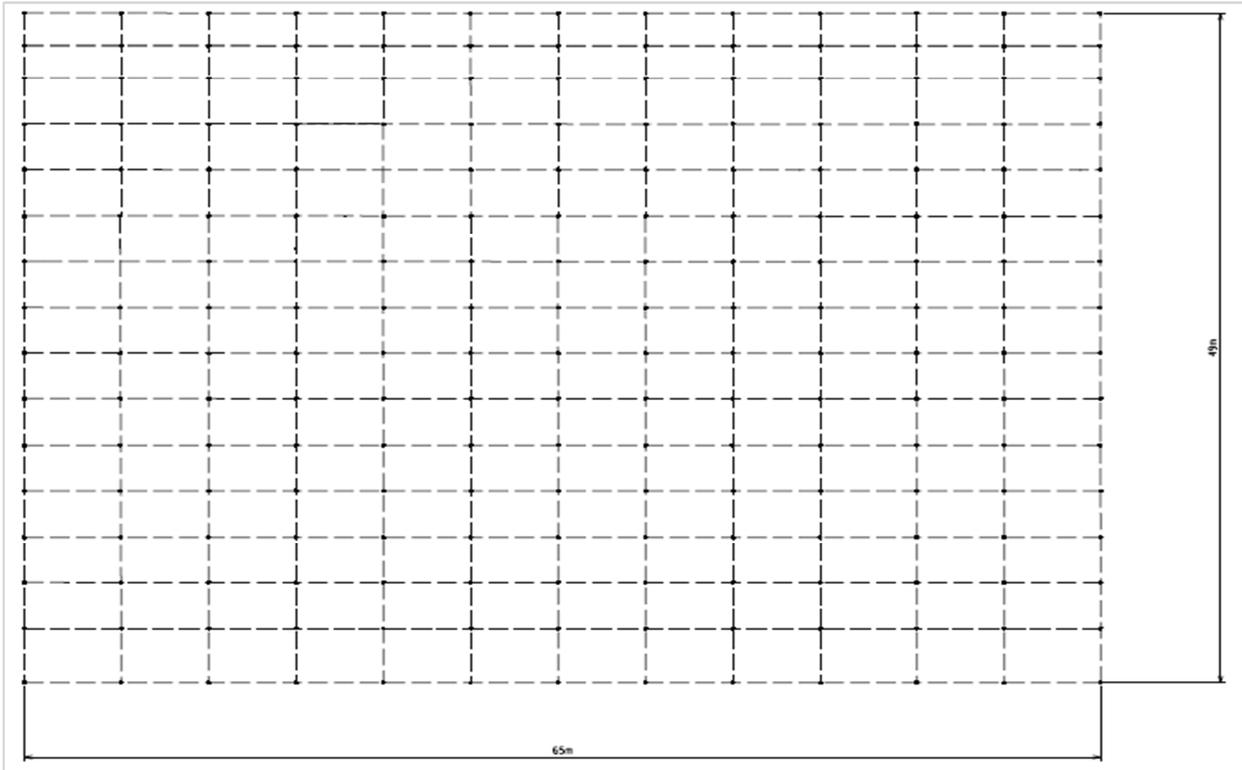


Figure 4.4: Existing Ruighoek substation earth mat configuration [2].

Ruighoek substation has a grounding grid of 65 x 49m and 5.74 x 3.4 square meshes of horizontal grid solid round copper conductors buried about 1m below ground level. The grid extends over the whole area occupied by the substation. All metalwork in this substation (steel structures, gutters, fences, etc.) are bonded to the earth grid so that a direct low-resistance path to ground is provided for short-circuit currents. Ruighoek substation has yard stone of between 25-38mm in size, and wet resistivity of 3000 ohm metre over the whole area occupied by the substation, and this serves to increase the resistance in the accidental circuit (through the person) to limit the current to safe levels.

This means that less current will flow through the person per unit voltage, thereby increasing the step- and touch voltages that can be tolerated by the person. Secondary advantages are that it limits weed growth and limits the rate of evaporation from the soil, thereby improving (reducing) soil resistivity. This, in turn, improves the effectiveness of the earth grid.

Table 4.1: Substation Parameters

Description	Size	Unit
High Voltage	88	kV
Medium Voltage	22	kV
Transformers	10 and 20	MVA
HV(3- Phase fault current)	1.94	kA
HV(1- Phase fault current)	1.05	kA
MV(3- Phase fault current)	4.46	kA
MV(1- Phase fault current)	720	A
Switchyard operator	50	kg
Resistivity of the crushed rock layer	3000	Ω .m
Grid buried depth	1	m
Fault clearing time	0.5	s

The information presented in table 4.1 will be used as the base for the analysis of the existing grounding system, as discussed in section 4.4.

4.4 Existing grounding system design

The analysis of the existing grounding system is presented in this section. Visual inspection of existing substation earth electrodes, measurement of substation earth electrodes resistance and soil resistivity are discussed.

4.4.1 Visual Inspection

It is of utmost importance that the condition of the earthing system is verified visually. This is to confirm that the grid conductor cross-sectional area is not being affected by corrosion and is adequate, considering the design earth fault current together with the maximum earth fault duration applicable.

The following were inspected visually:

- Condition of the surface layer material (e.g. crusher stone), is free of fines and soil and is at least 100mm thick as per standard.
- There are no loose or otherwise faulty connections
- There are no stolen or missing earth tails
- Visible earthing conductors and connections are still in good condition
- Earthing bonds to equipment are still in good condition
- Metal structures, particularly fence at ground level, are inspected and no sign of corrosion is visible.

Visual inspection of the main earth grid and connections is performed. This is done by digging a number of test holes (see figure 4.5).



Figure 4.5: Existing earth electrodes

No corrosion could be traced in all test holes. The earth grid cross section area and connections are still adequate to sustain the design earth fault current.

4.4.2 Earth electrode resistance measurement

The earth electrodes resistance (also commonly referred to as the grid resistance) is measured to verify the resistance between the earth electrode and true earth. The fall of potential method, as shown in figure 4.6, is used to measure the resistance of the existing earth grid.

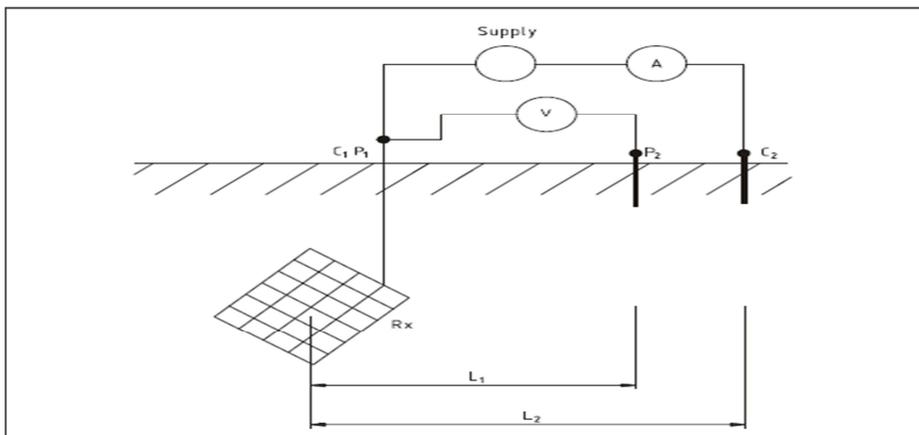


Figure 4.6: Fall of potential method of measuring earth resistance [7, 13].

Where probes C_1 and P_1 are connected to the same point in the substation earth grid, probe C_2 is connected 180m (L_2) away from the edge of the earth grid and probe P_2 is connected at prescribed distances. Measurements were taken as shown in table 4.2.

Table 4.2: Measured resistances

Probe Spacing		Distance	Resistance (Ohm)
Ra	10% L_2	18	0.55
Rb	20% L_2	36	0.78
Rc	30% L_2	54	0.91
Rd	40% L_2	72	1.05
Re	50% L_2	90	1.14
Rf	60% L_2	108	1.2
Rg	70% L_2	126	1.24

The earth resistance was measured at seven separate positions of the potential spike. The following resistance curve is obtained:

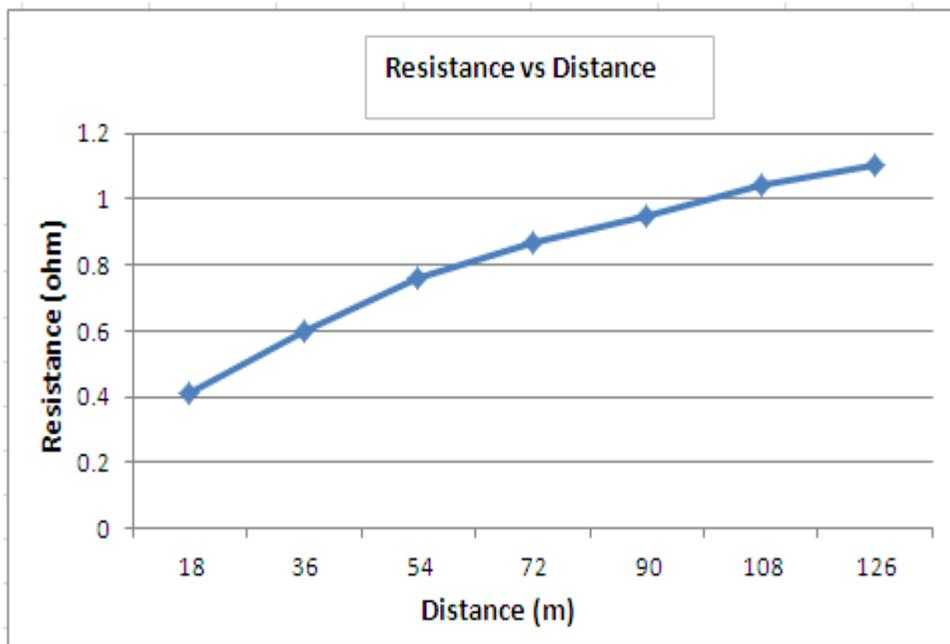


Figure 4.7: Earth resistance curve

To determine the curve slope coefficient μ , the change of slope of the earth resistance curve

was measured:
$$\mu = \frac{R_f - R_d}{R_d - R_b} = \frac{1.2 - 1.05}{1.05 - 0.78} = 0.62962963$$

Using table 8.1 in **Appendix B**, $\frac{D\tau}{L_2} = 0.6089 \Rightarrow \therefore D\tau = 0.6089 \times 180 = 109.602m$ was obtained

R_{grid} at $D\tau = 109.602m$ was measured and $R_{grid} = 1.02\Omega$ obtained.

4.4.3 Soil resistivity measurement

The measurements of soil resistivity constitute the basis of the grounding study and are therefore of primary importance. The Wenner four-pin method, as shown in figure 4.8 below, was used to determine the soil model (top, bottom soil layer resistivities and soil top layer thickness) in the vicinity of the substation, taking into account possible factors that will influence the accuracy of the results.

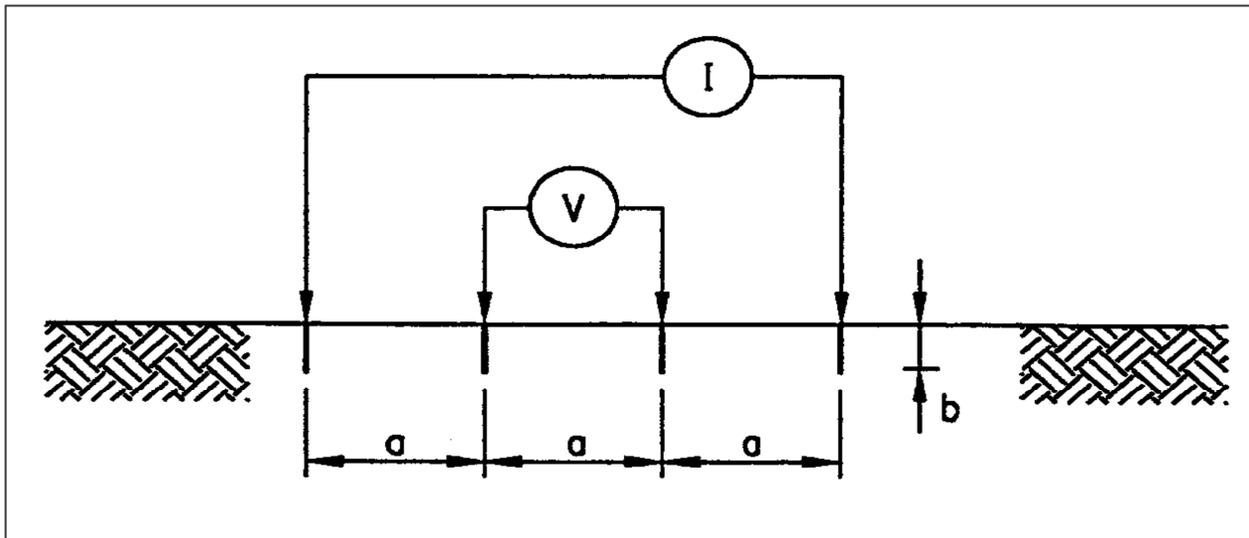


Figure 4.8: Wenner four-pin method [7].

The four-pin method is one of the accurate methods in practice for measuring the average resistivity of undisturbed earth.

The following measurement procedure is followed:

- a. Four test probes are driven into the soil in a straight line at equal distances **a** and to a depth of not more than 10% of **a** (refer to figure 4.9).
- b. The leads between the measuring instrument and test probes are connected, as shown in figure 4.9. Care is exercised to ensure that the insulated leads are in good working order, as damaged or non-insulated leads may result in incorrect values being recorded.
- c. The earth tester is operated and resistance measurement, **R**, is recorded.
- d. The average soil resistivity to a depth, **D**, in the vicinity of the voltage probes is calculated according to the following relation:

Average resistivity to depth **D**:

$$\rho = 2 \cdot \pi \cdot a \cdot R \quad [\Omega.m] \quad 4.0$$

Where **a** is the test probe spacing in metres and **R** is the earth tester readings in ohms. The depth, **D**, is given as eighty percent of the probe spacing (i.e. **D** = 0.8 x **a**).

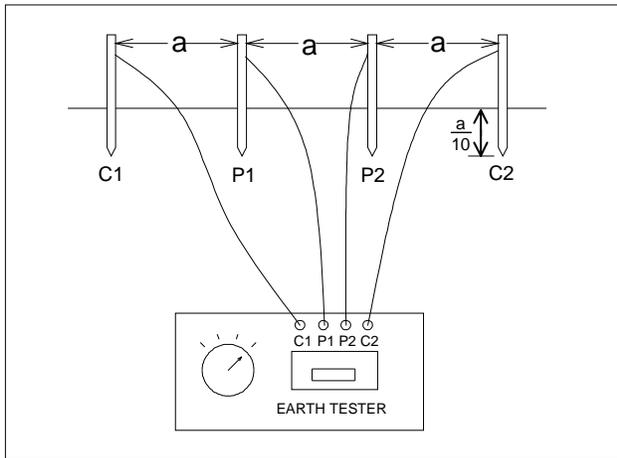


Figure 4.9: Wenner arrangement [12]

Readings are taken and resistivity calculated for progressively widened probe spacings to obtain resistivity values at various depths. The centre position of the spike system is kept constant whilst the probe spacings are increased. The values used for **a** are as shown in table 4.3. The depth to which the test probes are driven was never more than 10% of the spacings **a** between the electrodes.

The specific depth, \mathbf{D} , for a given spacing, \mathbf{a} , is calculated as:

$$D = 0.8 \cdot a \quad 4.1$$

Geometric factor given by $K = 2 \cdot \pi \cdot a$ 4.2

The two sets of readings are taken diagonally across the site, maintaining the centre position of the probes (refer figure 4.10).

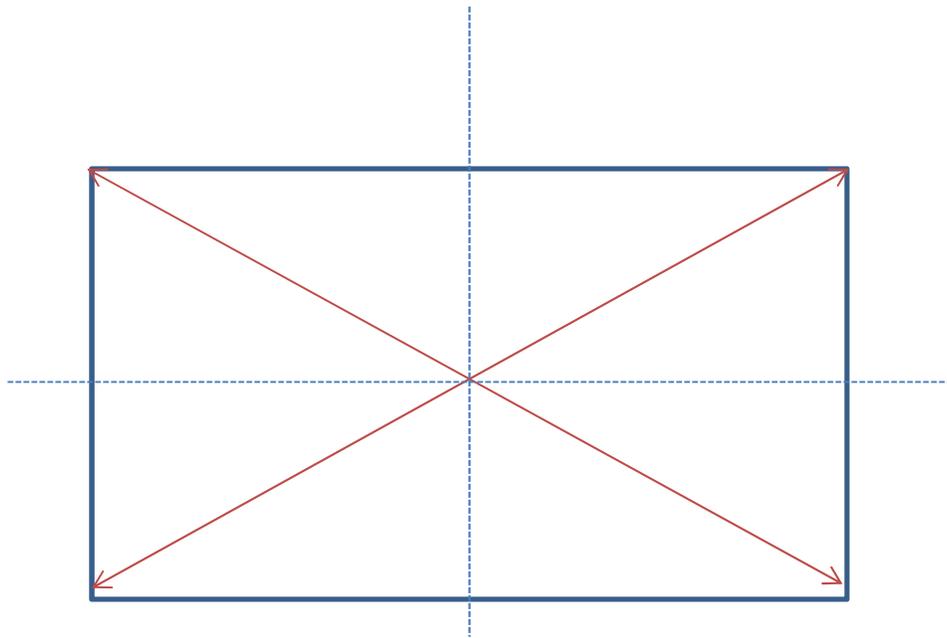


Figure 4.10: Direction of soil resistivity measurement on site

The soil resistivity measurements were made in the vicinity of the substation, since it will be impossible to detect within the existing substation, due to interference from grounding system conductors. The shortest measurements were done to sample shallow depth soil resistivity. The measurements are therefore indicative of local surface soil characteristics. The longer measurements were done to sample the soil resistivity at greater depths. The results are tabulated in table 4.3.

Table 4.3: Soil resistivity survey measurement results – Wenner method

Probe spacing	Tester reading 1	Tester reading 2	Average Resistance	Geometric Factor K	Resistivity $\Omega.m$
a (m)	R 1(Ω)	R 2(Ω)	R3(Ω)	$K=2 \cdot \pi \cdot a$	$\rho=R3 \cdot K$
1.0m	12.2	12	12.1	6.28	75.988
2.0m	12.1	11.9	12	12.57	150.84
3.0m	11.29	11.31	11.3	18.85	213.005
5.0m	10.94	10.9	10.92	31.42	343.1064
10.0m	8.18	8.22	8.2	62.83	515.206
15.0m	5.43	5.45	5.44	94.25	512.72
20.0m	4.3	4.44	4.37	125.66	549.1342
30.m	2.57	2.71	2.64	188.5	497.64
40.m	1.61	1.59	1.6	251.8	402.88
50.m	1.57	1.55	1.56	314.1	489.996

Two sets of soil resistance measurements are taken (i.e. R_1 and R_2), and average (R_3) is calculated and used to determine the soil resistivity.

For most power system grounding problems, it has been found in practice that a horizontal two - layer stratification is a good approximation of the real earth structure [6, 7].

The two-layer model is illustrated in figure 4.11.

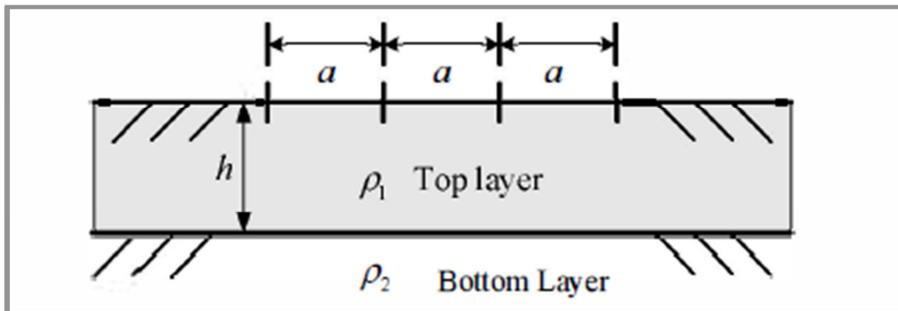


Figure 4.11: Two layer earth model

- h-thickness of top layer (m)
- ρ_1 - resistivity of top soil layer (Ωm)
- ρ_2 - resistivity of bottom soil layer (Ωm)
- a - probe spacing (m)

Autogrid Pro software was used to determine the resistivities of the top and bottom soil layer, as well as the thickness of the top layer. Results are tabulated in table 4.4.

Table 4.4: Autogrid Pro Results [16].

Layer Number	Resistivity(Ωm)	Thickness (m)
Rho1	125.8	1.9
Rho2	495.5	Infinity

The top layer is 1.9m thick and the earth grid is buried in it, with soil resistivity of $\rho_1 = 125.8\Omega m$, and bottom layer has soil resistivity of $495.5\Omega m$. Vertical rods installation will not be considered, because the bottom layer has high soil resistivity.

Grid resistance is given by the following equation:

$$R_g = \rho \left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1+h\sqrt{20/A}} \right) \right] \quad 4.1$$

$$R_g = 125.8 \left[\frac{1}{1515} + \frac{1}{\sqrt{20 \times 3185}} \left(1 + \frac{1}{1+\sqrt{20/3185}} \right) \right] \Rightarrow \therefore R_g = 1.04\Omega$$

Note: parameters in equation 4.1 are calculated in section 4.4.4, in detail.

It can be deduced that the grid resistance values measured in section 4.4.2 are comparable to the one calculated in section 4.4.3, with a small error of less than 2%. The soil structure is therefore a good approximation of the true earth.

4.4.4 Existing substation earth grid analysis:

The standard $10mm^2$ round copper was used to construct the existing earth mat.

Grid parameters:

- Grid length = 65m and grid width = 49m,
- Distance between parallel conductors is $D_x = 5.74m$,
- Distance between parallel conductors is $D_y = 3.4m$.

➤ Calculate the number of conductors perpendicular to the length,

$$\text{➤ } D_x = \frac{L_x}{Q_x - 1} \Rightarrow \therefore Q_x = \frac{L_x}{D_x} + 1 = \frac{65}{5.74} + 1 \Rightarrow \therefore Q_x = 12.32 \quad 4.2$$

➤ Calculate the number of conductors perpendicular to the width,

$$\text{➤ } D_y = \frac{L_y}{Q_y - 1} \Rightarrow Q_y = \frac{L_y}{D_y} + 1 = \frac{49}{3.4} + 1 \Rightarrow \therefore Q_y = 15.41 \quad 4.3$$

Therefore, total conductor length is $L_T = (L_x \cdot Q_x) + (L_y \cdot Q_y)$ 4.4

$$\therefore L_T = (65 \times 12.32) + (49 \times 15.41) = 1556.24m$$

Area occupied by ground grid is $A = L_x \cdot L_y = 65 \times 49 = 3185m^2$ 4.5

and the depth of the grid is $h = 1m$.

From equation 4.1,

$$1.02 = \rho \left[\frac{1}{1515} + \frac{1}{\sqrt{20 \times 3185}} \left(1 + \frac{1}{1 + \sqrt{20/3185}} \right) \right] \Rightarrow \therefore \rho = 122.99 \Omega m$$

$$E_{step} = I_b \cdot (R_b + 6 \cdot \rho_s \cdot C_s) \text{ (Tolerable step voltage)} \quad 4.7$$

Where I_b is the safe body current, $R_b = 1000 \Omega$ body resistance, $\rho_s = 3000 \Omega m$ crusher stone resistivity and C_s is the surface layer derating factor.

$$I_b = \frac{0.116}{\sqrt{t_c}}, \text{ use } t_c = 0.5s \Rightarrow I_b = \frac{0.116}{\sqrt{0.5}} = 0.164A, \quad 4.8$$

$$C_s = 1 - \frac{0.09(1 - \frac{\rho}{\rho_s})}{2 \cdot h_s + 0.09} = 1 - \frac{0.09(1 - \frac{122.99}{3000})}{2 \times 1 + 0.09} = 0.958703 \quad 4.9$$

From equation (4.6), $\therefore E_{step} = 0.164(1000 + 6 \times 3000 \times 0.958703) = 2994.1V$ and

$$E_{touch} = I_b \cdot (R_b + 1.5\rho_s \cdot C_s) \text{ (Tolerable touch voltage)} \quad 4.10$$

$$\therefore E_{touch} = 0.164 \times (1000 + 1.5 \times 3000 \times 0.958703) = 871.5V$$

The maximum grid current is given by the following equation:

$$I_G = D_f \times S_f \times I_f \quad 4.11$$

Where: D_f is the decrement factor for the entire duration of the fault, S_f is the current division factor and I_f is the RMS value of the symmetrical ground current [A].

$$S_f = \frac{R_{rest}}{R_{rest} + R_g}, \text{ Note } n_l = 1 \text{ (number of lines connected to the substation), therefore use} \quad 4.12$$

$R_{rest} = 7.3\Omega$, the resistance associated with the overhead lines, external earth electrodes and earth mat.

$$\therefore S_f = \frac{7.3}{7.3 + 1.02} = 0.877404 \text{ and } D_f = 1.010 \text{ (from table 3.1)}$$

From equation (4.11), the grid is:

$$\therefore I_G = 1.010 \times 0.877404 \times 1.050 = 0.93kA$$

$$\text{Ground potential rise is } GPR = I_G \cdot R_g = 0.93 \times 1000 \times 1.02 = 948.6V \quad 4.13$$

The mesh potential is given by the following equation:

$$E_m = \frac{\rho \times K_m \times K_i \times I_G}{L_c}, \quad 4.14$$

Where: K_m is the geometric factor and K_{ii} is the corrective weighting factor that adjusts for the effects of inner conductors on the corner mesh.

$$K_m = \frac{1}{2\pi} \left[\ln \frac{D^2}{16 \times h \times d} + \frac{(D + 2 \times h)^2}{8 \times D \times d} - \frac{h}{4 \times d} \right] + \frac{K_{ii}}{K_h} \times \ln \left[\frac{8}{\pi(2 \times n - 1)} \right] \quad 4.15$$

$$\text{And } K_{ii} = \frac{1}{(2 \cdot n)^{\frac{2}{n}}} \quad 4.16$$

The number of parallel conductors of an equivalent rectangular grid is represented by the following equation:

$$n = n_a \times n_b \times n_c \times n_d \quad 4.17$$

Where:

$$L_p = 2 \times (L_x + L_y) = 2 \times (65 + 49) = 228m \quad (\text{peripheral length of the grid}) \quad 4.18$$

$$\therefore n_a = \frac{2 \times L_c}{L_p} = \frac{2 \times 1556.24}{228} = 13.65, \quad 4.19$$

$$n_b = \sqrt{\frac{L_p}{4 \times \sqrt{A}}} = \sqrt{\frac{228}{4 \times \sqrt{3185}}} = 1.005, \quad 4.20$$

$$n_c = \left[\frac{L_x \times L_y}{A} \right]^{\frac{0.7 \times A}{L_x \times L_y}} = \left[\frac{65 \times 49}{3185} \right]^{\frac{0.7 \times 3185}{65 \times 49}} = 1 \quad 4.21$$

$$D_m = \sqrt{L_x^2 + L_y^2} = \sqrt{(65^2 + 49^2)} = 81.4m \quad 4.22$$

$$n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}} = \frac{81.4}{81.4} = 1 \quad 4.23$$

$$\therefore n = n_a \times n_b \times n_c \times n_d = 13.65 \times 1.005 \times 1 \times 1 = 13.72 \quad 4.24$$

$$K_h = \sqrt{1 + h} = \sqrt{1 + 1} = 1.414, \text{ is the corrective weighting factor} \quad 4.25$$

And from equation (4.16), $\therefore K_{ii} = \frac{1}{(2.n)^{\frac{2}{n}}} = \frac{1}{(2 \times 13.72)^{\frac{2}{13.72}}} = 0.62$

Also from equation (4.15):

$$K_m = \frac{1}{2 \times 3.142} \left[\ln \left[\frac{5.74}{16 \times 1 \times 0.010} + \frac{(5.74 + 2 \times 1)^2}{8 \times 5.74 \times 0.010} - \frac{1}{4 \times 0.010} \right] + \frac{0.62}{1.414} \times \ln \left[\frac{8}{3.142 \times (2 \times 13.72 - 1)} \right] \right]$$

$\therefore K_m = 0.79$

The correction factor is given by the following equation:

$$K_i = 0.644 + 0.148 \times n = 0.644 + 0.148 \times 13.72 = 2.67 \quad 4.26$$

From equation (4.14), $\therefore E_m = \frac{122.99 \times 0.79 \times 2.67 \times 0.93 \times 1000}{1556.24} = 155.03V$

And the step potential is represented by the following equation:

$$E_s = \frac{\rho \times K_s \times K_i \times I_G}{L_s} \quad 4.27$$

Where:

$$K_s = \frac{1}{\pi} \left[\frac{1}{2 \times h} + \frac{1}{D + h} + \frac{1}{D} (1 - 0.5^{n-2}) \right], \text{ is the spacing factor for step potential} \quad 4.28$$

$$\therefore K_s = \frac{1}{3.142} \left[\frac{1}{2 \times 1} + \frac{1}{5.74 + 1} + \frac{1}{5.74} (1 - 0.5^{13.72-2}) \right] = 0.26$$

And effective length, $L_s = 0.75 \times L_c + 0.85 \times L_R = 0.75 \times 1556.24 = 1167.18m$ 4.29

From equation (4.27), $\therefore E_s = \frac{122.99 \times 0.26 \times 2.67 \times 0.93 \times 1000}{1167.18} = 68.03V$

The following must be true for the earth grid to be safe:

- **Mesh potential < Safe touch potential limit**
- **Step potential < Safe step potential limit**
- **GPR < 5kV**

Table 4.5: Existing ground grid results

Safe touch potential limit	Mesh potential (actual)	Safe step potential limit	Step potential (actual)	Ground potential rise limit	Ground potential rise (actual)
871.5V	155.03V	2994.1V	68.03V	5000V	948.6V

∴ The existing grounding system is sufficient and safe for existing fault current/levels.

Eskom maintains an insulation level of 5kV rms from the HV earth electrode to the customer MV earth electrode. This implies that substation GPR will not be transferred in the case of MV-fed customers [6].

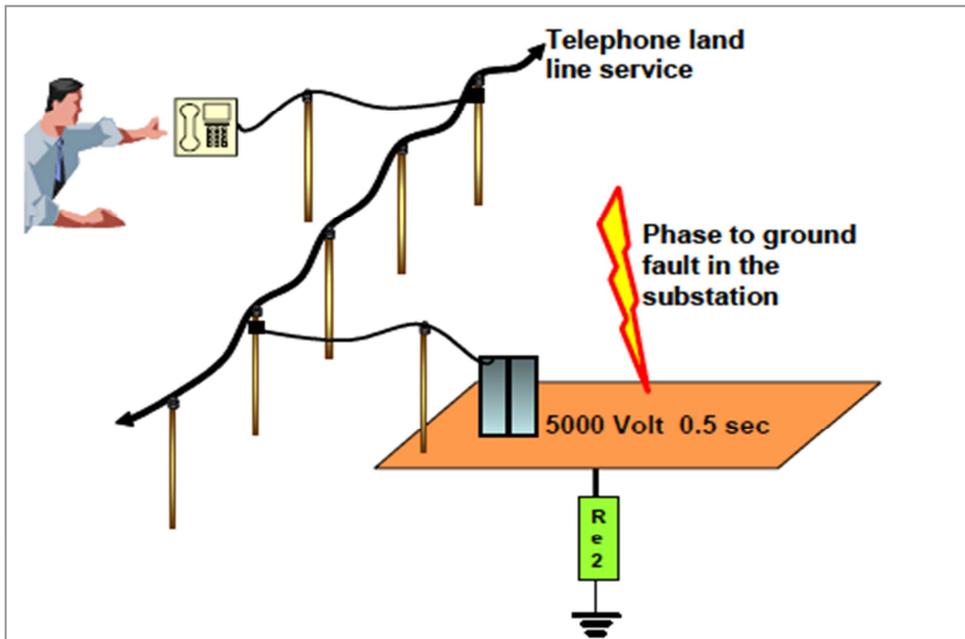


Figure 4.12: An illustration of transferred GPR [6, 8].

Figure 4.12 illustrates one of the potential hazardous situations that substation designers have to avoid. When services such as telephone connections shared by other customers are directly connected to a substation, it poses a potential threat to the customers on the service. This situation can be avoided by inserting isolation interfaces between the external connection to the substation and the substation. A more difficult situation to deal with is the case where customers who receive power directly from the utility substation at MV voltage and have their own substations from where they transform and distribute power directly to their plant. In most of these cases it is not possible to decouple the customer's installation from Eskom's substation earth grid and GPR [6, 8].

It is very difficult, or impossible, to separate these earth electrodes, as armoured cables interconnect the systems. The substations are often also so close to each other that, even if it were disconnected by some means, the GPR will still be transferred by means of coupling through the ground. One positive benefit of this situation is that the net earth electrode resistance is in this case lowered by the parallel connection between the earth electrodes of the utility, the customer substation and any incidental electrodes that the customer may have in his plant.

In this case it is imperative to either separate the customer earth, or for the customer to maintain similar step- and touch potential design principles when designing power substations in the customer's plant. Separation HV and MV earth electrodes are in many cases not possible for example in the case where MV motors are used in the plant [6].

4.5 Grounding system design with increased faults currents

Due to increased load demands, new generation sources are added to the transmission and distribution network. This increases fault current intensities, both three-phase and phase-to-ground, throughout the power system. Figure 4.13 depicts a new network configuration. Ruighoek substation is converted from an 88kV to 132kV substation and the existing 88kV Hare line radial feed is upgraded to 2x132kV Kingbird lines firm supply.

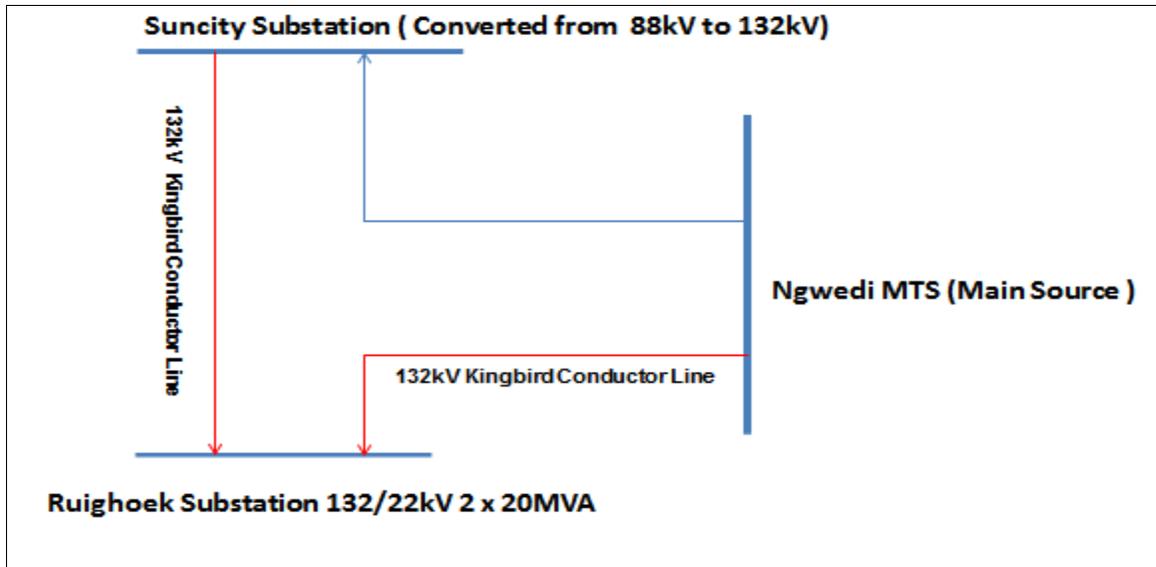


Figure 4.13: New 132kV network diagram

The fault current intensities increased due to network reconfiguration, and the single phase fault current increased from $I_0 = 1.050kA$ to $I_0 = 11.4kA$.

Table 4.6: New substation parameters

Description	Size	Unit
High Voltage	132	kV
Medium Voltage	22	kV
Transformers	20	MVA
HV(3- Phase fault current)	13.96	kA
HV(1- Phase fault current)	11.46	kA
MV(3- Phase fault current)	9.33	kA
MV(1- Phase fault current)	720	A
Switchyard operator	50	kg
Resistivity of the crushed rock layer	3000	$\Omega.m$
Grid buried depth	1	m
MV overhead lines	22	kV
Fault clearing time	0.5	s

Ruighoek substation will be converted from 88/22kV, 1x20MVA and 1x10MVA to 132/22kV 2x20MVA and 8x22kV overhead lines. It will be supplied through loop in, loop out 132kV Kingbird (rated at 120MVA) lines, replacing a single 88kV Hare (rated at 80MVA) line.

The new substation parameters are shown in table 4.3 and will be used to analyse the existing grounding system. The new single line diagram for Ruighoek substation is shown in figure 4.14, which encapsulates the new feeder bays connected to the 132kV Kingbird lines and 132/22kV 20MVA transformers. Customers are fed from overhead MV lines and the customers' earth electrodes are decoupled from utility substation earth electrode, because there is simply not any direct galvanic connection. MV lines do not have shield wires, and even if there were shield wires, the design of the MV-LV transformer installation is specifically done to prevent the transfer of fault GPR to customers [6].

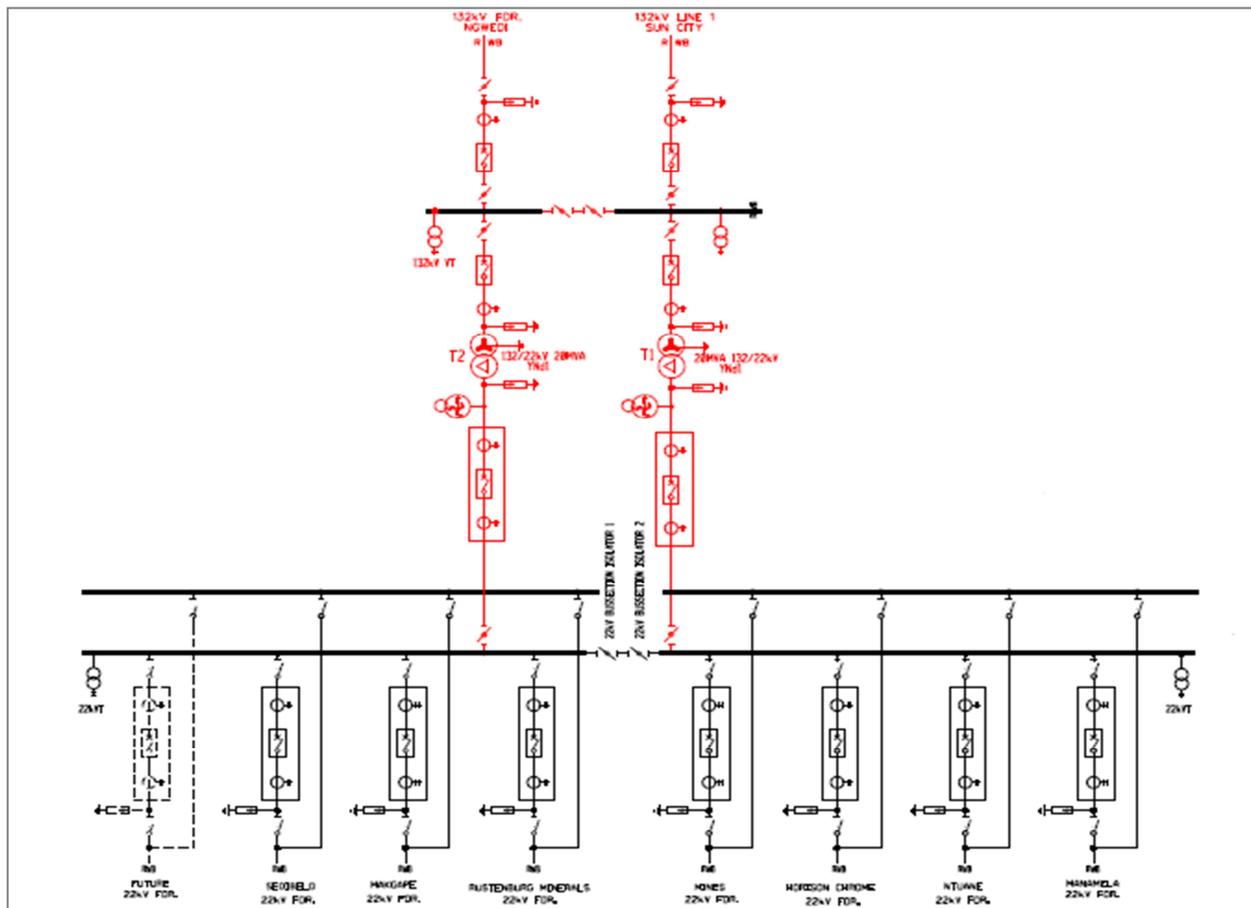


Figure 4.14: New Ruighoek substation single electric diagram

The rms symmetrical ground fault current is 11.46kA, as shown in table 4.3. The number of lines that will be connected to Ruighoek substation are Ngwedi – Ruighoek 132kV Kingbird line with two shield wires and Sun City – Ruighoek 132kV Kingbird line with single shield wire respectively. Both lines will be build parallel to each other.

These overhead ground wires will be connected to the substation ground, and a substantial portion of the ground fault current will be diverted away from the substation ground grid [7].

4.5.1 Ground potential rise analysis

The resistance associated with overhead lines, external earth electrodes and earth mass is defined by the following equation (refer to page 51):

$$R_{rest} = \frac{R_{L1} \cdot R_{L2}}{R_{L1} + R_{L2}} \quad 4.30$$

The distribution lines are fitted with two shield wires. The resistance values used are obtained from table 3.2.

$$\therefore R_{rest} = \frac{3.5 \cdot 10.6}{3.5 + 10.6} = 2.631\Omega ,$$

The current division factor (split factor) of the symmetrical fault current to that portion of the current that flows between the grounding grid and surrounding earth, is calculated below.

From equation (4.12):

$$S_f = \frac{R_{rest}}{R_{rest} + R_g} = \frac{2.631}{2.631 + 1.02} = 0.720624$$

Part of the fault current flows back over the overhead ground wires to the source (Ngwedi MTS), thereby reducing the grid current, as calculated below.

From equation (4.11):

$$I_G = 1.010 \times 0.720624 \times 11.46 = 8.34kA ,$$

GPR is proportional to both the current flowing in the ground grid and the equivalent grid impedance. The split factor is added in the calculations.

From equation (4.13):

$$\therefore GPR = I_G \times R_g = 8.34 \times 1.02 = 8.51kV$$

It can be seen that, even though the grid current had decreased because of the split factor, the GPR is still above the safe limit. This means that ground potential rise in case of ground faults may cause dangerous voltages between telecommunication and local ground. The GPR, as well as distribution of the earth surface potential during the current flow in the grounding system, are important parameters for the protection against electric shock. This transferred potential may be transmitted by communication circuits, metal pipes, metallic fences and low voltage neutral wire. Since Ruighoek substation does not have telecommunication circuits, metal pipes, metallic fences and low voltage neutral wire directly coupled to the adjacent substation earth electrodes, the aggravated GPR due to an increase in faults current, is not relevant.

4.5.2 Mesh potential analysis

The allowable touch voltage is calculated in equations 4.10. Mesh potential represents the highest possible touch potential that may be encountered within a substation's grounding system. Mesh potential is the basis for designing a safe grounding system inside and immediately outside the substation.

From equation (4.14):

$$E_m = \frac{122.99 \times 0.79 \times 2.67 \times 8.34 \times 1000}{1556.24} = 1390.27V,$$

The calculated mesh potential exceeds the touch potential tolerable value of 871.5V by 63%. This implies that substation ground grid is unsafe, a person standing while at the same time having his hands in contact with a grounded structure will experience unsafe touch potential of 63% more than the allowable touch potential. The safety of a person depends on preventing the critical amount of shock energy from being absorbed before the fault is cleared and the system de-energised.

In this case the magnitude and duration of the current conducted through a human body can cause ventricular fibrillation of the heart, since the tolerable value of touch potential is exceeded.

4.5.2 Step potential analysis

The allowable step voltage is calculated in equations 4.7. For the ground system to be safe, the step potential has to be less than the tolerable step potential, so that the critical amount of shock energy that a person will experience is prevented before the fault is cleared and the system de-energised.

From equation (4.27):

$$E_s = \frac{122.99 \times 0.26 \times 2.67 \times 8.34 \times 1000}{1167.18} = 610.1V$$

The calculated step potential is less than the tolerable step potential value of 2994.1V. This implies that the substation ground grid has safe step potential. This means that a person can bridge a distance of 1m with his feet in Ruighoek substation without contacting any other grounded object and without being exposed to dangerous step potential. It clear that there is no safety concerns regarding step voltages in and around this substation.

The grounding system safety analysis is based on the step and touch voltage criterion. The maximum driving voltage of any accidental circuit (step or touch voltage) should not exceed the maximum permissible limits.

Table: 4.7: Summary of results

Particular	Unit	Result
Grid resistance	Ω	1.02
Max. grid current (case 1)	kA	0.93
Max. grid current (case 2)	kA	8.34
Tolerable GPR	Volts	5000
Actual GPR (case 1)	Volts	948.6
Actual GPR (case 2)	Volts	8510

Tolerable step voltage	Volts	2994.1
Tolerable touch voltage	Volts	871.5
Actual step voltage (case 1)	Volts	68.03
Actual step voltage (case 2)	Volts	610.1
Actual touch voltage (case 1)	Volts	155.03
Actual touch voltage (case 2)	Volts	1390.27
No. of conductors in X direction	-	12.32
No. of conductors in Y direction	-	15.41
Total length	m	1556.24
Safety (case 1)	-	Safe
Safety (case 2)	-	Unsafe

The safety characteristics of a substation grounding system depend upon the actual step, touch, and mesh voltages being less than or equal to the tolerable potentials. Table 4.4, shows a summary of results, where **case 1** represents the results of the existing grounding system before increase in fault current and **case 2** represents the results of the existing grounding system with increase in fault current. It can be seen that safety characteristics of a substation system are satisfied in **case 1**, but in **case 2** are not all satisfied.

4.6 Conclusion

Eskom has power distribution improvement and expansion plans to reinforce its power distribution system to accommodate load growth in the future. The plans consist of construction of Ngwedi MTS, distribution substations, sub-transmission lines and installation of new equipment (e.g transformers, circuit breakers). This expansion plan will increase the effective short-circuit current at the Ruighoek substation. Substation earthing plays a vital role in the safety of the environment when a phase-to-ground fault occurs in or close to the substation.

This impact on the safety of staff inside the substation, as well as the safety of staff of substations and the factories of customers connected to the faulting substation. The two layer soil structure is used as a good approximation of the real earth structure. The ground grid design for Ruighoek substation is examined with the main objective to assess its grounding system condition in terms of GPR, step- and touch potential. These three parameters are analysed to ensure that they satisfy the safety criteria defined in the IEEE Std. 80-2000, with two scenarios classified by fault levels: 1.050kA for the existing configuration, 11.46kA for expansion plan or future configuration. The existing grounding system is able to support the 1.050kA short-circuit current. The GPR, step- and touch potential criteria are satisfied.

The grounding system of the future configuration does not satisfy all safety criteria, except the step potential that is within the safe limit. The ground potential rise and touch potential are aggravated by the increased fault currents, but since customers earth electrodes are decoupled from Ruighoek substation earth electrode, the effect of aggravated GPR due to an increase in fault currents is not relevant in this case study. The touch voltage in the substation area is considerably higher than maximum allowable touch voltage. Therefore the existing grounding system with increased in fault current does not comply with all safety requirements. Overhead line earth wires which are connected to the substation earth grid, diverts part of the earth fault current to the tower footing earthing and to the source. The step and touch voltages are dangerous for human body, because human body may get electric shocks from step and touch voltages. Therefore it is important to have step and touch voltage lower than the tolerable values. The existing earth grid visual inspection was done and no sign of corrosion was found, therefore the existing grid conductor will still be re-used.

CHAPTER 5: POSSIBLE DESIGN IMPROVEMENTS

This chapter presents the possible remedies that can be applied to compensate for the effects of high fault current on the existing grounding system. Only possible remedies for touch potential will be investigated, since step potential is within the safe limit and GPR is irrelevant in this case study.

5.1: Grid design improvement

Touch potential is the potential difference between the grid potential rise and the surface potential at the point where a person is standing, while at the same time having his hands in contact with an earthed structure, as shown in figure 5.1.

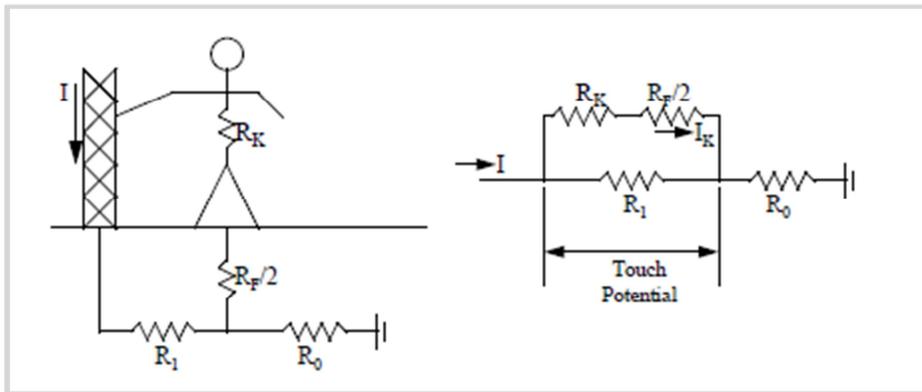


Figure 5.1: Illustration of touch potential [12].

Limit of safe touch potential is defined by equation 4.10:

$$I_K (R_K + 0.5 \cdot R_F) = \frac{0.116}{\sqrt{t_c}} (1000 + 1.5 \rho_s C_s) = E_{touch}$$

The mesh potential is the maximum touch voltage to be found within a mesh of an earth grid.

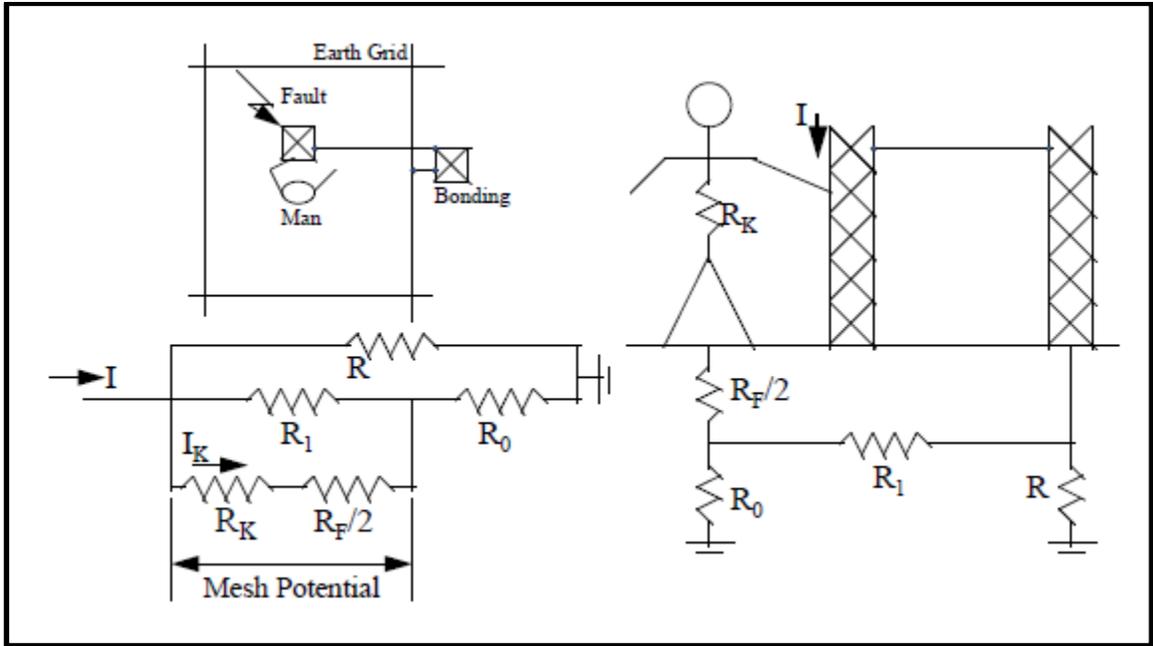


Figure 5.2: Illustration of mesh potential [12].

Mesh potential = Voltage across a man standing in the centre of the mesh and touching a structure bonded to the earth grid some distance away, as denoted in figure 5.2.

$$\text{Mesh potential limit} = I_K (R_K + 0.5 \cdot R_F) = \frac{\rho \times K_m \times K_i \times I_G}{L_c} = E_m \text{ from equation 4.14.}$$

Ruighoek substation has an existing grounding grid of 65 x 49m and 5.74 x 3.4 meshes of horizontal grid solid round copper conductors with 12.32 conductors in X direction and 15.41 conductors in Y direction buried about 1m below ground level, as shown in figure 4.4. The grid is extending over the whole area occupied by the substation. Driving deep vertical rods along the grid perimeter will not be considered in this case study, because the bottom soil layer has higher soil resistivity compared to the top soil layer. The maximum allowable touch and step voltages are the criteria that should be met to ensure a safe grounding system, but since touch voltage criteria is not met the grounding system is deemed unsafe. The maximum touch voltage within the grounding system is 1390.27V, which exceeds the maximum acceptable touch voltage limit of 871.5V.

The iterative calculations of touch and step potential are done and results are tabulated in table 5.1, five cases of calculation are presented.

Table 5.1: Grid parameters

Factors	Case A	Case B	Case C	Case D	Case E
$L_y(m)$	49	49	49	49	49
$L_x(m)$	65	67.5	70	72.5	75
$A(m^2)$	3185	3307.5	3430	3552.5	3675
Q_x	12.32404181	28	29	30	31
Q_y	15.41176471	15.41176471	15.41176471	15.41176471	15.41176471
$L_t(m)$	1556.239188	2645.176471	2785.176471	2930.176471	3080.176471
$L_p(m)$	228	233	238	243	248
n	13.71928773	22.85081673	23.59069355	24.34765382	25.12091319
K_{ii}	0.617042982	0.715674864	0.721271991	0.726748269	0.732098941
K_m	0.78995093	0.575135239	0.575286728	0.575436738	0.575585075
K_i	2.674454585	4.025920876	4.135422645	4.247452765	4.361895152
$I_G(A)$	8.345835572	8.494879209	8.503982178	8.545529988	8.585324422
GPR	8.494879209	8.193058559	8.078795488	7.969483201	7.864784045
$E_m(V)$	1393.473199	910.8546844	893.3953377	876.6801449	860.668007
K_s	0.261802987	0.261802987	0.261802987	0.261802987	0.261802987
$L_s(m)$	1167.179391	1983.882353	2088.882353	2197.632353	2310.132353
$E_s(V)$	615.7218414	552.8310202	542.0915427	531.8104931	521.9626886

Case A:

In this case, based on the results in table 5.1, the substation is not able to support the 11.46kA short-circuit current with the existing ground grid configuration. The touch potential is more than the tolerable touch voltage limit of 871.1V, by 63%.

Case B - E:

From case B to E, the number of conductors in X direction is increased gradually from 12.32 to 31, while the number of conductors in Y direction is left unchanged. The spacing between parallel conductors in X direction is decreased to 2.5m, while spacing between parallel conductors in Y direction is kept unchanged. This implies that the area occupied by the grid and the total length of buried conductor increases.

In turn the touch potential decreases to the safe limit of 860.7V. It can be seen from table 5.1, that step- and touch potential continuously reduces when the grid area increases, and the spacing between parallel conductors is reduced. The number of conductors in Y direction is kept constant, because is not possible to extend the grid area in Y direction, due to the limited space on site. The most cost effective extension is in X direction. It is of interest to note that, from the results, GPR reduces, as well as the grid area increases, but the GPR is not considered, because it is not relevant in this case study. The existing earth electrodes will be re-used since they are still in good condition.

Table 5.2: Summary of Results

Particular	Unit	Result
Grid resistance	Ω	1.02
Max. grid current (before)	kA	0.93
Max. grid current (after)	kA	8.34
Tolerable GPR	Volts	5000
Actual GPR (case 1)	Volts	948.6
Actual GPR (case 2)	Volts	8510
Tolerable step voltage	Volts	2994.1
Tolerable touch voltage	Volts	871.5
Actual step voltage (case 1)	Volts	68.03
Actual step voltage (case 2)	Volts	610.1
Actual step voltage (case 3)	Volts	522V
Actual touch voltage (case 1)	Volts	155.03
Actual touch voltage (case 2)	Volts	1390.27
Actual touch voltage (case 3)	Volts	860.7
Safety (case 1)	-	Safe
Safety (case 2)	-	Unsafe
Safety (case 3)	-	safe

Table 5.2, shows a summary of results, where **case 1** represents the results of the existing grounding system before increase in fault current, **case 2** represents the results of the existing grounding system with increase in fault current and **case 3** representing an improved grounding system with increased in fault current . It can be seen that safety characteristics of a substation grounding system are satisfied in **case 1** and **3**.

The grid area increases from $A = 65\text{m} \times 49\text{m} = 3185\text{m}^2$ to $A = 75\text{m} \times 49\text{m} = 3675\text{m}^2$, the substation is extended in X – direction by 10m, with minimum horizontal spacing of 2.5m. Area occupied by the grounding grid has major effect on step- and touch potential. Thus, the step- and touch potential decreases significantly with increased grid area.

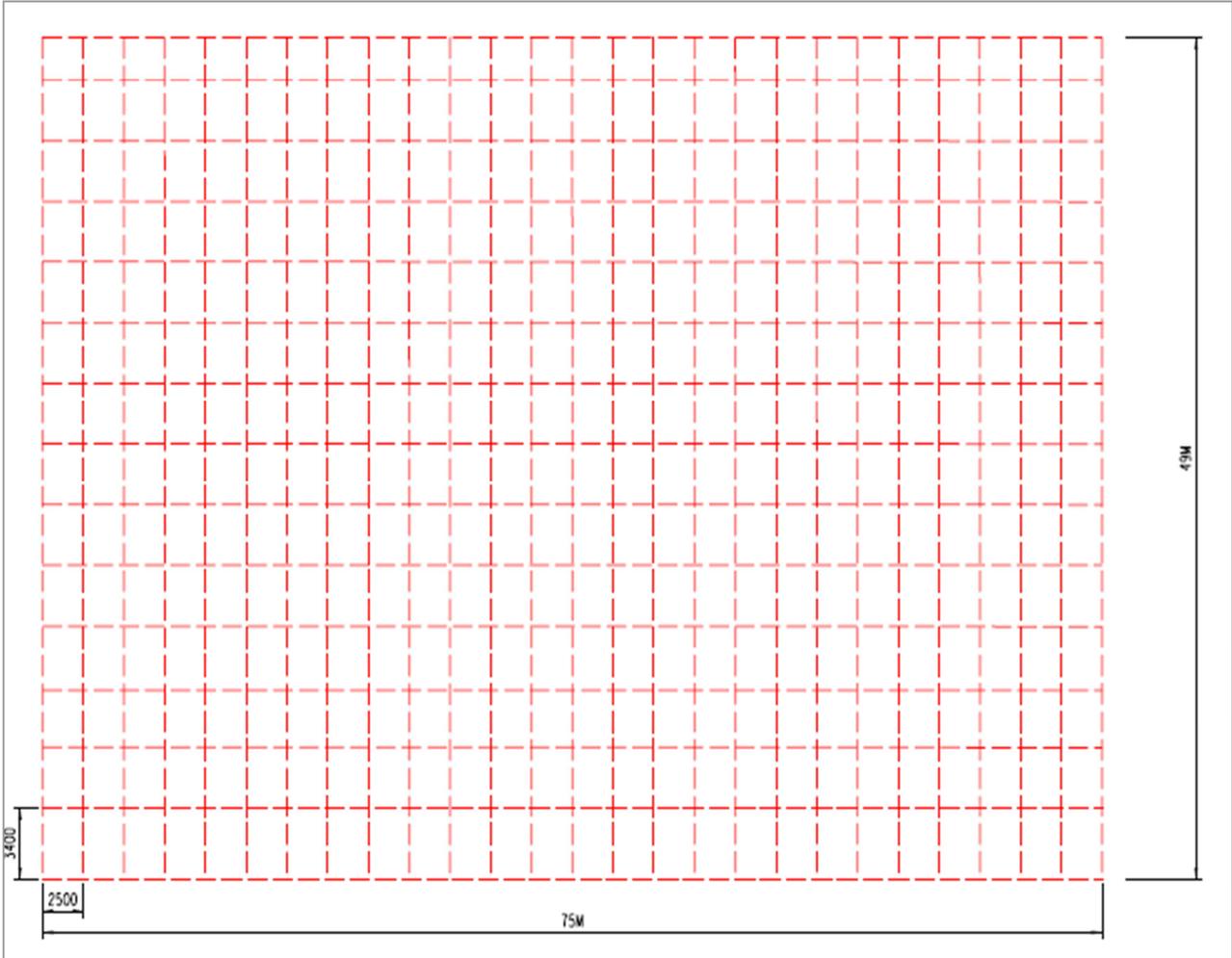


Figure 5.3 An Improved Ruighoek substation earth mat configuration

The number of conductors parallel to the length and to the width of the earth grid determines the size of the grid meshes. The size of the grid meshes has a strong impact on the step and touch potentials that will arise under fault conditions. Adding conductors and thereby reducing the size of the meshes results in a reduction of step and touch potentials. By employing closer spacing of grid conductors, dangerous potentials within the substation are eliminated.

5.2 Conclusion

It can be concluded that step- and touch potential can be improved by increasing the area occupied by the grid, as well as decreasing the horizontal spacing of parallel conductors. This means that step- and touch potential is inversely proportional to the area occupied by the grid, and directly proportional to the horizontal spacing of parallel conductors. An improved grounding system is able to support the 11.46kA short-circuit current. This improvement involved reducing the horizontal spacing between earth electrodes and increasing the grid area, which was very effective in reducing touch potential, and therefore the calculated touch voltage is much lower than the tolerable limits and this in turn satisfies the safety criteria.

CHAPTER 6 – CONCLUSION

The effects of increased fault currents on an existing substation grounding system have been studied. It was found that ground potential rise and touch potential were aggravated by the increased fault currents. In order to effectively prevent hazardous situations in substations upon increased ground faults on the existing grounding system, a safety-based design of the grid should be implemented. In addition, it is of paramount importance to be aware of the present ground-fault current levels at the customer's plant, as they should not exceed, due to increased power flows on the existing utility transmission and distribution assets.

The ground grid design for Ruighoek substation is examined with the main objective of assessing its grounding system condition in terms of GPR, step- and touch potential. These three parameters are analysed to ensure that they satisfy the safety criteria defined in the IEEE Std. 80-2000, with two scenarios classified by fault levels: 1.050kA for the existing configuration, 11.46kA for expansion plan or future configuration. The existing grounding system is able to support the 1.050kA short-circuit current, and the GPR and step- and touch potential criteria are satisfied. The grounding system of the future configuration does not satisfy all safety criteria, except the step potential that is within the safe limit. This case study showed that, the ground potential rise and touch potential are aggravated by the increased fault currents. Since customers earth electrodes are decoupled from Ruighoek substation earth electrode, the effect of unsafe GPR due to an increase in fault currents is not considered.

Improvement measures have been proposed and showed that step- and touch potentials can be improved by increasing the area occupied by the grid, as well as decreasing the horizontal spacing of parallel conductors. This means that step- and touch potential is inversely proportional to the area occupied by the grid and directly proportional to the horizontal spacing of parallel conductors. An improved grounding system is able to support 11.46kA short-circuit current. This implies that it is important to apply the suggested remedies, in order to meet the safety characteristics, as to ensure that a person in the vicinity of grounded object is not exposed to electric shock, and to provide a low impedance path to carry the fault current into ground without exceeding any equipment limits.

CHAPTER 7: REFERENCES

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APPENDIX

Note: The numbers in the first row of the table represent the third decimal of the μ value in the first column.

Table 8.1: Curve Slope Coefficient μ

μ	0	1	2	3	4	5	6	7	8	9
0.40	0,6432	0,6431	0,6429	0,6428	0,6426	0,6425	0,6423	0,6422	0,6420	0,6419
0.41	0,6418	0,6416	0,6415	0,6413	0,6412	0,6410	0,6409	0,6408	0,6406	0,6405
0.42	0,6403	0,6402	0,6400	0,6399	0,6437	0,6396	0,6395	0,6393	0,6392	0,6390
0.43	0,6389	0,6387	0,6386	0,6384	0,6383	0,6382	0,6380	0,6379	0,6377	0,6376
0.44	0,6374	0,6373	0,6372	0,6370	0,6369	0,6367	0,6366	0,6364	0,6363	0,6361
0.45	0,6360	0,6359	0,6357	0,6356	0,6354	0,6353	0,6351	0,6350	0,6348	0,6347
0.46	0,6346	0,6344	0,6443	0,6341	0,6340	0,6338	0,6337	0,6336	0,6334	0,6333
0.47	0,6331	0,6330	0,6328	0,6327	0,6325	0,6324	0,6323	0,6321	0,6320	0,6318
0.48	0,6317	0,6315	0,6314	0,6312	0,6311	0,6310	0,6308	0,6307	0,6305	0,6304
0.49	0,6302	0,6301	0,6300	0,6298	0,6297	0,6295	0,6294	0,6292	0,6291	0,6289
0.50	0,6288	0,6286	0,6285	0,6283	0,6282	0,6280	0,6279	0,6277	0,6276	0,6274
0.51	0,6273	0,6271	0,6270	0,6268	0,6267	0,6265	0,6264	0,6262	0,6261	0,6259
0.52	0,6258	0,6256	0,6255	0,6253	0,6252	0,6252	0,6248	0,6347	0,6245	0,6244
0.53	0,6242	0,6241	0,6239	0,6238	0,6236	0,6235	0,6233	0,6232	0,6230	0,6229
0.54	0,6227	0,6226	0,6224	0,6223	0,6221	0,6220	0,6218	0,6217	0,6215	0,6214
0.55	0,6212	0,6210	0,6209	0,6207	0,6206	0,6204	0,6203	0,6201	0,6200	0,6198
0.56	0,6197	0,6195	0,6194	0,6192	0,6191	0,6189	0,6188	0,6186	0,6185	0,6183
0.57	0,6182	0,6180	0,6179	0,6177	0,6176	0,6174	0,6172	0,6171	0,6169	0,6168
0.58	0,6166	0,6165	0,6163	0,6162	0,6160	0,6159	0,6157	0,6156	0,6154	0,6153
0.59	0,6151	0,6150	0,6148	0,6147	0,6145	0,6144	0,6142	0,6141	0,6139	0,6138
0.60	0,6136	0,6134	0,6133	0,6131	0,6130	0,6128	0,6126	0,6125	0,6123	0,6121
0.61	0,6120	0,6118	0,6117	0,6115	0,6113	0,6112	0,6110	0,6108	0,6107	0,6105
0.62	0,6104	0,6102	0,6100	0,6099	0,6097	0,6096	0,6094	0,6092	0,6091	0,6089
0.63	0,6087	0,6086	0,6084	0,6083	0,6081	0,6079	0,6076	0,6076	0,6074	0,6073
0.64	0,6071	0,6070	0,6068	0,6066	0,6065	0,6063	0,6061	0,6060	0,6058	0,6057
0.65	0,6055	0,6053	0,6052	0,6050	0,6049	0,6047	0,6045	0,6044	0,6042	0,6040
0.66	0,6039	0,6037	0,6036	0,6034	0,6032	0,6031	0,6029	0,6027	0,6026	0,6024
0.67	0,6023	0,6021	0,6019	0,6018	0,6016	0,6015	0,6013	0,6011	0,6010	0,6008
0.68	0,6006	0,6005	0,6003	0,6002	0,6000	0,5998	0,5997	0,5995	0,5993	0,5992
0.69	0,5990	0,5989	0,5987	0,5985	0,5984	0,5982	0,5980	0,5979	0,5977	0,5976

Table 8.1: Continues.

μ	0	1	2	3	4	5	6	7	8	9
0.70	0.5974	0.5973	0.5971	0.5969	0.5967	0.5965	0.5964	0.5962	0.5960	0.5959
0.71	0.5957	0.5955	0.5953	0.5952	0.5950	0.5948	0.5947	0.5945	0.5943	0.5942
0.72	0.5940	0.5938	0.5936	0.5935	0.5933	0.5931	0.5930	0.5928	0.5926	0.5924
0.73	0.5923	0.5921	0.5920	0.5918	0.5916	0.5914	0.5912	0.5911	0.5909	0.5907
0.74	0.5906	0.5904	0.5902	0.5900	0.5899	0.5897	0.5895	0.5894	0.5892	0.5890
0.75	0.5889	0.5887	0.5885	0.5883	0.5882	0.5880	0.5878	0.5877	0.5875	0.5873
0.76	0.5871	0.5870	0.5868	0.5866	0.5865	0.5863	0.5861	0.5859	0.5858	0.5856
0.77	0.5854	0.5853	0.5851	0.5839	0.5847	0.5846	0.5844	0.5842	0.5841	0.5839
0.78	0.5837	0.5835	0.5834	0.5832	0.5830	0.5829	0.5827	0.5825	0.5824	0.5822
0.79	0.5820	0.5818	0.5817	0.5815	0.5813	0.5812	0.5810	0.5808	0.5806	0.5805
0.80	0.5803	0.5801	0.5799	0.5797	0.5796	0.5794	0.5792	0.5790	0.5788	0.5786
0.81	0.5785	0.5783	0.5781	0.5779	0.5777	0.5775	0.5773	0.5772	0.5770	0.5768
0.82	0.5766	0.5764	0.5762	0.5760	0.5759	0.5757	0.5755	0.5753	0.5751	0.5749
0.83	0.5748	0.5746	0.5744	0.5742	0.5740	0.5738	0.5736	0.5735	0.5733	0.5731
0.84	0.5729	0.5727	0.5725	0.5723	0.5722	0.5720	0.5718	0.5716	0.5714	0.5712
0.85	0.5711	0.5709	0.5707	0.5705	0.5703	0.5701	0.5699	0.5698	0.5696	0.5694
0.86	0.5692	0.5690	0.5688	0.5686	0.5685	0.5683	0.5681	0.5679	0.5677	0.5675
0.87	0.5674	0.5672	0.5670	0.5668	0.5666	0.5664	0.5662	0.5661	0.5659	0.5657
0.88	0.5655	0.5653	0.5651	0.5650	0.5648	0.5646	0.5644	0.5642	0.5640	0.5638
0.89	0.5637	0.5635	0.5633	0.5631	0.5629	0.5627	0.5625	0.5624	0.5622	0.5620
0.90	0.5618	0.5616	0.5614	0.5612	0.5610	0.5608	0.5606	0.5604	0.5602	0.5600
0.91	0.5598	0.5596	0.5594	0.5592	0.5590	0.5588	0.5586	0.5584	0.5582	0.5580
0.92	0.5578	0.5576	0.5574	0.5572	0.5570	0.5568	0.5565	0.5563	0.5561	0.5559
0.93	0.5557	0.5555	0.5553	0.5551	0.5549	0.5547	0.5545	0.5543	0.5541	0.5539
0.94	0.5537	0.5535	0.5533	0.5531	0.5529	0.5527	0.5525	0.5523	0.5521	0.5519
0.95	0.5517	0.5515	0.5513	0.5511	0.5509	0.5508	0.5505	0.5503	0.5501	0.5499
0.96	0.5497	0.5495	0.5493	0.5491	0.5489	0.5487	0.5485	0.5483	0.5481	0.5479
0.97	0.5477	0.5475	0.5473	0.5471	0.5469	0.5467	0.5464	0.5462	0.5460	0.5458
0.98	0.5456	0.5454	0.5452	0.5450	0.5448	0.5446	0.5444	0.5442	0.5440	0.5438
0.99	0.5436	0.5434	0.5432	0.5430	0.5428	0.5426	0.5424	0.5422	0.5420	0.5418

Table 8.1: Continues.

μ	0	1	2	3	4	5	6	7	8	9
1.00	0.5426	0.5414	0.5412	0.5409	0.5407	0.5405	0.5403	0.5400	0.5398	0.5396
1.01	0.5394	0.5391	0.5389	0.5387	0.5385	0.5383	0.5380	0.5378	0.5376	0.5374
1.02	0.5371	0.5369	0.5367	0.5365	0.5362	0.5360	0.5358	0.5356	0.5354	0.5351
1.03	0.5349	0.5347	0.5345	0.5344	0.5340	0.5338	0.5336	0.5333	0.5331	0.5329
1.04	0.5327	0.5325	0.5322	0.5320	0.5318	0.5316	0.5313	0.5311	0.5309	0.5307
1.05	0.5305	0.5302	0.5300	0.5298	0.5296	0.5293	0.5291	0.5289	0.5287	0.5284
1.06	0.5282	0.5280	0.5278	0.5276	0.5273	0.5271	0.5269	0.5267	0.5264	0.5262
1.07	0.5260	0.5258	0.5255	0.5253	0.5251	0.5249	0.5247	0.5244	0.5242	0.5240
1.08	0.5238	0.5235	0.5233	0.5231	0.5229	0.5229	0.5224	0.5222	0.5219	0.5217
1.09	0.5215	0.5213	0.5211	0.5209	0.5206	0.5204	0.5202	0.5200	0.5197	0.5195
1.10	0.5193	0.5190	0.5188	0.5185	0.5183	0.5189	0.5178	0.5175	0.5173	0.5170
1.11	0.5168	0.5165	0.5163	0.5160	0.5158	0.5155	0.5153	0.5150	0.5148	0.5145
1.12	0.5143	0.5140	0.5137	0.5135	0.5132	0.5130	0.5127	0.5125	0.5122	0.5120
1.13	0.5118	0.5115	0.5113	0.5110	0.5108	0.5105	0.5203	0.5100	0.5098	0.5095
1.14	0.5093	0.5090	0.5088	0.5085	0.5083	0.5080	0.5078	0.5075	0.5073	0.5070
1.15	0.5068	0.5065	0.5062	0.5060	0.5057	0.5055	0.5052	0.5050	0.5047	0.5045
1.16	0.5042	0.5040	0.5037	0.5035	0.5032	0.5030	0.5027	0.5025	0.5022	0.5020
1.17	0.5017	0.5015	0.5012	0.5010	0.5007	0.5005	0.5002	0.5000	0.4997	0.4995
1.18	0.4992	0.4990	0.4987	0.4985	0.4982	0.4980	0.4977	0.4975	0.4972	0.4970
1.19	0.4967	0.4965	0.4962	0.4960	0.4957	0.4955	0.4952	0.4950	0.4947	0.4945
1.20	0.4942	0.4939	0.4936	0.4933	0.4930	0.4928	0.4925	0.4922	0.4919	0.4916
1.21	0.4913	0.4910	0.4907	0.4904	0.4901	0.4899	0.4896	0.4893	0.4890	0.4887
1.22	0.4884	0.4881	0.4878	0.4875	0.4872	0.4870	0.4867	0.4864	0.4861	0.4858
1.23	0.4855	0.4852	0.4849	0.4846	0.4843	0.4841	0.4838	0.4835	0.4832	0.4829
1.24	0.4826	0.4823	0.4820	0.4817	0.4814	0.4812	0.4809	0.4806	0.4803	0.4800
1.25	0.4797	0.4794	0.4791	0.4788	0.4785	0.4783	0.4780	0.4777	0.4774	0.4771
1.26	0.4768	0.4765	0.4762	0.4759	0.4756	0.4754	0.4751	0.4748	0.4745	0.4742
1.27	0.4739	0.4736	0.4733	0.4730	0.4727	0.4725	0.4722	0.4719	0.4716	0.4713
1.28	0.4710	0.4707	0.4704	0.4701	0.4698	0.4696	0.4693	0.4690	0.4687	0.4684
1.29	0.4681	0.4678	0.4675	0.4672	0.4669	0.4667	0.4664	0.4661	0.4658	0.4655

Table 8.1: Continues.

μ	0	1	2	3	4	5	6	7	8	9
1.30	0.4652	0.4649	0.4645	0.4642	0.4638	0.4635	0.4631	0.4628	0.4625	0.4621
1.31	0.4618	0.4616	0.4611	0.4607	0.4604	0.4601	0.4597	0.4594	0.4590	0.4586
1.32	0.4583	0.4580	0.4577	0.4573	0.4570	0.4566	0.4563	0.4559	0.4556	0.4553
1.33	0.4549	0.4546	0.4542	0.4539	0.4535	0.4532	0.4529	0.4525	0.4522	0.4518
1.34	0.4515	0.4511	0.4508	0.4505	0.4501	0.4498	0.4494	0.4491	0.4487	0.4484
1.35	0.4481	0.4477	0.4474	0.4470	0.4467	0.4463	0.4460	0.4457	0.4453	0.4450
1.36	0.4446	0.4443	0.4439	0.4436	0.4432	0.4429	0.4426	0.4422	0.4419	0.4415
1.37	0.4412	0.4408	0.4405	0.4402	0.4398	0.4395	0.4391	0.4388	0.4384	0.4381
1.38	0.4378	0.4374	0.4371	0.4367	0.4364	0.4360	0.4357	0.4354	0.4350	0.4347
1.39	0.4343	0.4340	0.4336	0.4333	0.5330	0.4326	0.4323	0.4319	0.4316	0.4312
1.40	0.4309	0.4305	0.4301	0.4296	0.4292	0.4288	0.4284	0.4280	0.4275	0.4271
1.41	0.4267	0.4263	0.4258	0.4254	0.4250	0.4246	0.4242	0.4237	0.4233	0.4229
1.42	0.4225	0.4221	0.4216	0.4212	0.4208	0.4204	0.4200	0.4195	0.4191	0.4187
1.43	0.4183	0.4178	0.4174	0.4170	0.4166	0.4162	0.4157	0.4153	0.4149	0.4145
1.44	0.4141	0.4136	0.5132	0.4128	0.4124	0.4120	0.4115	0.4111	0.4107	0.4103
1.45	0.4099	0.4094	0.4090	0.4086	0.4082	0.4077	0.4073	0.4069	0.4065	0.4061
1.46	0.4056	0.4052	0.4048	0.4044	0.4040	0.4035	0.4031	0.4027	0.4023	0.4018
1.47	0.4014	0.4010	0.4005	0.4001	0.3997	0.3993	0.3989	0.3985	0.3980	0.3976
1.48	0.3972	0.3968	0.3964	0.3959	0.3955	0.3951	0.3947	0.3943	0.3938	0.3934
1.49	0.3930	0.3926	0.3921	0.3917	0.3913	0.3909	0.3905	0.3900	0.3896	0.3892
1.50	0.3888	0.3883	0.3878	0.3874	0.3869	0.3864	0.3859	0.3854	0.3850	0.3845
1.51	0.3840	0.3835	0.3830	0.3825	0.3820	0.3816	0.3811	0.3806	0.3801	0.3796
1.52	0.3791	0.3786	0.3781	0.3776	0.3771	0.3766	0.3760	0.3755	0.3750	0.3745
1.53	0.3740	0.3735	0.3730	0.3724	0.3719	0.3714	0.3709	0.3704	0.3698	0.3693
1.54	0.3688	0.3683	0.3677	0.3672	0.3667	0.3662	0.3656	0.3651	0.3646	0.3640
1.55	0.3635	0.3630	0.3624	0.3619	0.3613	0.3608	0.3602	0.3597	0.3591	0.3586
1.56	0.3580	0.3574	0.3569	0.3563	0.3557	0.3552	0.3546	0.3540	0.3534	0.3528
1.57	0.3523	0.3517	0.3511	0.3506	0.3500	0.3494	0.3488	0.3482	0.3477	0.3471
1.58	0.3465	0.3459	0.3453	0.3447	0.3441	0.3435	0.3429	0.3423	0.3417	0.3411
1.59	0.3405	0.3399	0.3393	0.3386	0.3380	0.3374	0.3368	0.3362	0.3355	0.3349