

İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

THREE DIMENSIONAL GROUNDING GRID DESIGN

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FOREWORD

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TABLE OF CONTENTS

	<u>Page</u>
ABBREVIATIONS.....	vii
LIST OF TABLES.....	ix
LIST OF FIGURES.....	xi
SUMMARY.....	xiii
ÖZET	xv
1. INTRODUCTION.....	1
1.1 Purpose of the Thesis.....	1
1.2 Background of the Grounding Grid Design Studies	3
1.3 Scope of the Thesis.....	4
2. BASIC INFORMATION ABOUT GROUNDING	7
2.1 Definitions	7
2.2 Formulas	12
2.3 Step by Step Design	17
2.4 Preliminary Design Remedies.....	19
3. SOFTWARE USED FOR GROUNDING GRID DESIGN.....	21
3.1 Design of a New Grounding Grid by Using a Computer Program.....	21
3.2 Models and Resistivity Measurements of Soil.....	21
3.3 Algorithm and Methodology of Soil Resistivity.....	22
3.4 Performing a Soil Analysis.....	24
3.5 Specifying the Soil Model Type	25
3.6 Performing the Safety Analysis	26
4. SIMULATIONS OF COMPARATIVE SAMPLES	29
4.1 Square Grid without Ground Rods.....	30
4.2 Square Grid with Ground Rods.....	33
4.3 Rectangular Grid with Ground Rods.....	36
4.4 L-Shaped Grid with Ground Rods	39
4.5 Equally Spaced Grid with Rods in Two Layer Soil	42
4.6 Unequally Spaced Grid with Rods in Uniform Soil.....	45
4.7 Equivalent Uniform Soil Model for Nonuniform Soil	48
5. CASE STUDY OF 380/34.5 kV AIR INSULATED SUBSTATION	51
5.1 Introduction.....	51
5.2 Prerequisites.....	51
5.2.1 Description of the Site	51
5.2.2 Network Data	52
5.3 Specific Soil Resistivity.....	52
5.4 Thermal Design of Earthing Conductors and Earth Electrodes.....	53
5.5 Design of Earth Grid with Respect to Permissible Touch Voltages	54
5.5.1 Resistance to Earth	54
5.5.2 Calculation of Touch Voltage.....	55
5.5.3 Calculation of Step Voltage.....	57

6. CONCLUSION AND RECOMMENDATIONS.....	61
REFERENCES	65
CURRICULUM VITAE	69

ABBREVIATIONS

3-D	: Three Dimensional
AC	: Alternative Current
DC	: Direct Current
GPR	: Ground Potential Rise
IEEE	: Institute of Electrical and Electronics Engineers
RMS	: Root Mean Square
Std	: Standard

LIST OF TABLES

	<u>Page</u>
Table 2.1: Index of Design Parameters.....	11
Table 2.2: Typical Grid Resistances.	13
Table 2.3: Standard Specified Values for Electrocution Circuit	13
Table 2.4: Material Constants.....	20
Table 4.1: Input Data for Grid Design Aspects and Safety Calculations of Case 1..	30
Table 4.2: Comparative Results for Grid Design Aspects and Safety Calculations of Case 1.	30
Table 4.3: Input Data for Grid Design Aspects and Safety Calculations of Case 2..	33
Table 4.4: Comparative Results for Grid Design Aspects and Safety Calculations of Case 2.	33
Table 4.5: Input Data for Grid Design Aspects and Safety Calculations of Case 3..	36
Table 4.6: Comparative Results for Grid Design Aspects and Safety Calculations of Case 3.	36
Table 4.7: Input Data for Grid Design Aspects and Safety Calculations of Case 4..	39
Table 4.8: Comparative Results for Grid Design Aspects and Safety Calculations of Case 4.	39
Table 4.9: Input Data for Grid Design Aspects and Safety Calculations of Case 5..	42
Table 4.10: Comparative Results for Grid Design Aspects and Safety Calculations of Case 5.	42
Table 4.11: Input Data for Grid Design Aspects and Safety Calculations of Case 6..	45
Table 4.12: Comparative Results for Grid Design Aspects and Safety Calculations of Case 6.	45
Table 4.13: Ground Parameters Computed with Two-Layer Soil Compared with Those Computed with Equivalent Uniform Soil Model.....	48
Table 4.14: Calculated Resistance and Apparent Resistivity Data for Soil Type 1 and Soil Type 2 Based on the Four Pin Method.	48
Table 5.1: Parameters of Network	52
Table 5.2: Earth Resistivity Measurement Results.....	53
Table 5.3: Parameters for Cross Section of the Earth Conductor.....	54
Table 5.4: Parameters for the Resistance to Earth of an Earth Grid	54
Table 5.5: Parameters for the Tolerable Touch Voltage.....	55
Table 5.6: Parameters for the Tolerable Step Voltage.....	57

LIST OF FIGURES

	<u>Page</u>
Figure 2.1 : Design Procedure Block Diagram.	18
Figure 3.1 : Wenner Four Pin Method.	22
Figure 3.2 : Soil Analysis Module.	24
Figure 3.3 : Soil Analysis Report View	25
Figure 3.4 : Soil Analysis Type View.....	26
Figure 4.1 : Uniform Soil Model for Square Grid without Ground Rods.....	31
Figure 4.2 : 3-D Grid Layout for Square Grid without Ground Rods.	31
Figure 4.3 : Real and Maximum Permissible Potentials Contour Plot for Case 1.	32
Figure 4.4 : Real and Maximum Permissible Potentials Profile Plot for Case 1	32
Figure 4.5 : Uniform Soil Model for Square Grid with Ground Rods.	34
Figure 4.6 : 3-D Grid Layout for Square Grid with Ground Rods.	34
Figure 4.7 : Real and Maximum Permissible Potentials Contour Plot for Case 2.	35
Figure 4.8 : Real and Maximum Permissible Potentials Profile Plot for Case 2	35
Figure 4.9 : Uniform Soil Model for Rectangular Grid with Ground Rods.....	37
Figure 4.10 : 3-D Grid Layout for Rectangular Grid with Ground Rods.	37
Figure 4.11 : Real and Maximum Permissible Potentials Contour Plot for Case 3.	38
Figure 4.12 : Real and Maximum Permissible Potentials Profile Plot for Case 3	38
Figure 4.13 : Uniform Soil Model for L-Shaped Grid with Ground Rods.	40
Figure 4.14 : 3-D Grid Layout for L-Shaped Grid with Ground Rods.....	40
Figure 4.15 : Real and Maximum Permissible Potentials Contour Plot for Case 4.	41
Figure 4.16 : Real and Maximum Permissible Potentials Profile Plot for Case 4	41
Figure 4.17 : Two-Layer Soil Model for Equally Spaced Grid with Ground Rods.	43
Figure 4.18 : 3-D Grid Layout for Equally Spaced Grid with Ground Rods.....	43
Figure 4.19 : Real and Maximum Permissible Potentials Contour Plot for Case 5.	44
Figure 4.20 : Real and Maximum Permissible Potentials Profile Plot for Case 5	44
Figure 4.21 : Uniform Soil Model for Unequally Spaced Grid with Ground Rods.	46
Figure 4.22 : 3-D Grid Layout for Unequally Spaced Grid with Ground Rods.....	46
Figure 4.23 : Real and Maximum Permissible Potentials Contour Plot for Case 6.	47
Figure 4.24 : Real and Maximum Permissible Potentials Profile Plot for Case 6	47
Figure 4.25 : Soil Model for Type 1.	49
Figure 4.26 : Soil Model for Type 2.	49
Figure 5.1 : Wenner Method Wiring Diagram.	52
Figure 5.2 : Soil Model for Case Study.	58
Figure 5.3 : 3-D Grid Layout for Case Study.....	58
Figure 5.4 : Real and Maximum Permissible Potentials Contour Plot for Case Study	59
Figure 5.5 : Real and Maximum Permissible Potentials Profile Plot for Case Study	59

THREE DIMENSIONAL GROUNDING GRID DESIGN

SUMMARY

Grounding systems are designed to guarantee personal security, protection of equipment and continuity of power supply. For a substation grounding system to be safe, the touch and step voltages should be limited below the tolerable voltages.

Excluding transferred potentials, the mesh voltage is used as the criteria for a safe ground grid design since it is usually the worst possible voltage in an alternative current substation. Hence, engineers must compute the equivalent resistance of the system and the potential distribution on the earth surface when a fault condition occurs.

Substation grounding grid design and analysis module specially designed to help engineers optimize the design of new grids and reinforce existing grids, of any shape, by virtue of easy to use, built-in danger point evaluation facilities. It is a useful tool for the analysis of practical grounding systems.

This study presents an advanced methodology and a computer model for analysis of grounding systems conforming to standards IEEE Std 80-2000, IEEE Std 81-1983 and IEEE Std 837-2002. The procedure enables accurate computation of design parameters such as touch and step voltages, body currents, grounding system impedance, voltage profile, etc. The accuracy of computer algorithm is dependent on how well the soil model and physical layout reflect actual field conditions.

The methodology and computer program have been validated with actual system measurements. The tolerable voltage limits and the maximum predicted voltage values calculated using empirical formulas in given standard. The step, touch and mesh voltages were calculated according to the recommendations in given standard and the differences between them were investigated and clarified by carrying out various simulations.

TOPRAKLAMA AĞLARININ ÜÇ BOYUTLU TASARIMI

ÖZET

Topraklama sistemleri personel güvenliğini, donanımların korunmasını ve enerji kaynağının sürekliliğini garanti altına almak için tasarlanmaktadır. Tesis topraklama sisteminin güvenli olabilmesi için, dokunma ve adım gerilimleri, mücadele edilen gerilimlerin altında kalmalıdır.

Ağ gerilimi, transfer potansiyelleri hariç, bir alternatif akım tesisinde mümkün olan en kötü gerilim olduğundan, güvenli topraklama ağı tasarımı için ölçüt olarak kullanılır. Bu yüzden, mühendisler sistemin eşdeğer direncini ve arıza durumunda topraklama yüzeyindeki potansiyel dağılımını hesaplamalıdır.

Kolay kullanım üstünlüğü ve halihazırdaki tehlikeli noktaların değerlendirilmesi olanağıyla her şekildeki mevcut ağların güçlendirilmesi ve yeni ağların tasarımının en uygun hale getirilmesinde mühendislere yardım etmek için tesis topraklama ağı tasarım ve analiz modülü özellikle tasarlanmıştır. Modül, pratik topraklama sistemlerinin analizi için kullanışlı bir araçtır.

Bu çalışma, IEEE Std 80-2000, IEEE Std 81-1983 ve IEEE Std 837-2002 standartlarına uyumlu topraklama sistemlerinin analizi için bir bilgisayar modeli ve gelişmiş metodoloji sunmaktadır. Yöntem dokunma ve adım gerilimlerinin, vücut akımlarının, topraklama sistemi empedansının, gerilim profili gibi tasarım parametrelerinin doğru hesaplanmasına olanak sağlamaktadır. Bilgisayar algoritmasının doğruluğu topraklama modelinin ve fiziksel düzenin gerçek saha koşullarına ne kadar iyi yansıtıldığına bağlıdır.

Metodoloji ve bilgisayar programı gerçek sistem ölçümleri ile doğrulanmıştır. Mücadele edilen gerilim sınırları ve maksimum tahmini gerilim değerleri standartta verilen deneysel formüller kullanılarak hesaplanmıştır. Adım, dokunma ve ağ gerilimleri standartta verilen tavsiyelere göre hesaplanmış ve aralarındaki farklılıklar çeşitli benzetimler yapılarak incelenip açıklanmıştır.

1. INTRODUCTION

Substation grounding system design studies are increasing as available fault currents increase on today's electrical power grid. The economics is an important factor as well as human safety. Engineers want to design systems that protect human and equipment while providing an optimized economic solution without over designing grounding systems. That is why the use of more accurate computer algorithms in designing the grounding system is necessary for some of the cases stated as below:

- Parameters exceed the limitations of the equations,
- Due to significant variations in soil resistivity, multilayer or two-layer soil model is preferred,
- By using the approximate methods, uneven grid conductor or ground rod spacings are unable to be analyzed,
- To determine local danger points with a flexible method,
- For complex grids in which conductors and buried metallic structures are not connected to the grounding system.

1.1 Purpose of the Thesis

The main objectives of this study are to:

- provide a suitable reference containing the necessary guidelines so that a grounding system designer can focus quickly on the most efficient design,
- retain the step and touch voltages within the safety tolerance limits and to keep ground resistance small,
- design a substation grounding system based on IEEE Std 80-2000 [1] standard in general,
- ensure the safety and well being of personnel, who may become electrically coupled to the grounding mats during unbalanced fault conditions,

- suggest the optimal configuration of equally or unequally spaced grounding grids,
- determine the required grid conductor specifications,
- compute the substation grounding resistance and study the effect of resistance formula, substation area, number of ground rods, soil homogeneity, grid conductor size and grid burial depth on the calculated value of substation resistance,
- compute the ground potential rise, GPR,
- compute the tolerable and maximum step voltage and check the step voltage criteria,
- compute the tolerable and maximum touch voltage and check the touch voltage criteria,
- display the surface potential profile as a percentage of GPR along any redetermined direction,
- suggest the suitable construction procedure according to the soil state and equipment availability,
- suggest the suitable joint procedure,
- suggest the suitable ground rods material and the necessary installation method take into consideration corrosion problems,
- give the necessary precautions to prevent hazard from the transferred potentials, taking into account all possible ways which may cause these hazards,
- introduce a final report contains all design details,
- describe an expert system approach for designing and testing the grounding grid system of power substations which is aimed to assist the grounding system engineer in obtaining an accurate and economical design of substation grounding grid,
- provide means to carry electric currents into the earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of the service,
- assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.

1.2 Background of the Grounding Grid Design Studies

Safety of personnel in and around electric power installations has been a prime concern since the early days of the electric power industry. The ground potential rise of grounded structures during electric power faults is the first effect on the safety of personnel. An accidental electric current conducted through a human with a grounded structure should be of magnitude and duration below those that cause ventricular fibrillation. Standards have been developed and safe limits have been established as a result of investigations into the effects of electric current on the human body.

Interest in harmonization of standards has increased with ever increasing fault current levels in today's interconnected power systems. The technical comparison of various standards indicating the same issue is still being investigated [2-5].

The limits to calculate tolerable voltages are described in current substation earthing standards [6-16], but still a number of discrepancies exists between them which leaves the designer on uncertainty. The newly revised IEEE Std 80-2000 [1], IEEE Guide for Safety in AC Substation Grounding, was published for guidance to safe grounding practices in AC substation design and has been approved by professionals and engineers for using in grounding design and analysis after previous editions developed in years 1961, 1976 and 1986 [17].

To achieve earth resistances below a specified value, earthing systems were designed in the past. Current earthing systems are designed to control mesh, touch and step voltages within and around the electrical installation by limiting both the magnitudes of transferred potentials and the extent of hot zones to remote locations. These potential differences are denominated as transferred voltage and hot zone.

Since the accuracy, speed and flexibility provided by the use of modern computers increased, computerized grounding analysis in uniform and two-layer soil types became famous. When the multilayer earth structure models are used in the computations, good agreement is obtained between the measured and computed results. If uniform soil models are considered, then poor agreements are achieved [18].

Grounding systems for power plants and substations have become really important to assure safety and reliability in the last few years since the rapid increase in the power system capability, the application of the new technologies and the development of modern power systems in the direction of extra high voltages caused a general increase in the ground fault currents.

The design of grounding grids has been carried out over the years by different approaches. After several studies made on the optimal shape of the grounding grids, keeping the conducting material equal, the unequally spaced grounding grids have a better performance in terms of safety, compared to the equally spaced structures. The unequally spaced grounding grids produce lower and more uniformly distributed touch voltages choosing the fault current, resistivity of the soil, number of conductors, their length and section equal. To design the unequally spaced grounding grids in the optimum way, a procedure is defined [19].

The application and development of evaluating and modelling techniques for power system studies have been subjected to many studies and improved considerably during last decade [20]. The size and complexity of power systems increased significantly so that it is necessary to study the entire system. As a result of this, the application of expert systems and artificial intelligence techniques to power systems and industrial problems has been considered for the past few years.

1.3 Scope of the Thesis

A computer program based on finite element method is used to accurately calculate the emanating current density, potential distribution, ground resistance, touch and step voltages of any configuration of grounding grids buried in uniform and two-layer soils. Good agreement between the data in the literature and the calculated results was obtained.

The accuracy of the program is dependent on how well the soil model and physical layout reflect actual field conditions and it is demonstrated experimentally. The program was also applied to obtain the optimum spacings between grid conductors and to determine the ground resistance and diagonal voltage profile for which calculated results using the grounding software. Good agreement has been obtained.

Unequally spaced grid is discussed [21]. A procedure to conveniently design a safe and economical unequally spaced grid for determining unequal grid conductor spacings is presented. All the results are determined by numerous calculations using program. Simulations are performed on several installed grounding grids.

The analysis of a typical square and rectangular grounding grids buried in a uniform soil is proceeded. The influence of ground rods and the effects of horizontal conductor spacing are considered on the design. Considering conductor spacing scenarios identical to those investigated for the uniform soil, two-layer soil structures are examined. The effects of ground rods on the grounding grid performance are considered [22].

Computation of body currents for a person in accidental contact with the ground, the maximum expected ground potential rise, earth current, touch and step voltages around the grounding system are proceeded.

A grounding system needs to be installed so that effectively connects nonenergized parts of the power system equipment and all metallic structures to the earth together in order to limit touch and step voltages. This system consists of:

- 1) the soil characteristic of the substation,
- 2) ground rods and electrodes connected to the ground grid and installed vertically,
- 3) the ground grid which interconnects embedded or buried conductors,
- 4) the surface layer covering the substation.

2. BASIC INFORMATION ABOUT GROUNDING

2.1 Definitions

Some descriptions about grounding are given below as stated in standard [1]:

a) Auxiliary Ground Electrode

It is a ground electrode with certain design or operating constraints. Its primary function may be other than conducting the ground fault current into the earth.

b) Decrement Factor

This factor is an adjustment factor used in conjunction with the symmetrical ground fault current parameter in safety-oriented grounding calculations. It determines the RMS equivalent of the asymmetrical current wave for a given fault duration, t_f , accounting for the effect of initial DC offset and its attenuation during the fault.

c) Fault Current Division Factor

It is a factor representing the inverse of a ratio of the symmetrical fault current to that portion of the current that flows between the grounding grid and surrounding earth.

$$S_f = \frac{I_g}{3I_0} \quad (2.1)$$

where

S_f is the fault current division factor inverse of a ratio of the symmetrical fault

I_g is the rms symmetrical grid current in A

I_0 is the zero-sequence fault current in A

d) Ground

It is a conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth or to some conducting body of relatively large extent that serves in place of the earth.

e) Grounded

It is a system, circuit or apparatus provided with a ground(s) for the purposes of establishing a ground return circuit and for maintaining its potential at approximately the potential of earth.

f) Ground Current

This is a current flowing into or out of the earth or its equivalent serving as a ground.

g) Ground Electrode

It is a conductor imbedded in the earth and used for collecting ground current from or dissipating ground current into the earth.

h) Ground Mat

It is a solid metallic plate or a system of closely spaced bare conductors that are connected to and often placed in shallow depths above a ground grid or elsewhere at the earth's surface, in order to obtain an extra protective measure minimizing the danger of the exposure to high step or touch voltages in a critical operating area or places that are frequently used by people. Grounded metal gratings, placed on or above the soil surface, or wire mesh placed directly under the surface material, are common forms of a ground mat.

i) Ground Potential Rise (GPR)

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. This voltage, GPR, is equal to the maximum grid current times the grid resistance.

j) Ground Return Circuit

This circuit is a circuit in which the earth or an equivalent conducting body is utilized to complete the circuit and allow current circulation from or to its current source.

k) Grounding Grid

It is a system of horizontal ground electrodes that consists of a number of interconnected, bare conductors buried in the earth, providing a common ground for electrical devices or metallic structures, usually in one specific location.

l) Grounding System

It is the system comprises all interconnected grounding facilities in a specific area.

m) Maximum Grid Current

This is a design value of the maximum grid current, 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 fault t_f , given in s

I_g is the RMS symmetrical grid current in A

n) Mesh Voltage

It is the maximum touch voltage within a mesh of a ground grid.

o) Primary Ground Electrode

It is a ground electrode specifically designed or adapted for discharging the ground fault current into the ground, often in a specific discharge pattern, as required (or implicitly called for) by the grounding system design.

p) Step Voltage

This is the difference in surface potential experienced by a person bridging a distance of 1 m with the feet without contacting any grounded object.

r) Surface Material

It is a material installed over the soil consisting of, but not limited to, rock or crushed stone, asphalt or man-made materials. The surfacing material, depending on the resistivity of the material, may significantly impact the body current for touch and step voltages involving the person's feet.

s) Symmetrical Grid Current

It is that portion of the symmetrical ground fault current that flows between the grounding grid and surrounding earth. It may be expressed as:

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

where

I_g is the RMS symmetrical grid current in A

I_f is the RMS symmetrical ground fault current in A

S_f is the fault current division factor

t) Touch Voltage

This is the potential difference between the ground potential rise (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.

u) Transferred Voltage

It is a special case of the touch voltage where a voltage is transferred into or out of the substation from or to a remote point external to the substation site.

Index of design parameters are also given with Table 2.1 below [1]:

Table 2.1: Index of Design Parameters

Symbol	Description
ρ	Soil resistivity, $\Omega\cdot\text{m}$
ρ_s	Surface layer resistivity, $\Omega\cdot\text{m}$
$3I_0$	Symmetrical fault current in substation for conductor sizing, 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 conductors, 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 center of the corner mesh for the simplified method, V
E_s	Step voltage between a point above the outer corner of the grid and a point 1 m diagonally outside the grid for the simplified method, V
$E_{\text{step}50}$	Tolerable step voltage for human with 50 kg body weight, V
$E_{\text{step}70}$	Tolerable step voltage for human with 70 kg body weight, V
$E_{\text{touch}50}$	Tolerable touch voltage for human with 50 kg body weight, V
$E_{\text{touch}70}$	Tolerable touch voltage for human with 70 kg body weight, V
h	Depth of ground 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
I_g	Symmetrical grid current, 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_m	Spacing factor for mesh voltage, 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_r	Length of ground rod at each location, 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 conductors in x direction, m
L_y	Maximum length of grid conductors in y direction, m
n	Geometric factor composed of factors n_a , n_b , n_c and n_d
n_R	Number of rods placed in area, A
R_g	Resistance of grounding system, Ω
S_f	Fault current division factor (split factor)
t_c	Duration of fault current for sizing ground conductor, s
t_f	Duration of fault current for determining decrement factor, s
t_s	Duration of shock for determining allowable body current, s

2.2 Formulas

Some formulas about grounding are given below as described in standard [1]. The conductor cross section A as a function of conductor current I is:

$$A = I \frac{1}{\sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_c \alpha_r \rho_r} \right) \ln \left(\frac{K_o + T_m}{K_o + T_a} \right)}} \quad (2.4)$$

where

T_m is the maximum allowable temperature in °C

T_a is the ambient temperature in °C

T_r is the reference temperature for material constants in °C

α_r is the thermal coefficient of resistivity at reference temperature T_r in 1/°C

ρ_r is the resistivity of the ground conductor at reference temperature T_r in 1/°C

ρ_r is the resistivity of the ground conductor at reference temperature T_r in $\mu\Omega\text{cm}$

K_0 $(1/\alpha_r) - T_r$ in °C

TCAP is the thermal capacity per unit volume from Table 2.3 in $\text{J}/(\text{cm}^3 \cdot ^\circ\text{C})$

Ground resistance given in Table 2.2 is calculated by the effect of grid depth:

$$R_g = \rho \left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h\sqrt{20/A}} \right) \right] \quad (2.5)$$

The surface layer derating factor is:

$$C_s = 1 - \frac{0.09(1 - \frac{\rho}{\rho_s})}{2h_s + 0.09} \quad (2.6)$$

For the step voltage the limit is:

$$E_{step} = (R_B + 2R_f) \cdot I_B \quad (2.7)$$

where

Table 2.2: Typical Grid Resistances

Soil Parameters	Sand and Gravel	Sandy Loam	Sand and Clay	Gravel and Sand	Soil and Clay
Resistivity ($\Omega\cdot\text{m}$)	2000	800	200	1300	28
Grid Area (m^2)	1365	5985	1695	1420	5530
Buried Length (m)	950	2900	540	1165	915
R_g (calculated Ω)	25.7	4.97	2.55	16.15	0.19
R_g (measured Ω)	39	4.1	3.65	18.2	0.21

Table 2.3: Material Constants

Description	Material Conductivity (%)	α_r Factor at 20°C ($1/^\circ\text{C}$) $\times 10^{-3}$	K_0 at 0°C ($^\circ\text{C}$)	Fusing Temperature T_m ($^\circ\text{C}$)	ρ_r 20°C ($\mu\Omega\cdot\text{cm}$)	TCAP Thermal Capacity $\text{J}/(\text{cm}^3\cdot^\circ\text{C})$
Copper, annealed soft-drawn	100.0	3.93	234	1083	1.72	3.42
Copper, commercial hard-drawn	97.0	3.81	242	1084	1.78	3.42
Copper-clad steel wire	40.0	3.78	245	1084	4.40	3.85
Copper-clad steel wire	30.0	3.78	245	1084	4.40	3.85
Copper-clad steel rod	20.0	3.78	245	1084	8.62	3.85
Aluminium, EC grade	61.0	4.03	228	657	2.86	2.56
Aluminium, 5005 alloy	53.5	3.53	263	652	3.22	2.60
Aluminium, 6201 alloy	52.5	3.47	268	654	3.28	2.60
Aluminium-clad steel wire	20.3	3.60	258	657	8.48	3.58
Steel, 1020	10.8	1.60	605	1510	15.90	3.28
Stainless-clad steel rod	9.8	1.60	605	1400	17.50	4.44
Zinc-coated steel rod	8.6	3.20	293	419	20.10	3.93
Stainless steel, 304	2.4	1.30	749	1400	72.00	4.03

I_B is the RMS magnitude of the current through the body in A.

R_B is the resistance of the human body in Ω .

R_f is the ground resistance of one foot in Ω .

For body weight of 50 kg:

$$E_{step50} = (1000 + 6C_s \cdot \rho_s) \frac{0.116}{\sqrt{t_s}} \quad (2.8)$$

For body weight of 70 kg:

$$E_{step70} = (1000 + 6C_s \cdot \rho_s) \frac{0.157}{\sqrt{t_s}} \quad (2.9)$$

Similarly the touch voltage limit is:

$$E_{touch} = (R_B + \frac{R_f}{2}) \cdot I_B \quad (2.10)$$

For body weight of 50 kg:

$$E_{touch50} = (1000 + 1.5C_s \cdot \rho_s) \frac{0.116}{\sqrt{t_s}} \quad (2.11)$$

For body weight of 70 kg:

$$E_{touch70} = (1000 + 1.5C_s \cdot \rho_s) \frac{0.157}{\sqrt{t_s}} \quad (2.12)$$

The mesh voltage values are obtained as a product of the geometrical factor, corrective factor, soil resistivity and the average current per unit of effective buried length of the grounding system conductor:

$$E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_G}{L_M} \quad (2.13)$$

The geometrical factor is as follows:

$$K_m = \frac{1}{2 \cdot \pi} \left[\ln \frac{D^2}{16 \cdot h \cdot d} + \frac{(D + 2 \cdot h)^2}{8 \cdot D \cdot d} - \frac{h}{4 \cdot d} \right] + \frac{K_{ii}}{K_h} \cdot \ln \left[\frac{8}{\pi(2 \cdot n - 1)} \right] \quad (2.14)$$

For grids with ground rods along the perimeter or for grids with ground rods in the grid corners, as well as both along the perimeter and throughout the grid area:

$$K_{ii} = 1 \quad (2.15)$$

For grids with no ground rods or grids with only a few ground rods, none located in the corners or on the perimeter:

$$K_{ii} = \frac{1}{(2 \cdot n)^{\frac{2}{n}}} \quad (2.16)$$

Corrective weighting factor that emphasizes the effects of grid depth:

$$K_h = \sqrt{1 + \frac{h}{h_0}} \quad h_0 = 1 \text{ m (grid reference depth)} \quad (2.17)$$

The effective number of parallel conductors in a given grid:

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

$$n_a = \frac{2 \cdot L_C}{L_p} \quad (2.18)$$

$n_b = 1$ for square grids

$n_c = 1$ for square and rectangular grids

$n_d = 1$ for square, rectangular and L-shaped grids

Otherwise

$$n_b = \sqrt{\frac{L_p}{4 \cdot \sqrt{A}}} \quad (2.19)$$

$$n_c = \left[\frac{L_x \cdot L_y}{A} \right]^{\frac{0.7 \cdot A}{L_x \cdot L_y}} \quad (2.20)$$

$$n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}} \quad (2.21)$$

L_p is the peripheral length of the grid in m

The irregularity factor used in conjunction with the above defined n is:

$$K_i = 0.644 + 0.148 \cdot n \quad (2.22)$$

Grids with no ground rods or only a few ground rods scattered around it, but none in the corners or along the perimeter of the grid, the effective buried length is:

$$L_M = L_c + L_R \quad (2.23)$$

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

$$L_M = L_c + \left[1.55 + 1.22 \left(\frac{L_r}{\sqrt{L_x^2 + L_y^2}} \right) \right] L_R \quad (2.24)$$

The step voltage values are obtained as a product of the geometrical factor, the corrective factor, the soil resistivity and the average current per unit of buried length of grounding system conductor is:

$$E_s = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_s} \quad (2.25)$$

Grids with or without ground rods, the effective buried conductor length is:

$$L_s = 0.75 \cdot L_c + 0.85 \cdot L_R \quad (2.26)$$

The geometrical factor is as follows:

$$K_s = \frac{1}{\pi} \left[\frac{1}{2 \cdot h} + \frac{1}{D + h} + \frac{1}{D} (1 - 0.5^{n-2}) \right] \quad (2.27)$$

2.3 Step by Step Design

The sequence and description of steps to design the ground grid illustrated in the block diagram given in Figure 2.1 are the followings as given in standard [1]:

- Step 1: The substation to be grounded should be well defined in order to describe boundary conditions of the field. The soil resistivity profile and the soil model used, whether uniform or two-layer, should be also determined by soil resistivity test.
- Step 2: The symmetrical fault current in substation conducted by any conductor in the grounding system and the clearing duration of this fault current should be described. The diameter of the conductor size is also determined.
- Step 3: Due to the choice of shock duration for determining allowable body current by the design engineer, the tolerable touch and step voltages for human with 50 kg or 70 kg body weights are determined.
- Step 4: The preliminary estimations of ground rod locations and conductor spacings should be referred to the field being grounded and the maximum grid current that flows between ground grid and surrounding earth. The initial design should include proper cross conductors providing convenient access for equipment grounds and a conductor loop surrounding all grounded area.
- Step 5: Assuming that correct soil model is chosen, more accurate resistance for the final design can be calculated by computer analysis based on modelling the components of the grounding system.
- Step 6: Symmetrical fault current in substation for conductor sizing that flows through the grid to remote earth should be considered to prevent overdesign of the grounding system. Maximum grid current that flows between ground grid and surrounding earth should reflect the worst fault type and location, the decrement factor and any future system expansion.
- Step 7: Additional conductor providing access to equipment grounds is needed and no more analysis is required if the ground potential rise of the initial design is below the tolerable touch voltage.
- Step 8: Approximate approaches or more accurate computer analysis techniques can be used in order to calculate the mesh and step voltages for the grid.

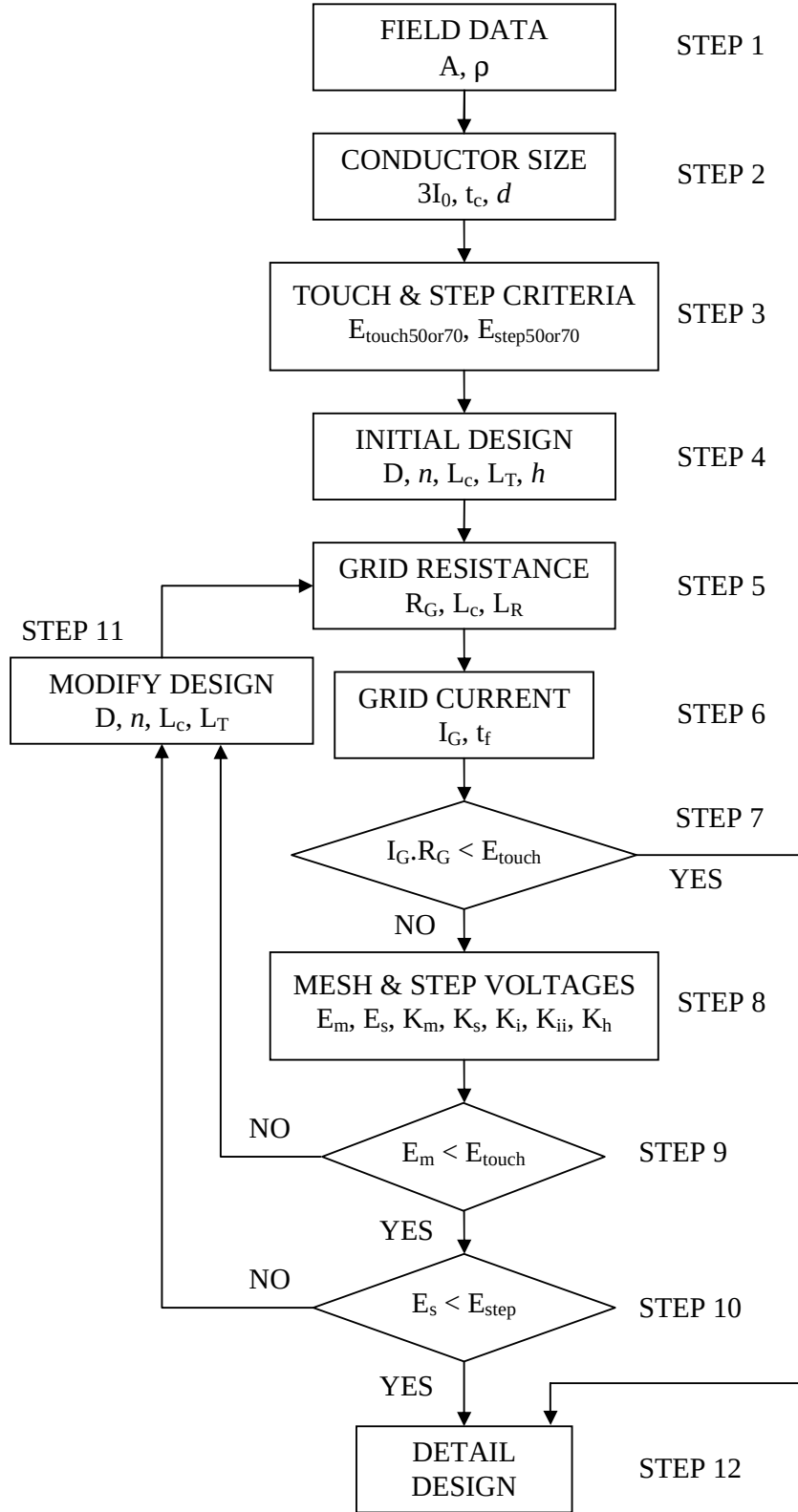


Figure 2.1: Design Procedure Block Diagram

- Step 9: If the calculated mesh voltage is greater than the tolerable touch voltage, the initial design should be modified. If the calculated mesh voltage is below the tolerable touch voltage, the design may be complete.
- Step 10: If both the calculated touch and step voltages are greater than the tolerable voltages, the initial design should be modified. If both the calculated touch and step voltages are below the tolerable voltages, the refinements of the design providing access to equipment grounds are required only.
- Step 11: Modification of the grid design such as additional ground rods, smaller conductor spacings, etc. is required if either the step or touch tolerable voltages are above the calculated limits.
- Step 12: To eliminate hazards associated with special areas of concern due to transferred potential, the final design should be reviewed. When the touch and step voltage requirements are satisfied, the additional ground rods at the base of surge arresters, transformer neutrals, etc. and the additional grid conductors near the equipment to be grounded may be necessary.

2.4 Preliminary Design Remedies

Design refinements below should be done if necessary when calculations based on the initial design still exists dangerous potential differences within the substation:

- a) A decrease in total grid resistance decreases the maximum transferred voltage and the ground potential rise.
- b) The condition of the continuous plate can be approached more closely by employing closer spacing of grid conductors.
- c) Diverting a greater part of the fault current to other paths by connecting overhead ground wires of transmission lines or by decreasing the tower footing resistances in the vicinity of the substation,
- d) Limiting the total fault current decreases all gradients in proportion and the ground potential rise.
- e) Barring access to certain areas reduces the probability of hazards to personnel.

As shown in Table 2.4 below, various standards [1,7,10,14] are compared due to electrocution circuit:

Table 2.4: Standard Specified Values for Electrocution Circuit

	IEEE Std. 80-2000	EA-TS 41-24	BS 7354	CENELEC
R_b : Body Resistance	1 k Ω	1 k Ω	1 k Ω	Related to current path and touch voltage, 50% probability of body impedance
R_{th} : Thevenin equivalent resistance	1.5 ρ for V_t 6 ρ for V_s	0	1.5 ρ for V_t 6 ρ for V_s	1.5 ρ for V_t
ρ_r : Surface layer resistivity	Considered in $C_s \cdot \rho_r$	Considered $R_e = 2$ k Ω (0.15m chippings)	Considered in ρ_{eff}	Mentioned but no value provided
R_{sh} : Footwear resistance	Ignored	4 k Ω	4 k Ω	1 k Ω
R_s : Source resistance	Ignored	Ignored	Ignored	Ignored
I_b : Tolerable body current	Defined by itself I_{b50} and I_{b70}	Curve C_1 in IEC 479-1	Curve C_2 in IEC 479-1	Curve C_2 in IEC 479-1

In Table 2.4, ρ is soil resistivity and ρ_{eff} is the effective chippings resistivity to reflect the contribution of ρ_r . V_s and V_t are step and touch voltages, respectively. R_e is the chippings resistance and C_s is a correction factor.

3. SOFTWARE USED FOR GROUNDING GRID DESIGN

3.1 Design of a New Grounding Grid by Using a Computer Program

Computer algorithms for modeling ground systems are based on:

- a) Individual component modeling like grid conductors and ground rods,
- b) Description of individual components with a set of equations,
- c) Ground-fault current calculation flowing into the earth,
- d) Surface potential calculation at any desired surface point.

Firstly, definition of a project and study should be done in performing a grounding study.

Secondly, the soil model that will be used for the subsequent analyses should be determined. In this step, the safety assessment calculations have also been performed including the maximum permissible step and touch voltage for particular surface and exposure conditions as defined in IEEE Std 80-2000 [1].

The third step is the electrode sizing determination (conductors and rods) which is taking into account the worst case fault parameters in the substation.

The next step is entering the geometrical configuration of the station layout such as coordinates, burial depth and physical dimensions.

Finally, it has to be assured whether the design for the station meets the necessary safety criteria or not. Potential profile plots should be generated to ascertain that touch and step potentials are not exceeded. The grid design may need to be modified and repeated if any of the safety criteria is not met. The procedure starts from the third step until acceptable results are obtained.

3.2 Models and Resistivity Measurements of Soil

Many graphical and analytical approaches have been suggested over the years in order to arrive at practical soil models. Since it is more common to find stratified

soils which are composed of layers having different resistivities, techniques to interpret a set of soil resistivity measurements as a multi-layer soil model are currently used. In this study, uniform and two-layer soil models offered since multi-layer soil models are not supported yet by the software used [23].

For many years in substation grounding practice, the two-layer model has been followed as a practical approach which has an upper layer of a definite depth and a lower layer of an infinite depth with a different resistivity. The software supports Wenner four pin soil measurement technique in which the distance (a) between each pair of probes is equal as given in Figure 3.1 below:

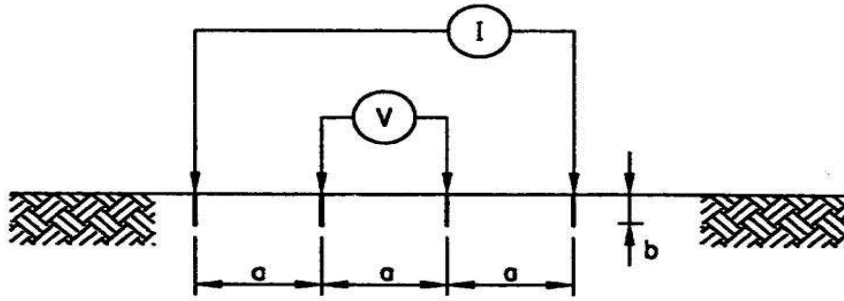


Figure 3.1: Wenner Four Pin Method

The voltage (V) is measured by the voltmeter when a current (I) is injected. The measured or apparent resistivity (ρ) is given by:

$$\rho = \frac{4\pi a(V/I)}{\left[1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}\right]} \quad \text{or} \quad \rho = 2\pi a(V/I) \quad \text{if } a \gg b \quad (3.1)$$

where b is the length of the probe.

3.3 Algorithm and Methodology of Soil Resistivity

Let ρ_a be the apparent earth resistivity as computed by a two-layer model, ρ_1 and ρ_2 the resistivity of the upper and lower soil layers, and h the thickness of the upper soil layer in where the thickness of the lower layer is assumed as infinite by the program. ρ_1 , ρ_2 and h will be calculated according to the mathematical equations described below and will be automatically transferred to use in the grid analysis which calculates the surface potentials.

$$P_a / P_1 = 1 + 4 \cdot F \quad (3.2)$$

where

$$F = \sum_{n=1}^{\infty} \left[\frac{K^n}{\sqrt{1 + (2 \cdot n \cdot h / a)^2}} - \frac{K^n}{\sqrt{4 + (2 \cdot n \cdot h / a)^2}} \right] \quad (3.3)$$

$$K: \text{reflection coefficient} = (\rho_2 - \rho_1) / (\rho_2 + \rho_1) \quad (3.4)$$

n: integer varying from 1 to ∞

a: electrode spacing

The program minimizes the following function by finding ρ_1 , ρ_2 and h:

$$f(x) = \sum_{i=1}^N [(P_{mi} - P(i))^2 / P_{mi}^2] \quad (3.5)$$

where all the available measurements are included in summation.

P_{mi} : Measured value of earth resistivity at probe distance

$P(i)$: Computed value of earth resistivity at probe distance

N: integer

To minimize the RMS error and to calculate the optimal soil model that best fits the available measurements, reduced gradient techniques is used by the program. In order to try to improve the accuracy of the soil model, the program identifies measurements that do not seem to fit very well computed resistivity function.

It interprets either resistivity measurements or resistance values and no vertical soil stratification is taken into account, only horizontal stratification is supported. At least three measurements for two-layer soil and one measurement for uniform soil must be entered with a maximum acceptance capacity of hundred measurements.

3.4 Performing a Soil Analysis

Soil analysis is performed as shown in Figure 3.2 below:

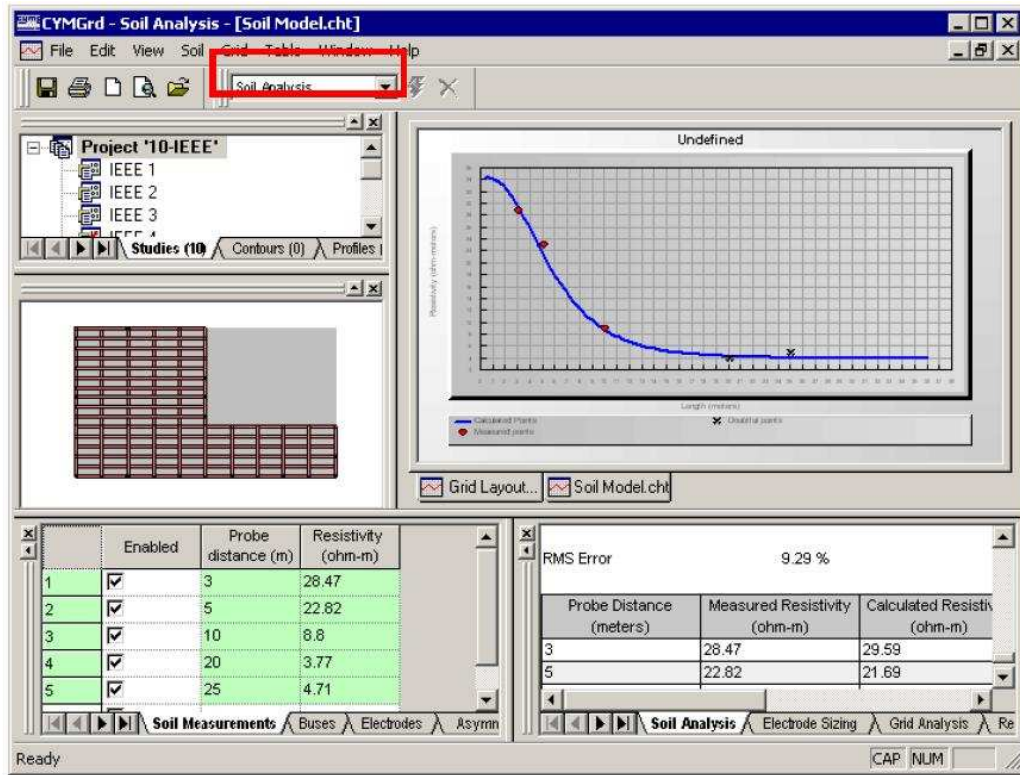


Figure 3.2: Soil Analysis Module

Any suspicious measurement before repeating the calculation for the soil model can be disabled using the checkmark in the dedicated column. The measurements that simulation found departing from the average RMS error is computed to indicate the degree of correspondence between the calculated soil model and the measured values, and is found as follows:

$$\text{RMS error} = \sqrt{\frac{\sum_{i=1}^N \text{error}^2(i)}{N}} \quad (3.6)$$

The user will need to decide either to retain or to discard them by performing a new simulation with a reduced set of measurements.

The calculated soil model results translated in the written report as seen in Figure 3.3 is a very good way of verifying the soil model that the program has in memory before proceeding with the potential rise calculations.

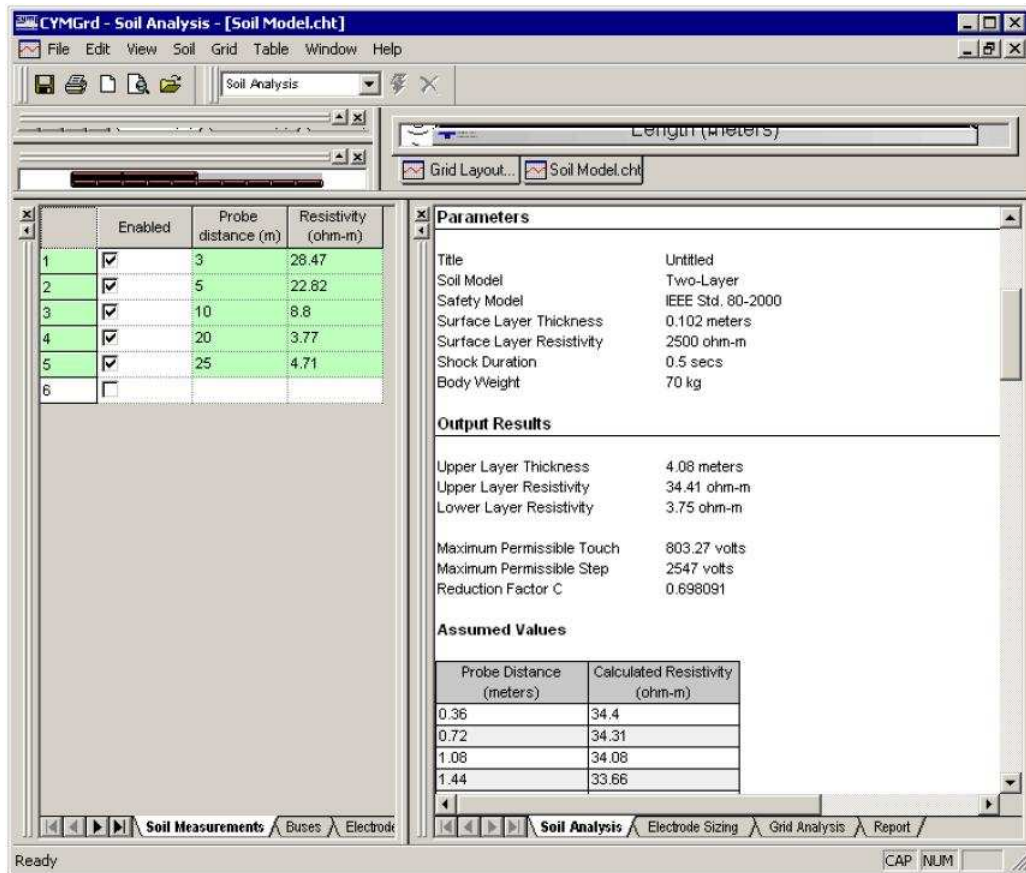


Figure 3.3: Soil Analysis Report View

3.5 Specifying the Soil Model Type

The program calculates the resistivity of the upper and of the lower layers of soil, along with the thickness of the first (upper) layer for a two-layer soil model. The program simply calculates a resistivity for the second (lower) layer which is assumed as ‘infinitely thick’.

The program offers the options of interpreting the soil measurements as an uniform or a two-layer soil model. The possibility of entering any soil model desired (user-defined) is also available. The program will provide only one soil resistivity value, which is the average of all the entered measurements, if an uniform soil model is selected.

All soil data needs to be defined as part of the soil analysis. Thus, the soil data can no longer be bypassed if new soil data are to be used for analyzing the same grid. Once analyzed, the soil data results are still communicated to the grid analysis module.

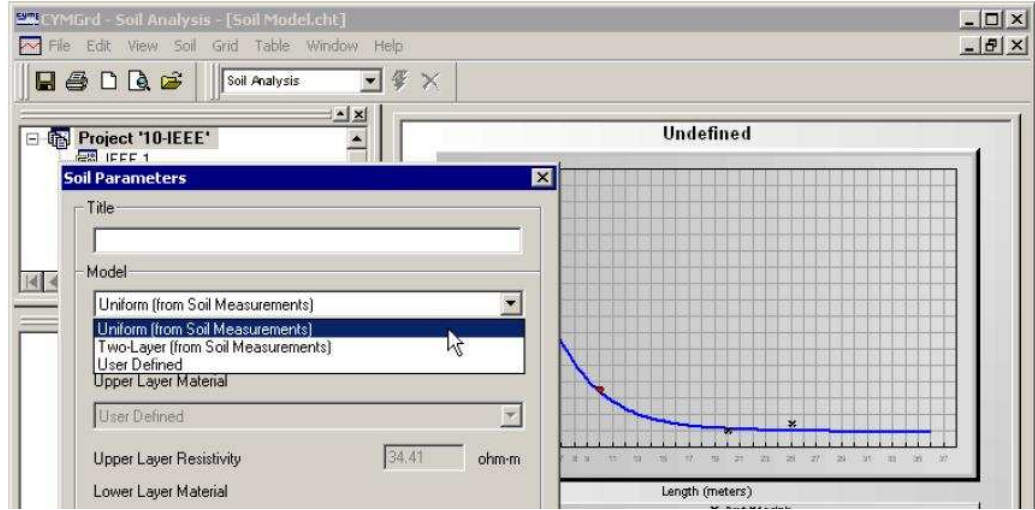


Figure 3.4: Soil Analysis Type View

The results are calculated and transferred automatically to grid analysis module without requiring the user to perform an analysis if an user-defined model is selected as shown in Figure 3.4.

A new calculation must be performed if one or more measurements are changed. The calculation will assure that the new soil model is used by the program for subsequent analysis.

3.6 Performing the Safety Analysis

The maximum permissible touch and step voltages under specific surface and exposure conditions are estimated. The safety assessment calculations comply with standard 'IEEE Guide for Safety in AC Substation Grounding', 2000 edition [1]. The purpose of the calculation is to arrive at a derating factor that will permit to take advantage of the high resistivity surface layer, thus permitting a higher touch voltage to be tolerated. The derating factor C_s can either be calculated as:

$$C_s = 1 - \frac{0.09 \cdot (1 - \rho / \rho_s)}{2h_s + 0.09} \quad (3.7)$$

For a 50 kg body weight:

$$E_{touch50} = (1000 + 1.5C_s \cdot \rho_s) \cdot 0.116 / \sqrt{t_s} \quad (3.8)$$

$$E_{step50} = (1000 + 6.0C_s \cdot \rho_s) \cdot 0.116 / \sqrt{t_s} \quad (3.9)$$

For a 70 kg body weight:

$$E_{touch70} = (1000 + 1.5C_s \cdot \rho_s) \cdot 0.157 / \sqrt{t_s} \quad (3.10)$$

$$E_{step70} = (1000 + 6.0C_s \cdot \rho_s) \cdot 0.157 / \sqrt{t_s} \quad (3.11)$$

where:

- t_s is shock duration in seconds.
- ρ_s is the resistivity of the surface material in ohm-meter.
- C_s is the derating factor when high resistivity surface material is present. The reduction factor C_s is a function of the reflection factor K and the thickness of the upper layer h .
- h_s is the thickness of the high resistivity surface layer material.
- ρ_s is the resistivity of the surface material
- ρ is the resistivity of the earth below the high resistivity surface material.

When calculating the derating factor the program assumes $\rho = \rho_s$ and when calculating maximum permissible touch and step voltages the program assumes $\rho = \rho_s$ for metal to metal calculations (IEEE Std 80-2000).

The safety calculations are the only part of program that uses the surface layer high resistivity and it does so for the sole purpose of calculating the maximum permissible touch and step voltages. Actual potential rise analysis of the grounding assemblies takes into account only the native soil resistivity model reported by the soil analysis.

4. SIMULATIONS OF COMPARATIVE STUDIES

The cases exposed in the Annex B and Annex E of the IEEE Std 80-2000 are used as a reference point [1], for which there are following comparative tables and the corresponding graphs in order to validate the results in this document.

- Case 1: Preliminary design stage. IEEE Std 80-2000, page 129.

Square grid 70 m x 70 m, 100 meshes with no ground rods.

- Case 2: Improved design. IEEE Std 80-2000, page 132.

Square grid 70 m x 70 m, 100 meshes with ground rods placed along the perimeter.

- Case 3: Finalized design. IEEE Std 80-2000, page 137.

Rectangular grid 63 m x 84 m, 108 meshes with ground rods placed along the perimeter and at selected places in the grid in an effort to further minimize surface touch potentials.

- Case 4: L-Shaped Grid with Ground Rods. IEEE Std 80-2000, page 139.

- Case 5: Equally spaced grid with ground rods in two layer soil - Example B.5

IEEE Std 80-2000, page 142.

- Case 6: Unequally spaced grid with ground rods in uniform soil - Example B.6

IEEE Std 80-2000, page 142.

- Case 7: Equivalent uniform soil model for nonuniform soil - Annex E

IEEE Std 80-2000, page 167.

A finite element analysis algorithm is utilized by the program, which is more accurate than the approximate formulas given in the IEEE Std 80-2000. The grounding systems of either symmetrical or asymmetrical configuration of ground conductors and rods can be analyzed by the finite element analysis algorithm.

A detailed written report containing the data and results of the project, specifying the touch and step voltages with its coordinates and corresponding status is possible to obtain by one of most important advantages of the program.

4.1 Square Grid without Ground Rods

The design data are the following ones in Table 4.1 for the considered case:

Table 4.1: Input Data for Grid Design and Safety Calculations of Case 1

Properties	Input Data
Body weight	70 kg
Crushed rock surface layer resistivity	2500 Ω .m
Crushed rock surface layer thickness	0.102 m
Clearing time	0.50 sec
Uniform soil resistivity	400 Ω .m
Max I_G fault current, X/R (Local)	6814 A, 16.2
I_G fault current (Remote)	3180 A
Split factor S_f	0.6
Conductor material	Copper, hard-drawn
Ambient temperature	40 °C
Square grid	70 m x 70 m, 100 meshes
Grid conductor diameter	0.01 m
Burial depth	0.5 m

As well as the maximum real voltages in the system for the calculations are being made, IEEE Std 80-2000 method also gives results for maximum allowable touch and step voltages. The obtained results using both techniques are in Table 4.2 below:

Table 4.2: Comparative Results for Grid Design and Safety Calculations of Case 1

Reference	Max. Allowable Touch Voltage (V)	Max. Allowable Step Voltage (V)	Reduction Factor C_s	R_G (Ω)	GPR (V)
CYMGRD	840.55	2696.10	0.740	2.675	5105.61
IEEE Std 80-2000	838.20	2686.00	0.740	2.780	5304.00

Soil model and three dimensional grid layout are given below in Figure 4.1 and Figure 4.2.

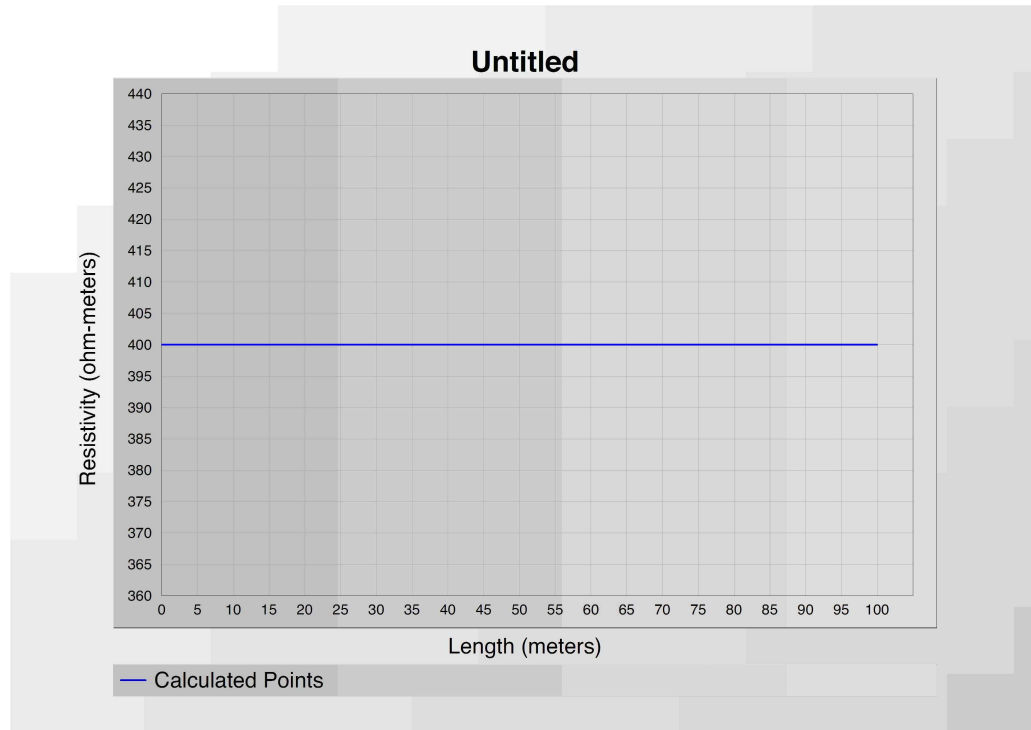


Figure 4.1: Uniform Soil Model for Square Grid without Ground Rods

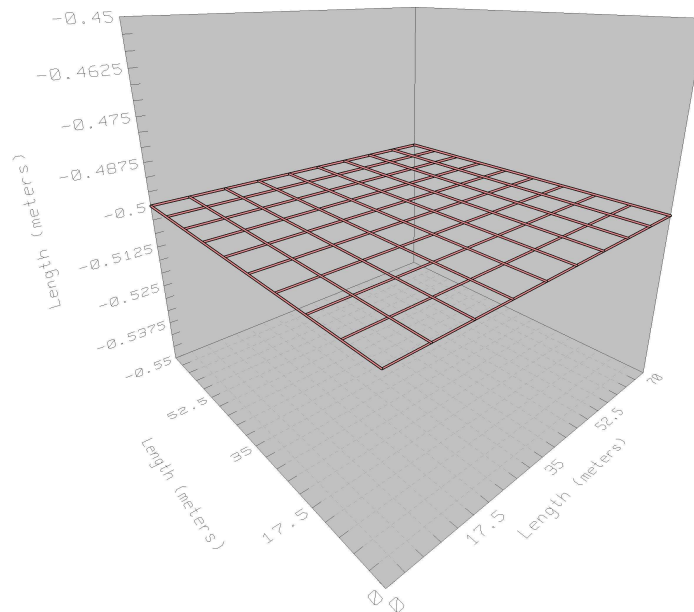


Figure 4.2: 3-D Grid Layout for Square Grid without Ground Rods

Touch voltages contours and two dimensions graphs for touch and step voltages are seen in Figure 4.3 and Figure 4.4. The maximum limit for touch voltages is violated on the corners of the grounding system which can be easily observed as below:

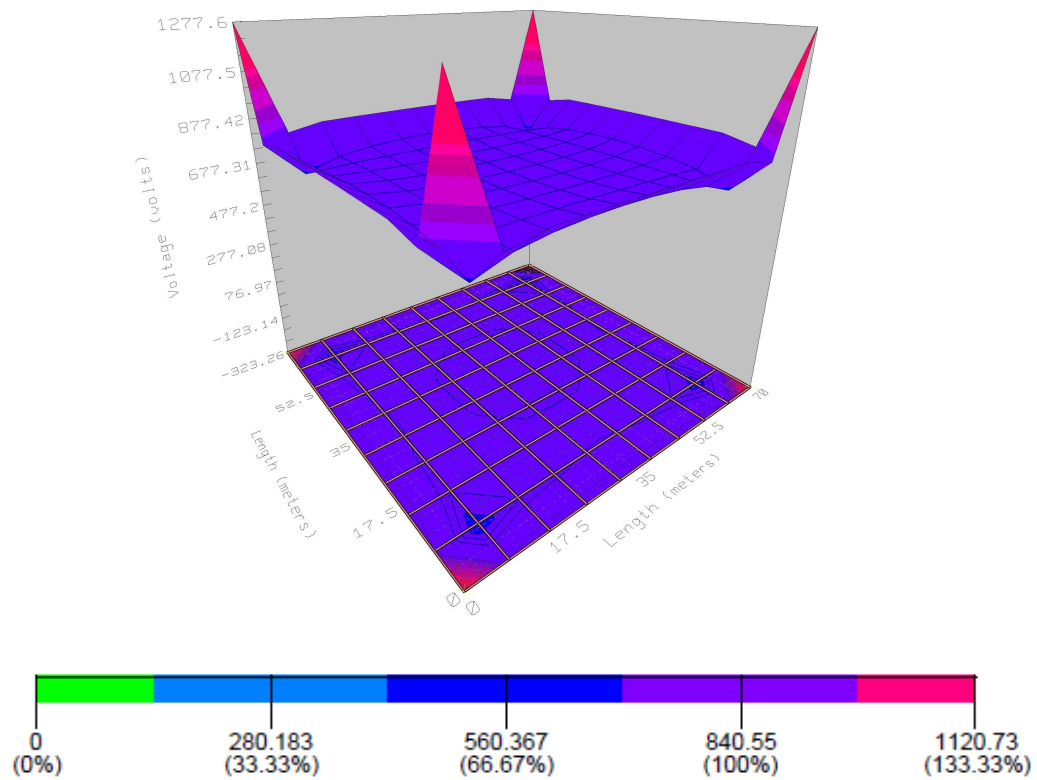


Figure 4.3: Real and Maximum Permissible Potentials Contour Plot for Case 1

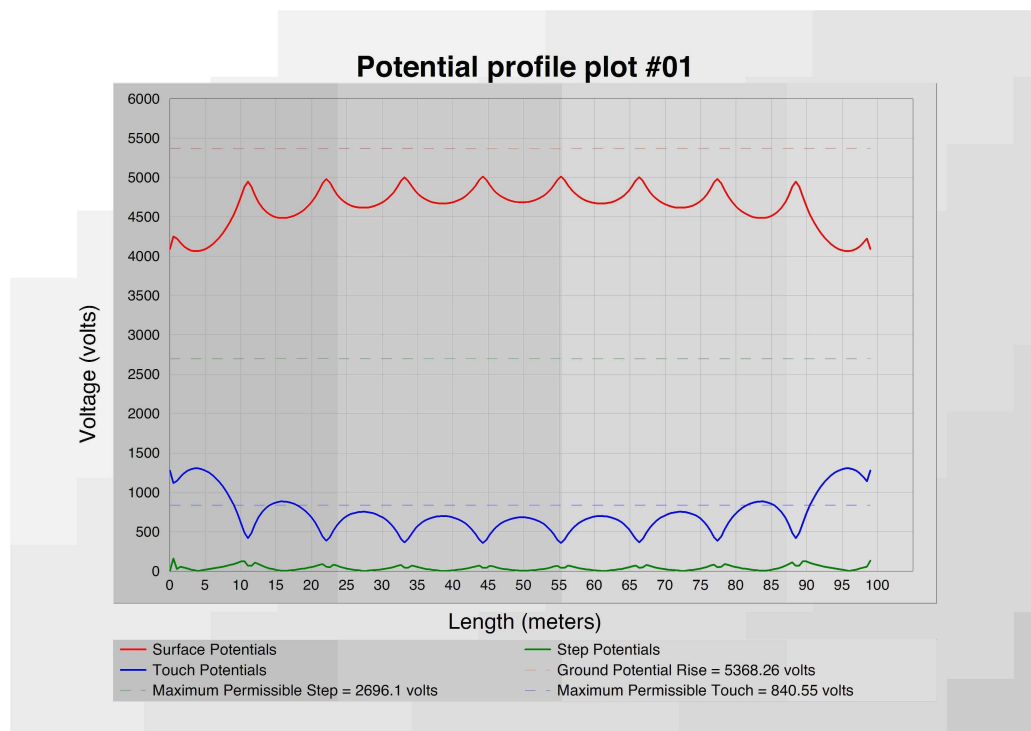


Figure 4.4: Real and Maximum Permissible Potentials Profile Plot for Case 1

4.2 Square Grid with Ground Rods

The design data are the following ones in Table 4.3 for the considered case:

Table 4.3: Input Data for Grid Design and Safety Calculations of Case 2

Properties	Input Data
Body weight	70 kg
Crushed rock surface layer resistivity	2500 Ω .m
Crushed rock surface layer thickness	0.102 m
Clearing time	0.50 sec
Uniform Soil Resistivity	400 Ω .m
Square Grid	70 m x 70 m, 100 meshes
Grid conductor diameter	0.01 m
Length of Ground rods	7.50 m
Ground rod diameter	0.01 m
Burial Depth	0.5 m
Injected ground current	1908 A

The obtained results using both techniques are in Table 4.4 as below:

Table 4.4: Comparative Results for Grid Design and Safety Calculations of Case 2

Reference	Max. Allowable Touch Voltage (V)	Max. Allowable Step Voltage (V)	Reduction Factor C_s	R_G (Ω)	GPR (V)
CYMGRD	840.55	2696.10	0.740	2.500	4780.00
IEEE Std 80-2000	838.20	2686.00	0.740	2.750	5247.00

Soil model and three dimensional grid layout are given below in Figure 4.5 and Figure 4.6.

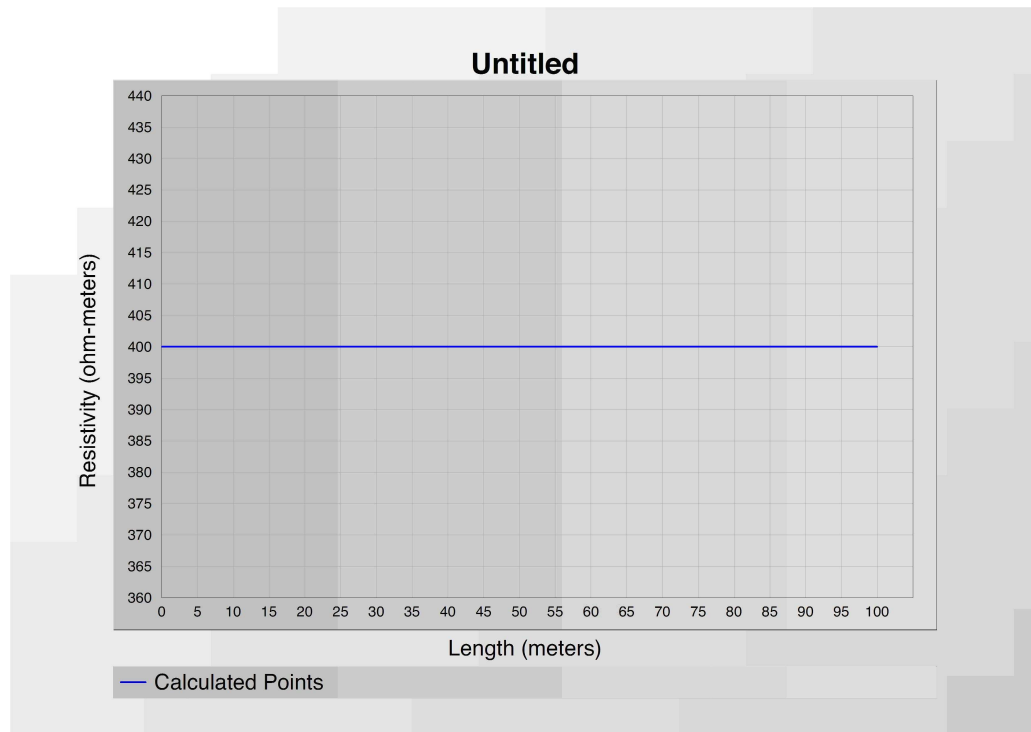


Figure 4.5: Uniform Soil Model for Square Grid with Ground Rods

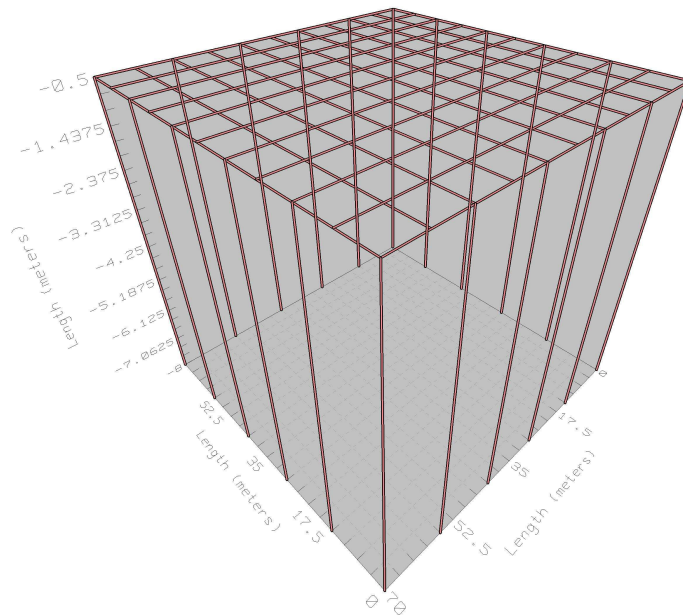


Figure 4.6: 3-D Grid Layout for Square Grid with Ground Rods

Touch voltages contours and two dimensions graphs for touch and step voltages are seen in Figure 4.7 and Figure 4.8 as below:

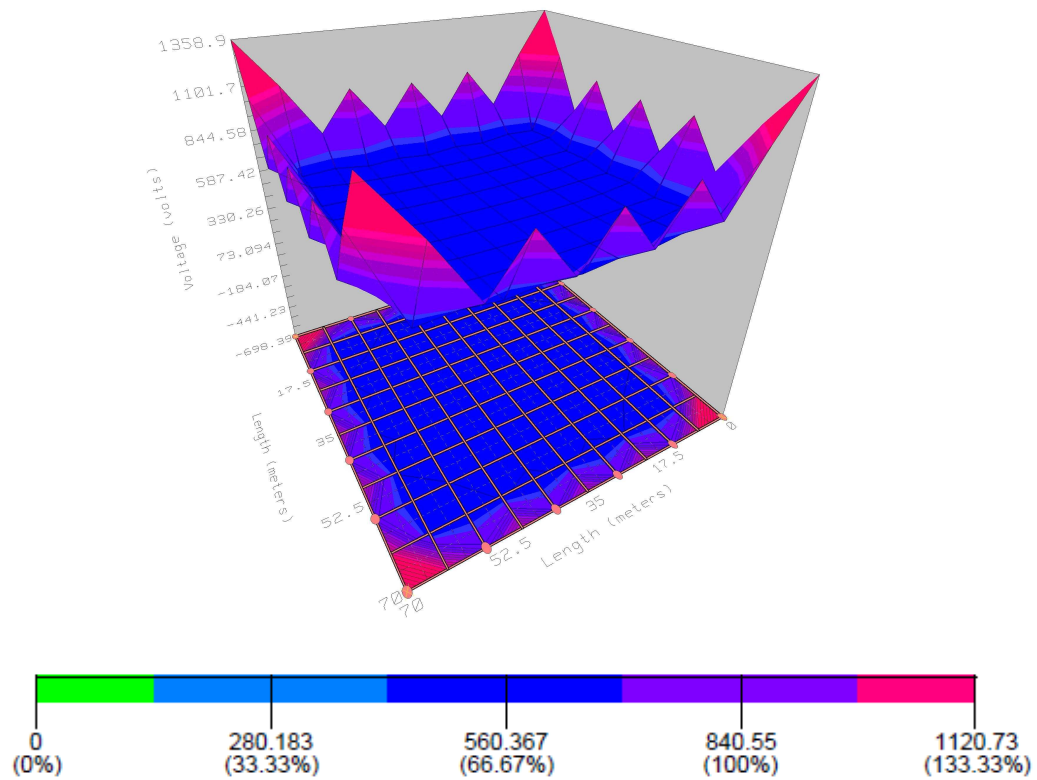


Figure 4.7: Real and Maximum Permissible Potentials Contour Plot for Case 2

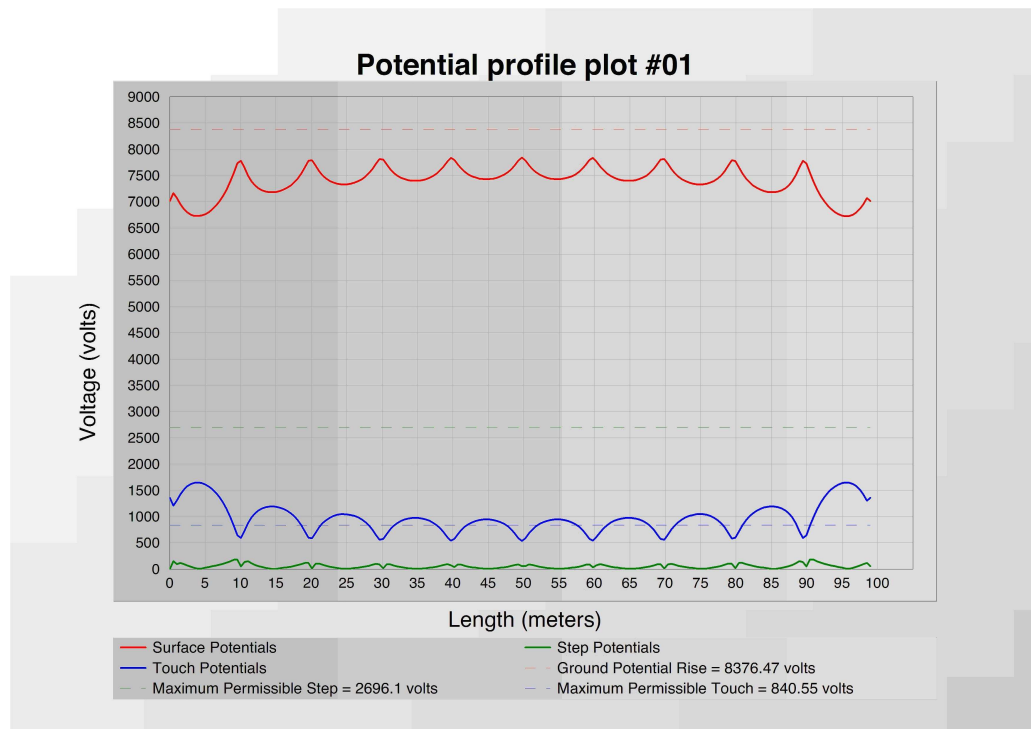


Figure 4.8: Real and Maximum Permissible Potentials Profile Plot for Case 2

4.3 Rectangular Grid with Ground Rods

A rectangular mesh consisting of vertical ground rods is extracted from IEEE Std 80-2000 annexes. The design data are the following ones in Table 4.5 for the considered case:

Table 4.5: Input Data for Grid Design and Safety Calculations of Case 3

Properties	Input Data
Body weight	70 kg
Crushed rock surface layer resistivity	2500 Ω .m
Crushed rock surface layer thickness	0.102 m
Clearing time	0.50 sec
Uniform Soil Resistivity	400 Ω .m
Rectangular Grid	63 m x 84 m, 108 meshes
Grid conductor diameter	0.01 m
Length of Ground rods	10.0 m
Ground rod diameter	0.01 m
Burial Depth	0.5 m
Injected ground current	1908 A

The obtained results using both techniques are in Table 4.6 as below:

Table 4.6: Comparative Results for Grid Design and Safety Calculations of Case 3

Reference	Max. Allowable Touch Voltage (Volt)	Max. Allowable Step Voltage (Volt)	Reduction Factor C_s	R_G (Ohm)	GPR (Volt)
CYMGRD	840.55	2696.10	0.740	2.278	4348.00
IEEE Std 80-2000	838.20	2686.00	0.740	2.620	4998.96

Soil model and three dimensional grid layout are given below in Figure 4.9 and Figure 4.10

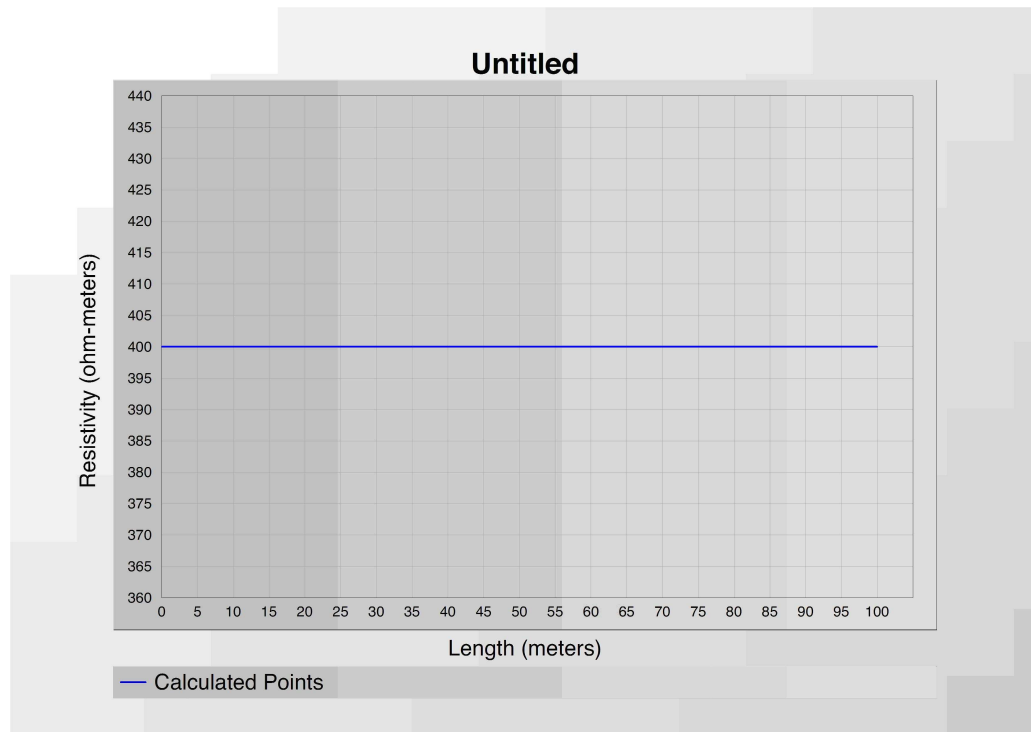


Figure 4.9: Uniform Soil Model for Rectangular Grid with Ground Rods

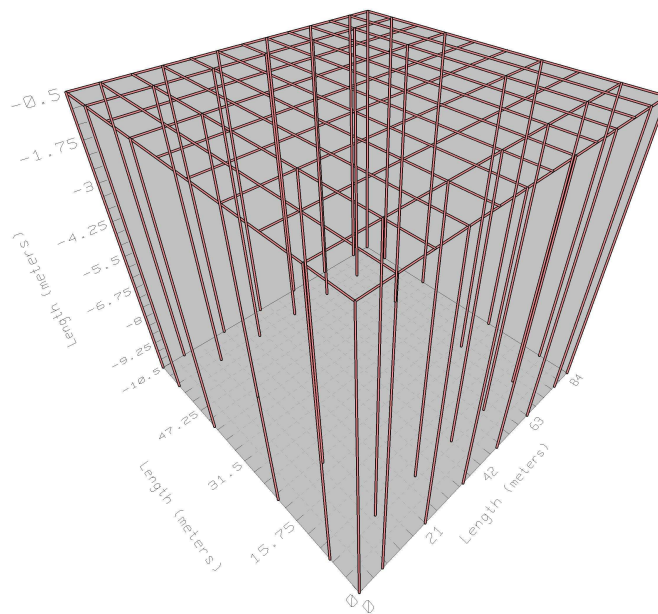


Figure 4.10: 3-D Grid Layout for Rectangular Grid with Ground Rods

Touch voltages contours and two dimensions graphs for touch and step voltages are seen in Figure 4.11 and Figure 4.12 as below:

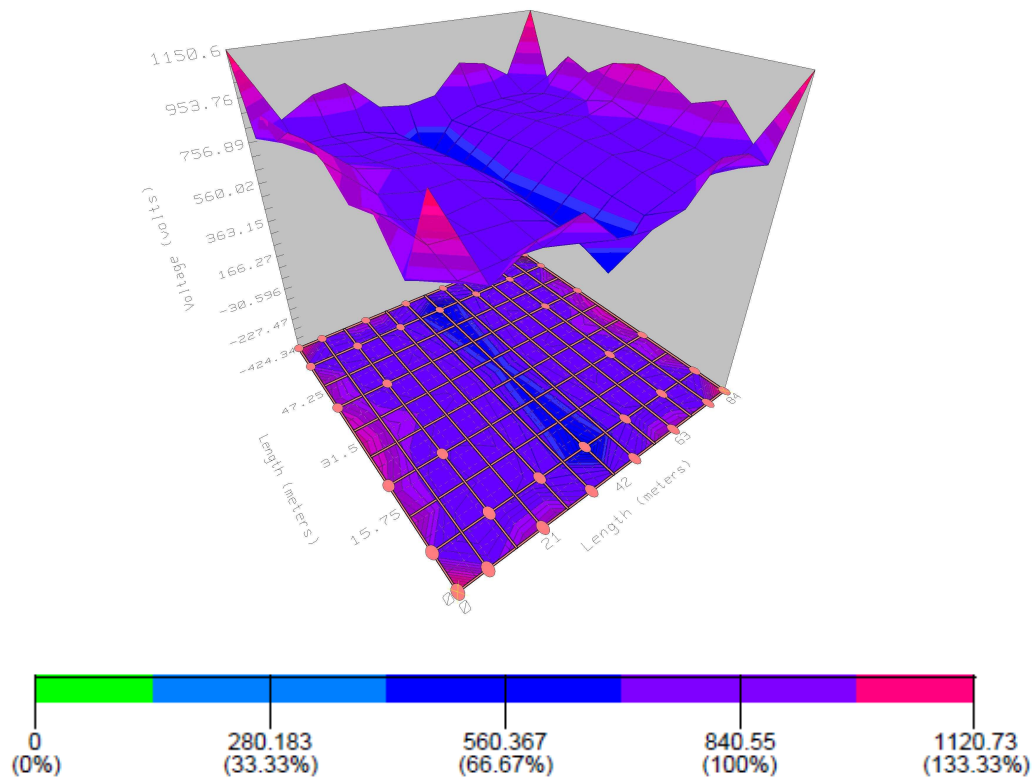


Figure 4.11: Real and Maximum Permissible Potentials Contour Plot for Case 3

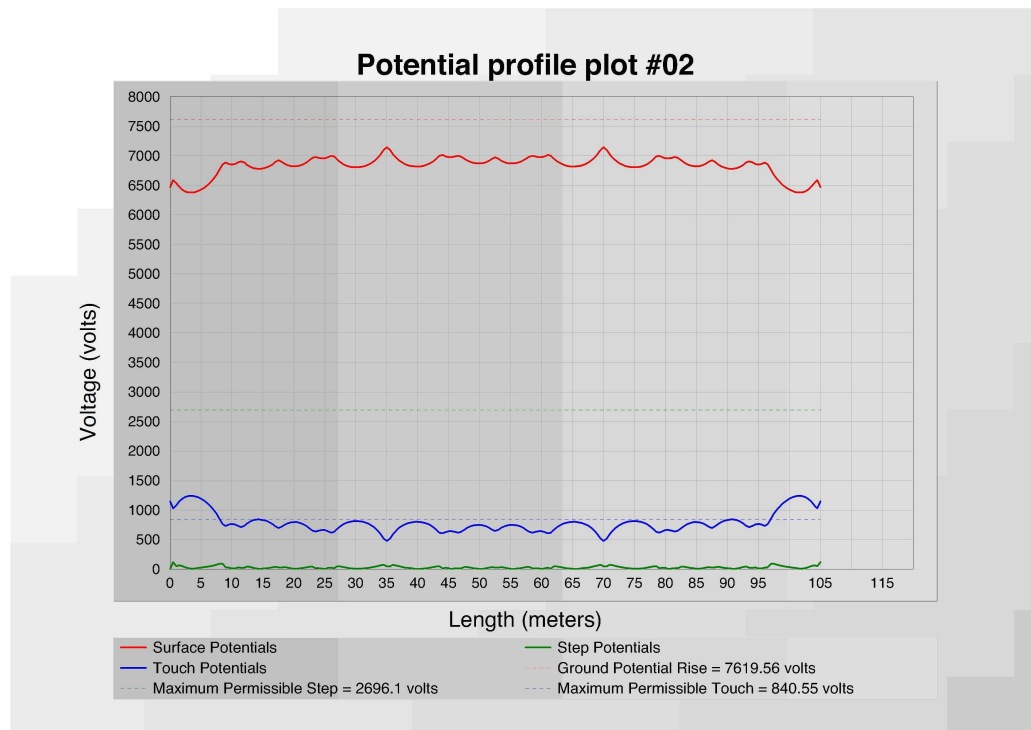


Figure 4.12: Real and Maximum Permissible Potentials Profile Plot for Case 3

4.4 L-Shaped Grid with Ground Rods

The design data are the following ones in Table 4.7 for the considered case:

Table 4.7: Input Data for Grid Design and Safety Calculations of Case 4

Properties	Input Data
Body weight	70 kg
Crushed rock surface layer resistivity	2500 Ω .m
Crushed rock surface layer thickness	0.102 m
Clearing time	0.50 sec
Uniform Soil Resistivity	400 Ω .m
L-Shaped Grid	70 m x 105 m, 100 meshes
Grid conductor diameter	0.01 m
Length of Ground rods	10.0 m
Ground rod diameter	0.01 m
Burial Depth	0.5 m
Injected ground current	1908 A

The obtained results using both techniques are in Table 4.8 as below:

Table 4.8: Comparative Results for Grid Design and Safety Calculations of Case 4

Reference	Max. Allowable Touch Voltage (V)	Max. Allowable Step Voltage (V)	Reduction Factor C_s	R_G (Ω)	GPR (V)
CYMGRD	840.55	2696.10	0.740	2.330	4562.49
IEEE Std 80-2000	838.20	2686.00	0.740	2.740	5227.92

Soil model and three dimensional grid layout are given below in Figure 4.13 and Figure 4.14.

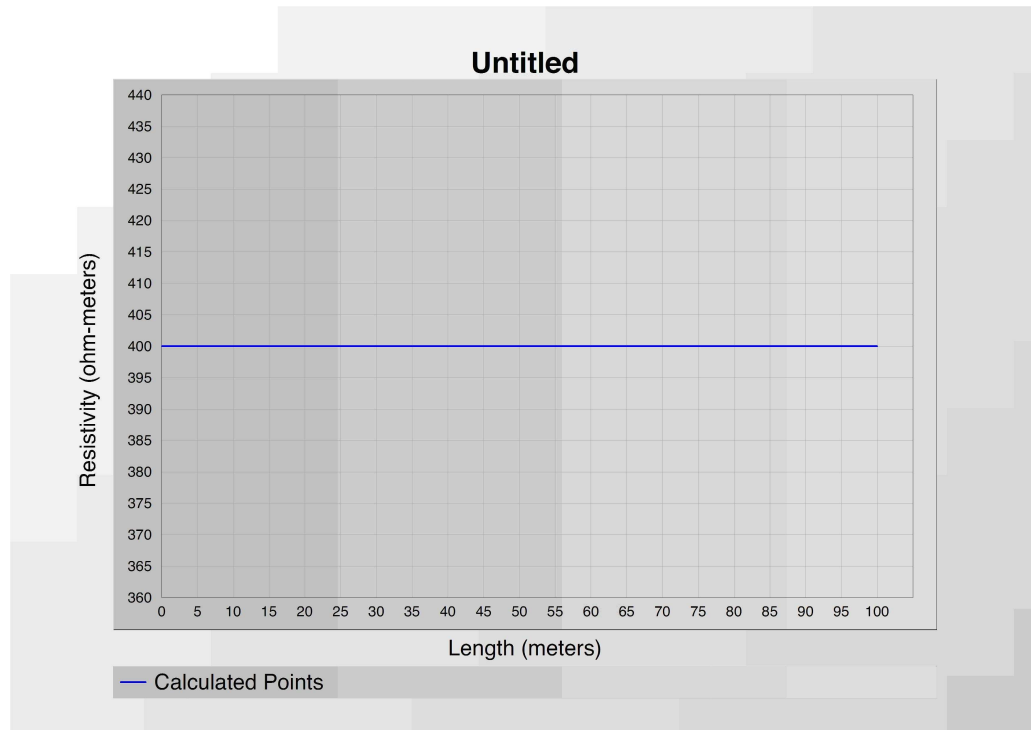


Figure 4.13: Uniform Soil Model for L-Shaped Grid with Ground Rods

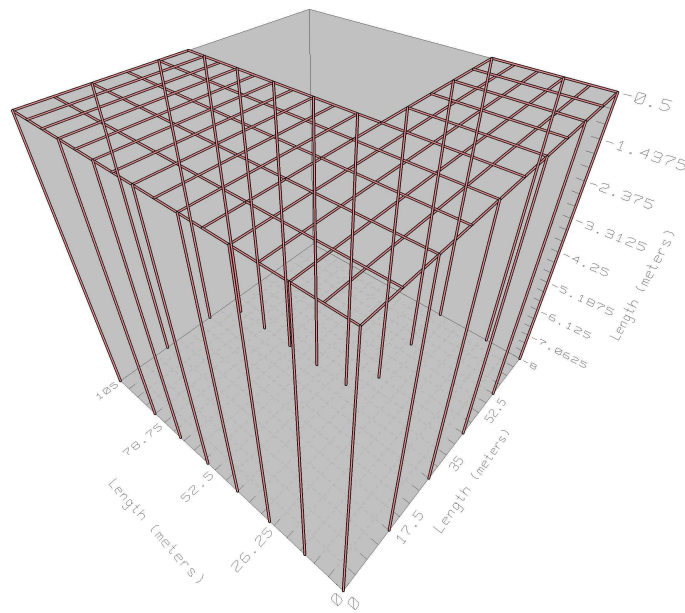


Figure 4.14: 3-D Grid Layout for L-Shaped Grid with Ground Rods

Touch voltages contours and two dimensions graphs for touch and step voltages are seen in Figure 4.15 and Figure 4.16 as below:

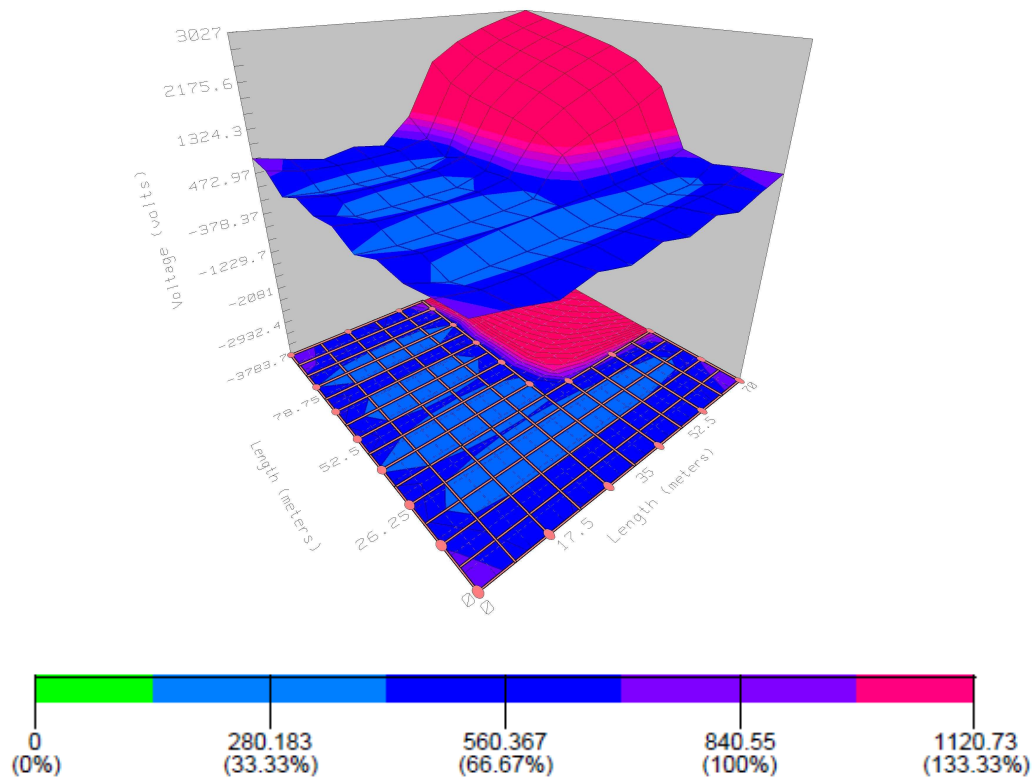


Figure 4.15: Real and Maximum Permissible Potentials Contour Plot for Case 4

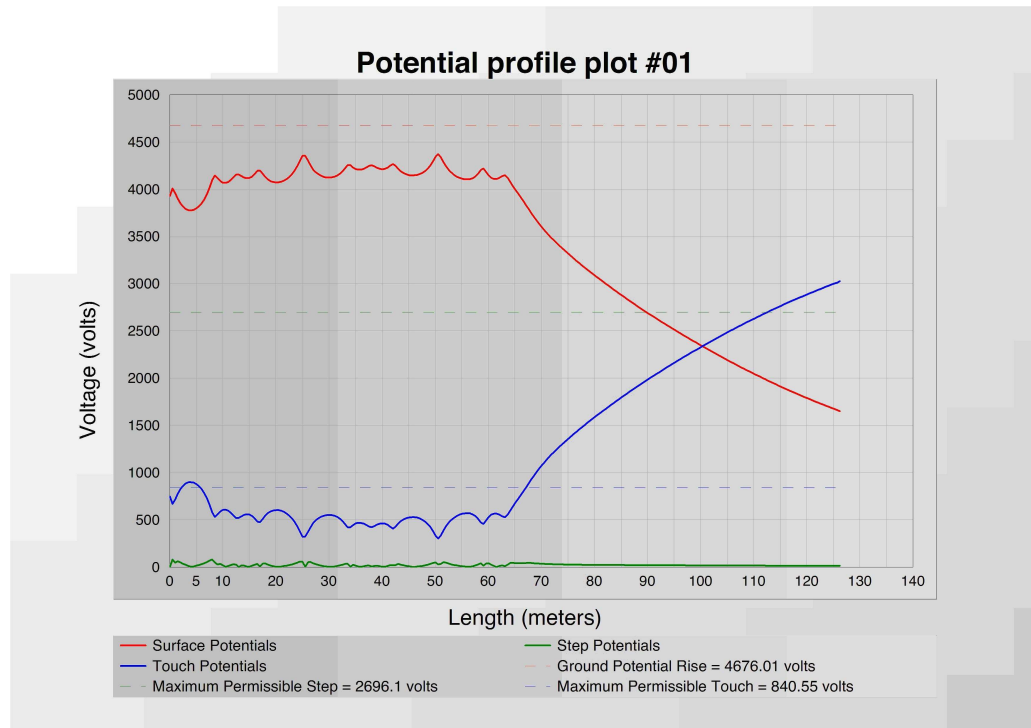


Figure 4.16: Real and Maximum Permissible Potentials Profile Plot for Case 4

4.5 Equally Spaced Grid with Rods in Two Layer Soil

The design data are the following ones in Table 4.9 for the considered case:

Table 4.9: Input Data for Grid Design and Safety Calculations of Case 5

Properties	Input Data
Body weight	70 kg
Crushed rock surface layer resistivity	2500 Ω .m
Crushed rock surface layer thickness	0.1 m
Upper layer soil resistivity	300 Ω .m
Upper layer thickness	4.572 m
Lower layer soil resistivity	100 Ω .m
Equally spaced square grid	60.96 m x 60.96 m, 16 meshes
Grid conductor diameter	0.01 m
Burial depth	0.5 m
Length of ground rods	9.144 m
Ground rod diameter	0.0127 m
Clearing time	0.50 sec
Injected ground current	1908 A

The obtained results using both techniques are in Table 4.10 as below:

Table 4.10: Comparative Results for Grid Design and Safety Calculations of Case 5

Reference	Max. Allowable Touch Voltage (V)	Max. Allowable Step Voltage (V)	Reduction Factor C_s	R_G (Ω)	GPR (V)
CYMGRD	840.55	2696.10	0.740	2.330	4562.49
IEEE Std 80-2000	838.20	2686.00	0.740	2.740	5227.92

Soil model and three dimensional grid layout are given below in Figure 4.17 and Figure 4.18.

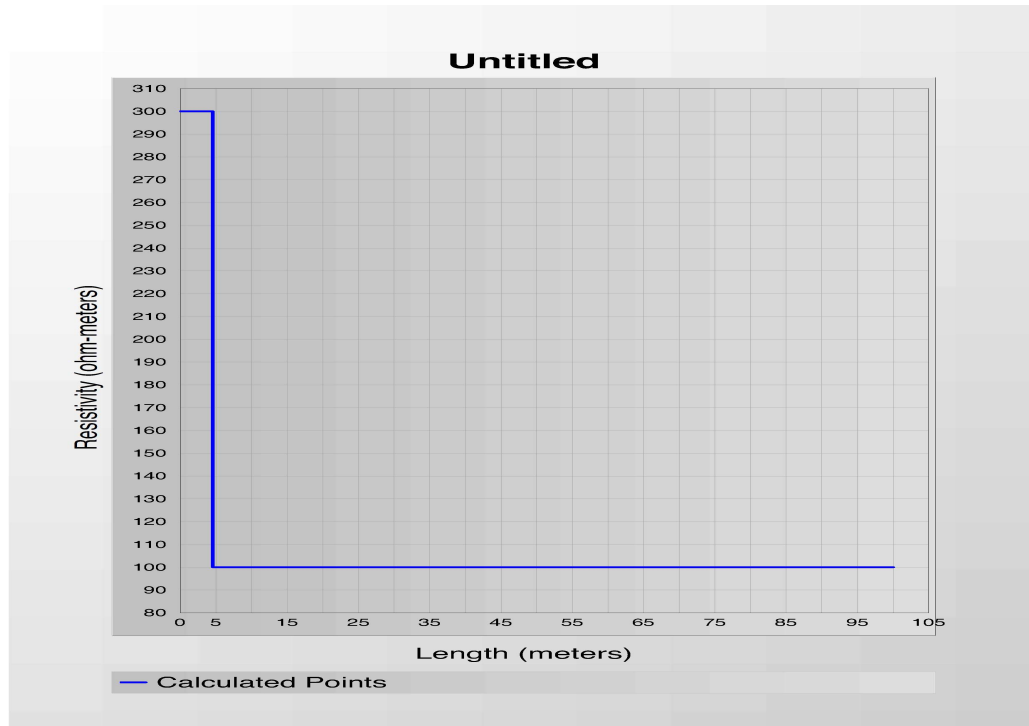


Figure 4.17: Two-Layer Soil Model for Equally Spaced Grid with Ground Rods

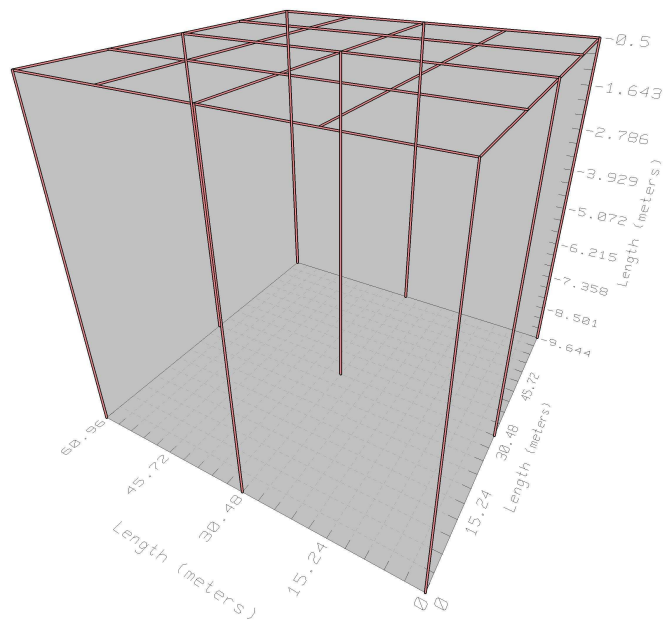


Figure 4.18: 3-D Grid Layout for Equally Spaced Grid with Ground Rods

Touch voltages contours and two dimensions graphs for touch and step voltages are seen in Figure 4.19 and Figure 4.20 as below:

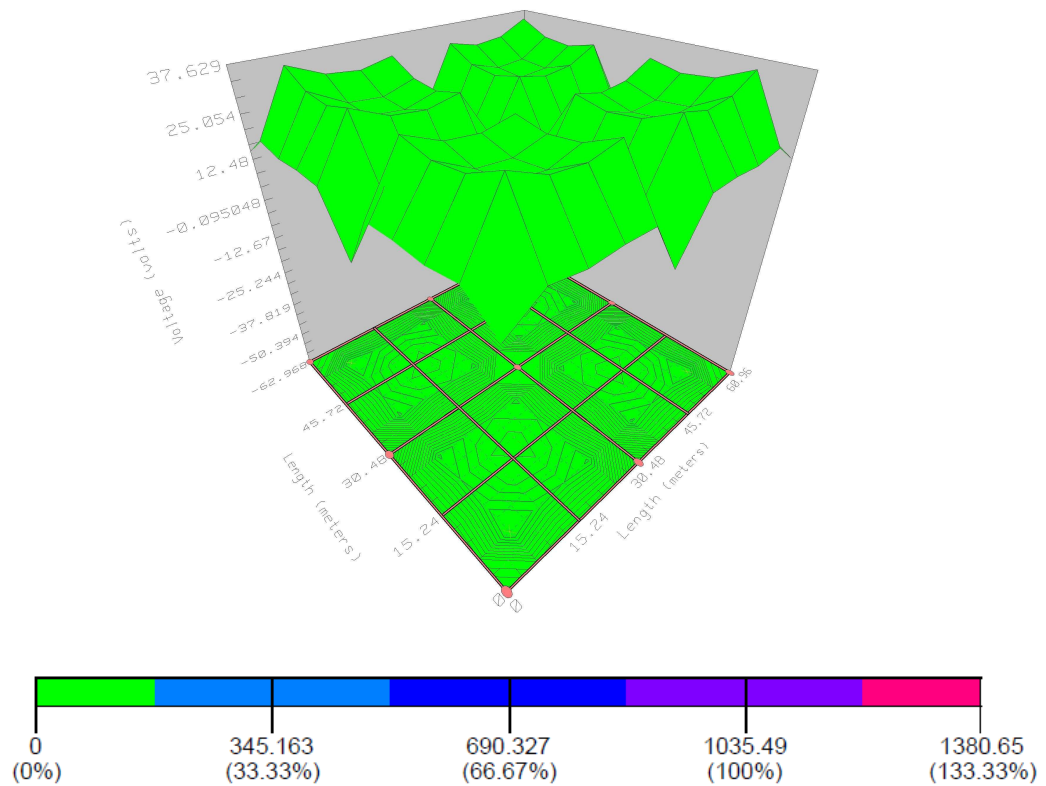


Figure 4.19: Real and Maximum Permissible Potentials Contour Plot for Case 5

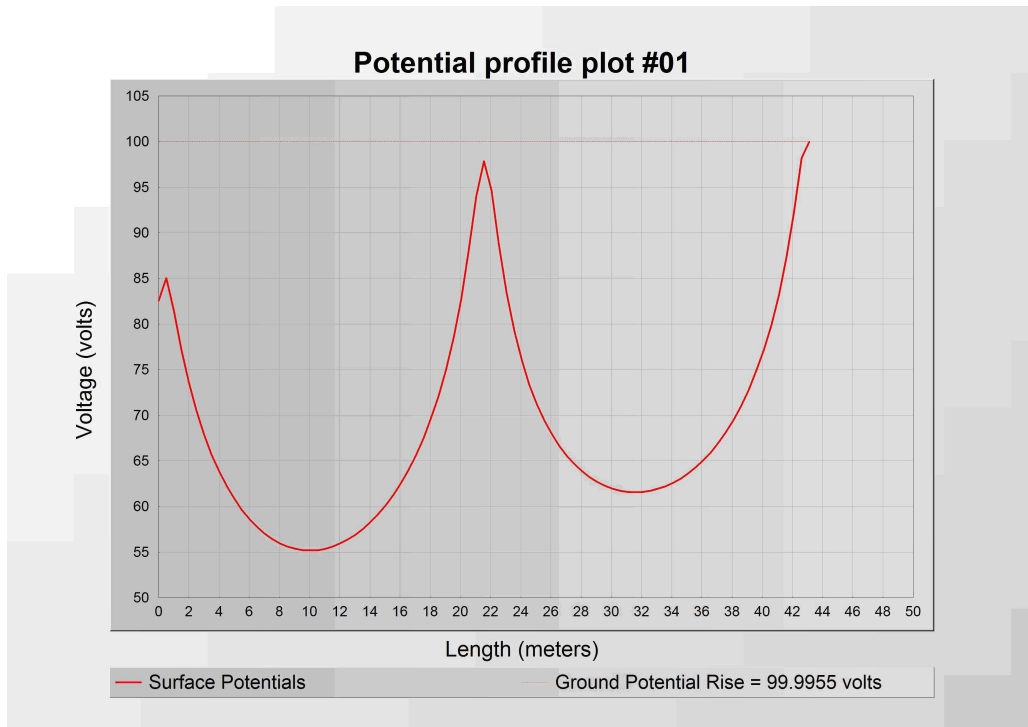


Figure 4.20: Real and Maximum Permissible Potentials Profile Plot for Case 5

4.6 Unequally Spaced Grid with Grid Rods in Uniform Soil

The design data are the following ones in Table 4.11 for the considered case:

Table 4.11: Input Data for Grid Design and Safety Calculations of Case 5

Properties	Input Data
Body weight	70 kg
Crushed rock surface layer resistivity	2500 Ω .m
Crushed rock surface layer thickness	0.1 m
Uniform soil resistivity	300 Ω .m
Unequally spaced square grid	91.44 m x 91.44 m, 64 meshes
Grid conductor diameter	0.01 m
Burial depth	0.5 m
Length of ground rods	9.2 m
Ground rod diameter	0.0127 m
Clearing time	0.5 sec
Injected ground current	1908 A

The obtained results using both techniques are in Table 4.12 as below:

Table 4.12: Comparative Results for Grid Design and Safety Calculations of Case 5

Reference	Max. Allowable Touch Voltage (V)	Max. Allowable Step Voltage (V)	Reduction Factor C_s	R_G (Ω)	GPR (V)
CYMGRD	840.55	2696.10	0.740	2.330	4562.49
IEEE Std 80-2000	838.20	2686.00	0.740	2.740	5227.92

Soil model and three dimensional grid layout are given below in Figure 4.21 and Figure 4.22

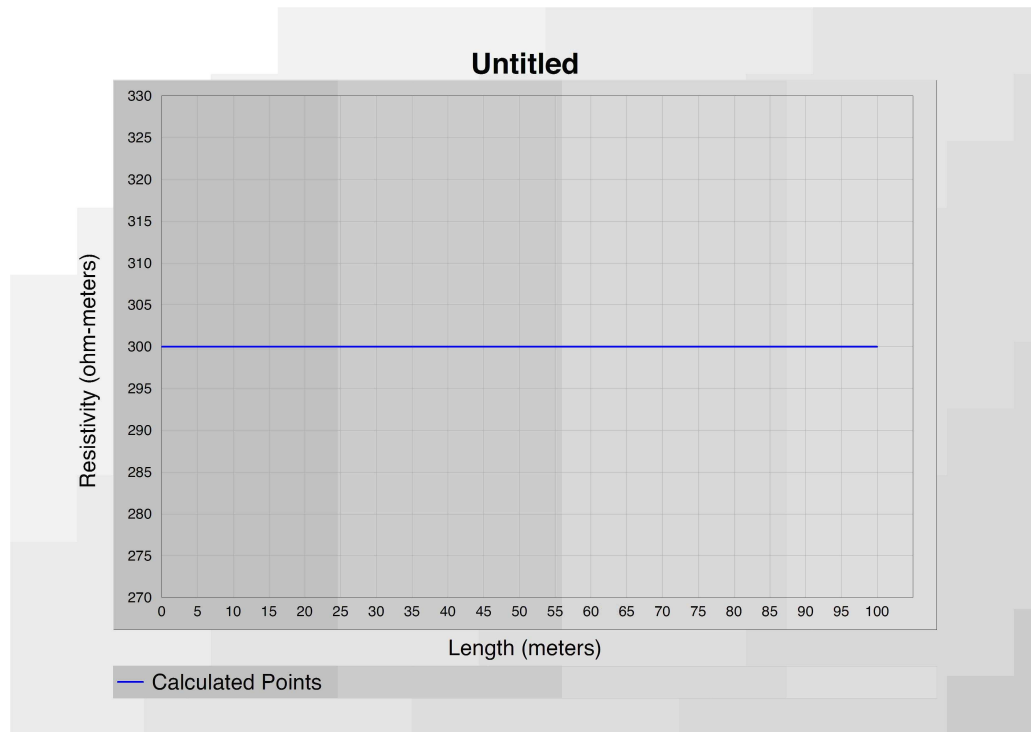


Figure 4.21: Uniform Soil Model for Unequally Spaced Grid with Ground Rods

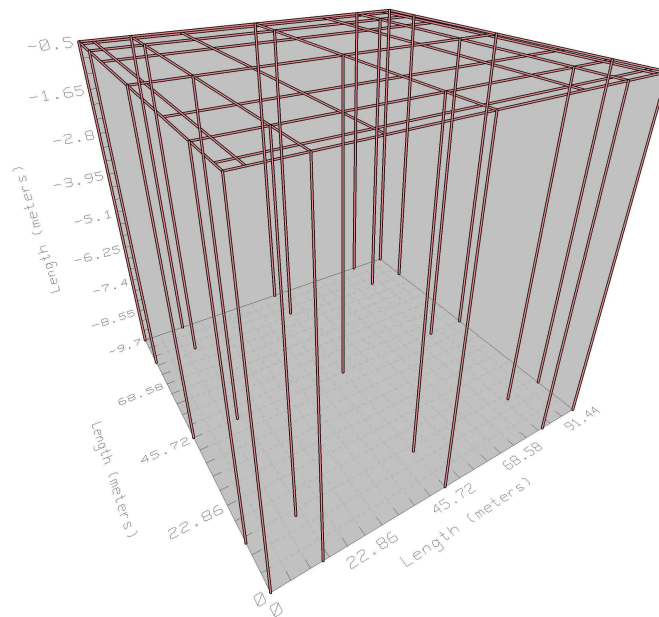


Figure 4.22: 3-D Grid Layout for Unequally Spaced Grid with Ground Rods

Touch voltages contours and two dimensions graphs for touch and step voltages are seen in Figure 4.23 and Figure 4.24 as below:

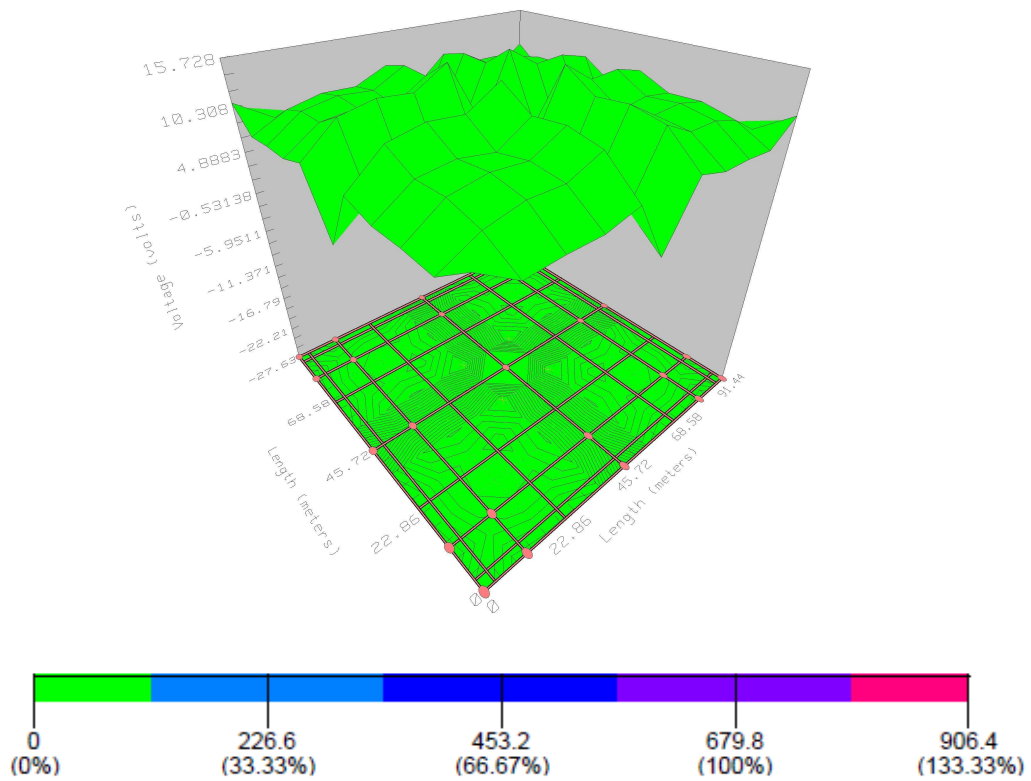


Figure 4.23: Real and Maximum Permissible Potentials Contour Plot for Case 6

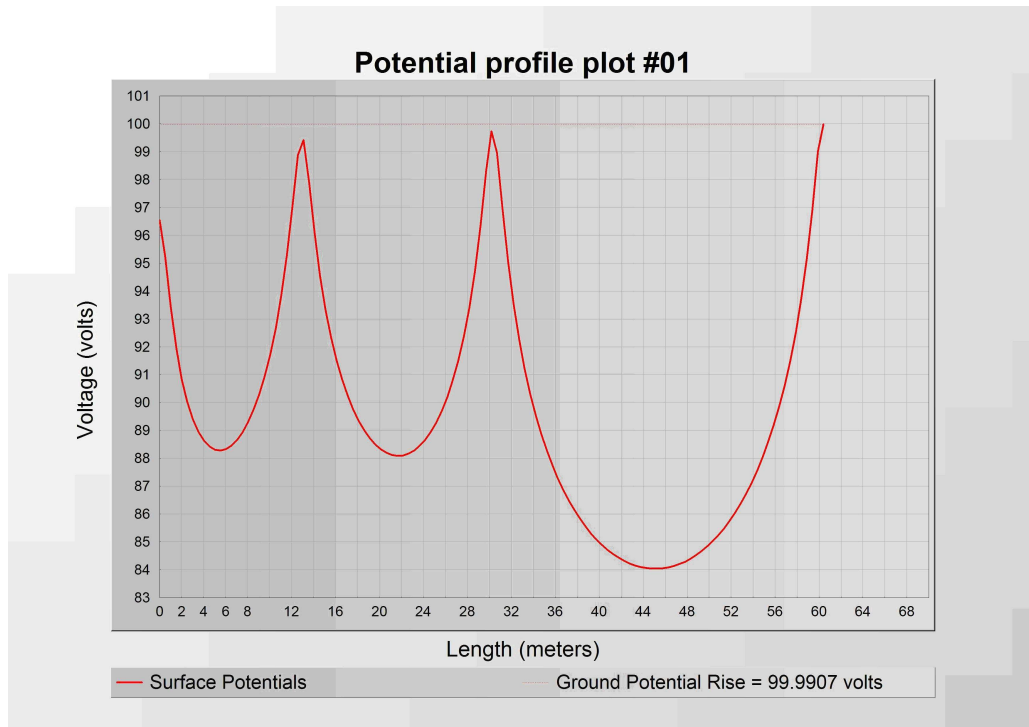


Figure 4.24: Real and Maximum Permissible Potentials Profile Plot for Case 6

4.7 Equivalent Uniform Soil Model for Nonuniform Soil

The design data are the following ones in Table 4.13 and in Table 4.14 for the considered cases:

Table 4.13: Ground parameters computed with two-layer soil compared with those computed with equivalent uniform soil model

Soil type	Computed grounding parameters with two-layer soil model				Computed grounding parameters with uniform soil model			
	ρ_1, ρ_2, h $\Omega.m, \Omega.m, m$	R_g Ω	$E_m(V)$	$E_s(V)$	ρ_{av2} $\Omega.m$	R_g Ω	$E_m(V)$	$E_s(V)$
1	100, 300, 6.1	1.28	126	85	158	0.89	151	86
2	300, 100, 6.1	0.72	187	92	193	1.09	185	106

Table 4.14: Calculated resistance and apparent resistivity data for soil type 1 and soil type 2 based on the four-pin method

Probe separation		Soil type 1		Soil type 2	
(ft)	(m)	Resistance Ω	Apparent resistivity $\rho_a, \Omega.m$	Resistance Ω	Apparent resistivity $\rho_a, \Omega.m$
1	0.305	29.73	56.94	89.13	170.74
3	0.915	15.33	88.07	45.85	263.46
5	1.524	9.97	95.48	29.55	283.06
15	4.573	3.85	110.71	9.39	269.67
20	6.098	3.15	120.76	6.46	247.57
30	9.146	2.49	143.10	3.52	202.12
50	15.244	1.90	181.70	1.50	144.05
70	21.341	1.56	208.78	0.90	120.28
90	27.439	1.32	227.75	0.64	110.68
110	33.537	1.15	241.48	0.51	106.41
130	39.634	1.01	251.77	0.42	104.34
150	45.731	0.90	259.76	0.36	103.16

Soil models for both types are seen in Figure 4.25 and Figure 4.26.

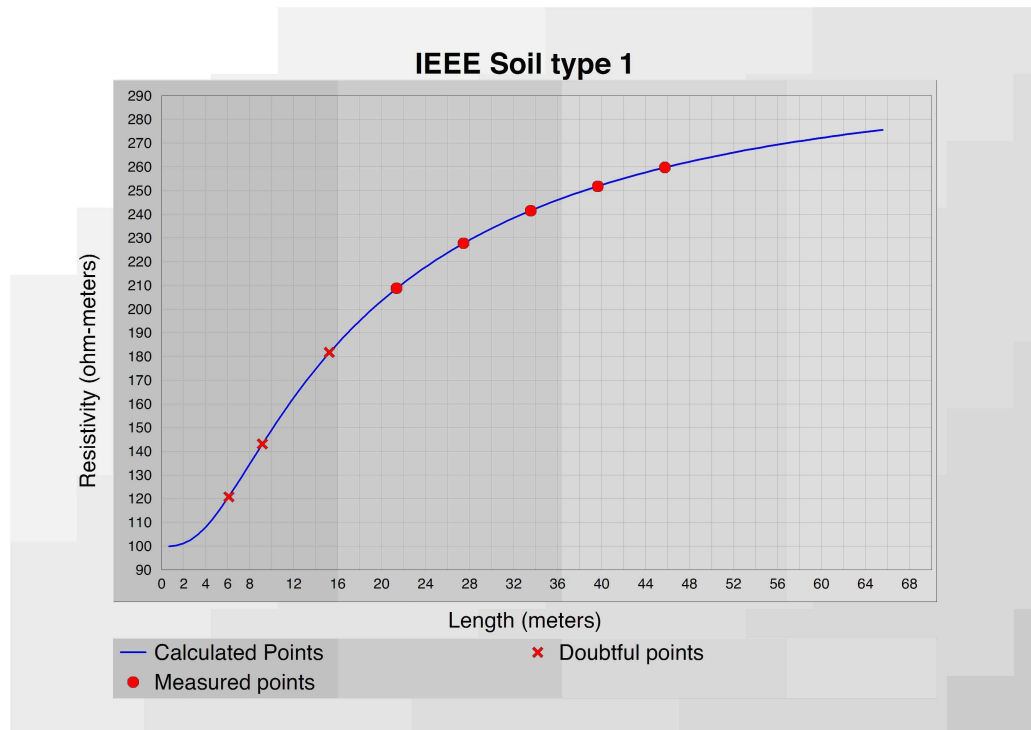


Figure 4.25: Soil Model for Type 1

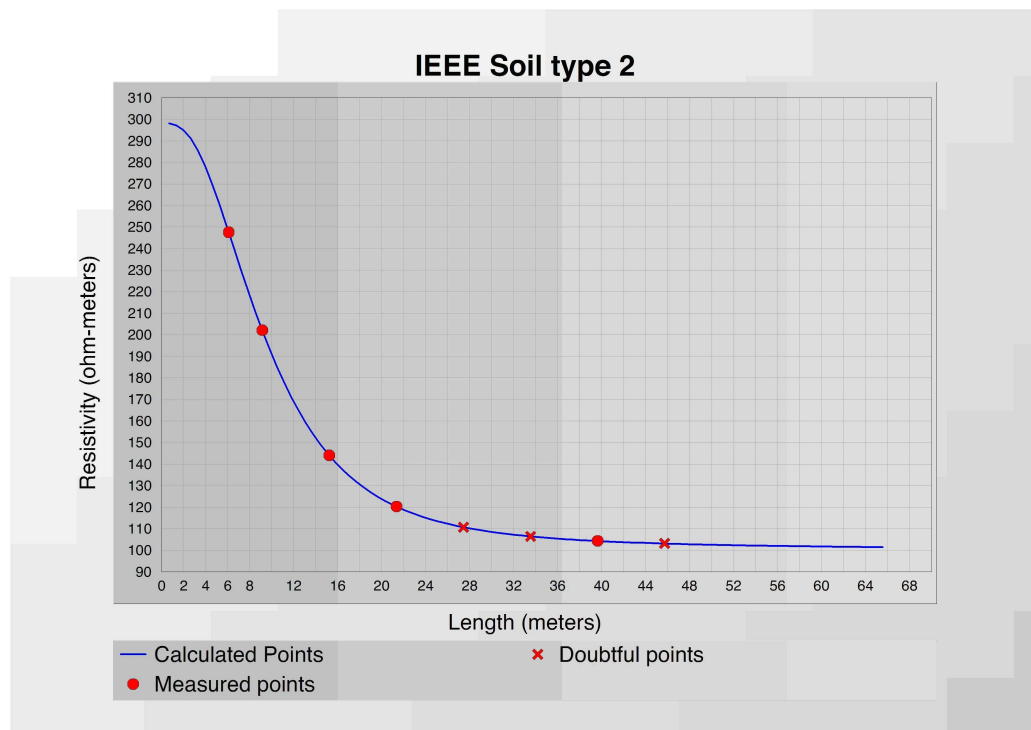


Figure 4.26: Soil Model for Type 2

5. CASE STUDY OF 380/34.5 kV AIR INSULATED SUBSTATION

5.1 Introduction

Planning, calculations and measurements of earthing systems can be performed according to regulations like the European harmonization document CENELEC [14] or IEEE Std. 80-2000 [1]. The basic values for both of these procedures are the maximum earth fault currents and the fault duration of the different voltage levels. As parts of the fault current return within the earthing system such as transformer neutrals, earth wire, cable sheath, etc. only the remaining part has to be considered for the design of earthing system of the high voltage station. Determination of the resulting current flowing into the earth electrodes is therefore an important task.

Another factor of importance is the knowledge of the decisive soil resistivity for an extended earthing system. Special measurements are necessary to consider the electric conditions in larger depth and the structure in different layers.

Planning and design of the earthing system of 380/34.5 kV air insulated substation case study is performed according to IEEE 80 Std 2000.[1]

5.2 Prerequisites

5.2.1 Description of the Site

380/34.5 kV air insulated substation case study covers a 180 m x 130 m rectangular shaped grid area of $A = 23400 \text{ m}^2$ and peripheral length $L_p = 620 \text{ m}$ with a boundary fence surrounds the whole substation.

5.2.2 Network Data

380 kV system has the following properties given in Table 5.1:

Table 5.1: Parameters of Network

Properties	Input Data
Frequency	$f = 50 \text{ Hz}$
Type of neutral treatment	System with neutral grounding
Maximum three phase short circuit current	$I_{sc3} = 50 \text{ kA}$
Maximum single phase short circuit current	$I_{sc1} = 35 \text{ kA}$
Fault duration for thermal design	$t_f = 0.5 \text{ s}$
Shock duration	$t_s = 0.5 \text{ s}$

5.3 Specific Soil Resistivity

The apparent specific soil resistivity is calculated by program using two layer analysis based on the following test result using Wenner method seen in Figure 5.1:

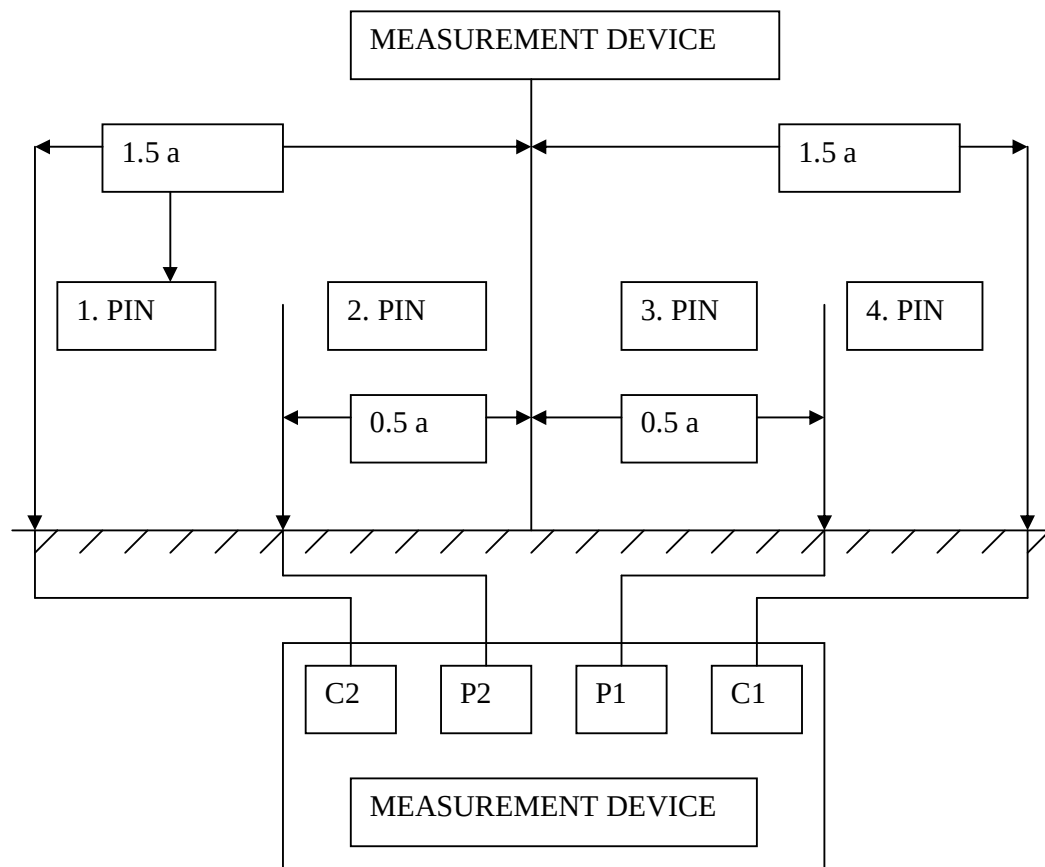


Figure 5.1: Wenner Method Wiring Diagram

Table 5.2: Earth Resistivity Measurement Results

Experiment Date:				12/10/2008		
Substation Name:				Case Study		
Ambient Temperature				18°C		
Moisture				%50		
Measurement Device Type				Digital Earthing Megger Geohm B4151		
Test No	1.5 a (m)	0.5 a (m)	a (m)	$2\pi a$	R1 (Ω)	$2\pi a R_1$
1	0.75	0.25	0.5	3.14	51.2	160.768
2	1.5	0.5	1	6.28	25.8	162.024
3	2.25	0.75	1.5	9.42	12.4	116.808
4	3	1	2	12.56	6.33	79.5048
5	3.75	1.25	2.5	15.7	3.66	57.462
6	4.5	1.5	3	18.84	2.68	50.4912
7	6	2	4	25.12	1.92	48.2304
8	7.5	2.5	5	31.4	1.17	36.738
9	9	3	6	37.68	0.88	33.1584
10	12	4	8	50.24	0.52	26.1248
11	15	5	10	62.8	0.45	28.26
12	18	6	12	75.36	0.33	24.8688
13	21	7	14	87.92	0.27	23.7384
14	24	8	16	100.48	0.19	19.0912

According to earth resistivity measurement results given in Table 5.2, the decisive soil resistivity for the substation area is $\rho = 24.17 \Omega.m$.

A layer of crushed rock will cover the area of the substation. For this layer the following resistivity is considered as $\rho_s = 2500 \Omega.m$.

5.4 Thermal Design of Earthing Conductors and Earth Electrodes

The selection of earthing conductor sizes is carried out with respect to the fault current, the maximum fault duration, final temperature and mechanical stresses. Considering multiple faults, it is common practice to carry out the thermal design of earthing systems with respect to rated current of switchgear and fault duration with $t_s = 0.5$ s.

The required cross section for earthing conductors and earth electrodes carrying the maximum earth fault current can be calculated with parameters given below:

Table 5.3: Parameters for Cross Section of the Earthing Conductor

Properties	Input Data
Maximum earth fault current	$I_{sc3} = 50 \text{ kA}$
Reflected earth fault current	$I_{sc1} = 35 \text{ kA}$
Maximum allowable temperature for copper	$T_m = 1083 \Delta^\circ\text{C}$
Ambient temperature	$T_a = 40 \Delta^\circ\text{C}$
Material constant for copper	$K_0 = 242 \Delta^\circ\text{C}$
Thermal capacity factor for copper	$T_{CAP} = 3.42 \frac{\text{J}}{(\text{cm}^3 \cdot \Delta^\circ\text{C})}$
Thermal coefficient of resistivity for copper	$\alpha_r = 0.00393 \frac{1}{\Delta^\circ\text{C}}$
Specific resistivity for copper	$\rho_r = 1.72 \times 10^{-6} \Omega \cdot \text{cm}$
Fault duration	$t_c = 0.5 \text{ s}$

Cross section of the conductor is calculated as below with data in Table 5.3:

$$A_{mm^2} = \frac{I_{sc1}}{\sqrt{\left(\frac{TCAP \cdot 10^{-4}}{t_c \alpha_r \rho_r} \right) \ln \left(\frac{K_o + T_m}{K_o + T_a} \right)}} = 88.454 \text{ mm}^2 \quad (5.1)$$

For earthing conductors or electrodes, which are remote to possible fault location, stranded copper wire size 95 mm^2 to 120 mm^2 is sufficient.

5.5 Design of Earth Grid with Respect to Permissible Touch Voltages

5.5.1 Resistance to Earth

The resistance to earth of the earth grid lies within the values, which can be calculated for a solid plate covering the same area and a single earth electrode surrounding the whole area.

Table 5.4: Parameters for the Resistance to Earth of an Earth Grid

Properties	Input Data
Soil resistivity	$\rho = 24.17 \Omega \cdot \text{m}$
Area covered by the earth grid	$A = 23400 \text{ m}^2$
Length of the earth electrodes	$L_T = 4990 \text{ m}$
Burial depth of grid	$h = 1.5 \text{ m}$

The resistance to earth of an earth grid is found as below with data in Table 5.4:

$$R_g = \rho \left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h\sqrt{20/A}} \right) \right] = 0.074 \Omega \quad (5.2)$$

5.5.2 Calculation of Touch Voltage

Touch voltage is the potential difference that occurs between hand and foot of a person who touches an earthed structure during a fault. To ensure that the earth grid design is safe, the calculated mesh voltage for earth grid has to be compared with the tolerable touch voltage.

The tolerable touch voltage is calculated considering a body resistance $R_B = 1000 \Omega$ and the resistance of two feet in parallel.

Table 5.5: Parameters for the Tolerable Touch Voltage

Properties	Input Data
Soil resistivity at the surface	$\rho_s = 2500 \Omega.m$
Thickness of surface material	$h_s = 0.15 \text{ m}$
Duration of shock current	$t_s = 0.5 \text{ s}$

Correction factor for surface resistivity is calculated as below with data in Table 5.5:

$$C_s = 1 - \frac{0.09(1 - \frac{\rho}{\rho_s})}{2h_s + 0.09} = 0.771 \quad (5.3)$$

Tolerable touch voltage is:

$$E_{touch70} = \frac{(R_B + 1.5C_s \cdot \rho_s) \cdot 0.157}{\sqrt{t_s}} = 0.992kV \quad (5.4)$$

The mesh voltage is defined as potential difference between earth electrode and surface in the center of the grid mesh. For this substation case:

Conductor spacing is: $D = 10 \text{ m}$

Burial depth is: $h = 1.5 \text{ m}$

If 120 mm^2 stranded copper wire is chosen then conductor diameter is: $d=0.01236 \text{ m}$

For grids with ground rods along the perimeter or for grids with ground rods in the grid corners, as well as both along the perimeter and throughout the grid area, the corrective weighting factor adjusting the effects of inner conductors is $K_{ii} = 1$.

The corrective weighting factor that emphasizes the effects of grid depth is:

$$K_h = \sqrt{1 + \frac{h}{h_0}} = 1.581 \quad h_0 = 1 \text{ m (grid reference depth)} \quad (5.5)$$

Total length of horizontal grid is:	$L_c = 2520 \text{ m}$
Peripheral length of grid is:	$L_p = 620 \text{ m}$
Maximum length of the grid in x direction:	$L_x = 180 \text{ m}$
Maximum length of the grid in y direction:	$L_y = 130 \text{ m}$
Maximum distance between any two points in the grid:	

$$D_m = \sqrt{L_x^2 + L_y^2} = 222.036m \quad (5.6)$$

The geometric factor n composed of factors n_a , n_b , n_c and n_d is: $n=n_a \cdot n_b \cdot n_c \cdot n_d$ where

$$n_a = \frac{2L_c}{L_p} = 8.129m \quad (5.7)$$

$$n_b = \sqrt{\frac{L_p}{4\sqrt{A}}} = 1.007m \quad (5.8)$$

$$n_c = \left[\frac{L_x \cdot L_y}{A} \right]^{\frac{0.7 \cdot A}{L_x \cdot L_y}} = 1 \quad (5.9)$$

$$n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}} = 1 \quad (5.10)$$

The geometrical factor K_m is as follows:

$$K_m = \frac{1}{2 \cdot \pi} \left[\ln \frac{D^2}{16 \cdot h \cdot d} + \frac{(D+2 \cdot h)^2}{8 \cdot D \cdot d} - \frac{h}{4 \cdot d} \right] + \frac{K_{ii}}{K_h} \cdot \ln \left[\frac{8}{\pi(2 \cdot n - 1)} \right] = 22.163 \quad (5.11)$$

The irregularity factor, K_i , used in conjunction with the above defined n is :

$$K_i = 0.644 + 0.148n = 1.855 \quad (5.12)$$

Length of the buried conductors $L_M = 4990 \text{ m}$

The grid current is: $I_G \leq 3947A$ and for a chosen grid current $I_{G1} = 2000 \text{ A}$.

The mesh voltage is calculated as:

$$E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_{G1}}{L_M} = 0.398kV \quad (5.13)$$

As the calculated mesh voltage is $E_m = 0.398 \text{ kV}$ less than the tolerable touch voltage of $E_{\text{touch}70} = 0.992 \text{ kV}$ the earth grid is sufficient with respect to touch voltages.

5.5.3 Calculation of Step Voltage

Step voltage is the potential difference that could be picked off between the feet of someone standing in the substation or just outside it during a fault. To ensure that the earth grid design is safe, the calculated step voltage for the earth grid has to be compared with the tolerable step voltage.

The tolerable step voltage is calculated considering a body resistance $R_B = 1000 \Omega$ and the resistance of two feet in series.

Table 5.6: Parameters for the Tolerable Step Voltage

Properties	Input Data
Soil resistivity at the surface	$\rho_s = 2500 \Omega.m$
Correction factor for surface resistivity	$C_s = 0.771$
Duration of shock current	$t_s = 0.5 s$

Tolerable step voltage is calculated as below with data in Table 5.6:

$$E_{step70} = (R_B + 6C_s \cdot \rho_s) \frac{0.157}{\sqrt{t_s}} = 3.304 \text{ kV} \quad (5.14)$$

Conductor spacing is: $D = 10 \text{ m}$

Burial depth is: $h = 1.5 \text{ m}$

If 120 mm^2 stranded copper wire is chosen then conductor diameter is: $d = 0.01236 \text{ m}$

The geometrical factor, K_s , is calculated as follows:

$$K_s = \frac{1}{\pi} \left[\frac{1}{2 \cdot h} + \frac{1}{D + h} + \frac{1}{D} (1 - 0.5^{n-2}) \right] = 0.165 \quad (5.15)$$

The total length of ground rods is: $L_R = 350 \text{ m}$

The effective conductor length is:

$$L_s = 0.75 \cdot L_c + 0.85 \cdot L_R = 2188 \text{ m} \quad (5.16)$$

The step voltage is calculated as:

$$E_s = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_s} = 6.771 \text{ kV} \quad (5.17)$$

Since $E_{step70} = 3.304 \text{ kV}$ is less than the step voltage of $E_s = 6.771 \text{ kV}$, the earth grid is safe with respect to step voltage. The ground potential rise (GPR) is estimated approximately with the equation: $GPR = R_G \cdot I_{sc1} = 2.591 \text{ kV}$.

Soil model and three dimensional grid layout are given below in Figure 5.2 and Figure 5.3:

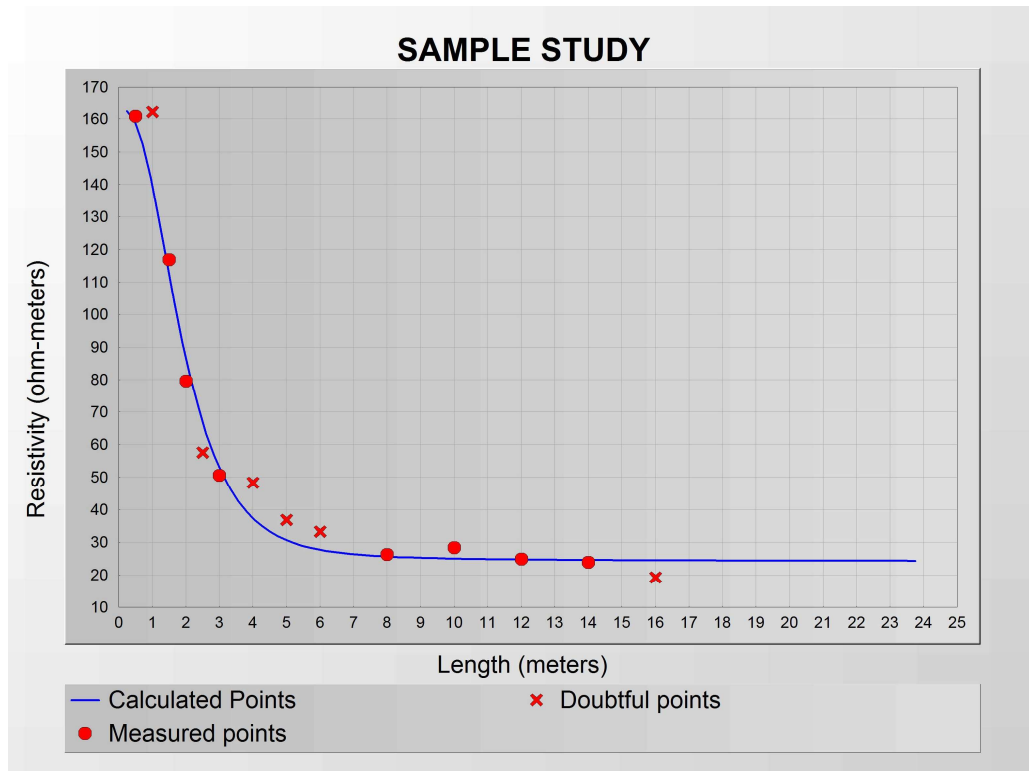


Figure 5.2: Soil Model for Case Study

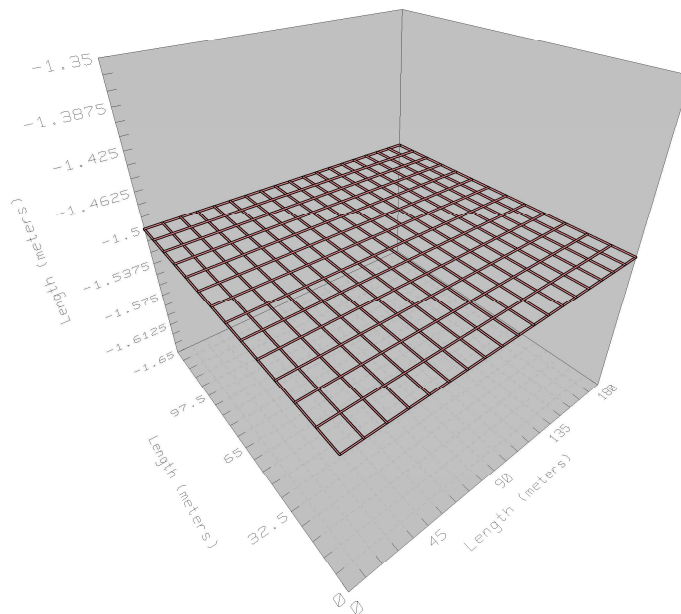


Figure 5.3: 3-D Grid Layout for Case Study

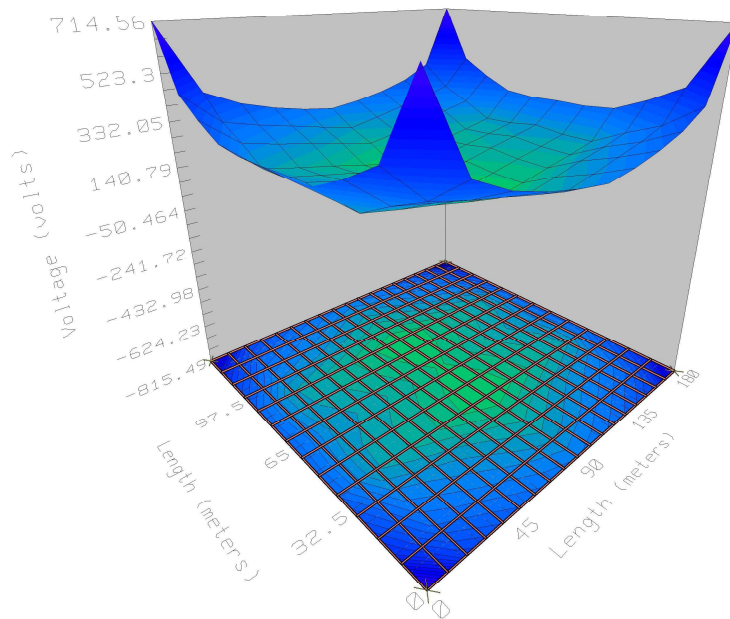


Figure 5.4: Real and Maximum Permissible Potentials Contour Plot for Case Study

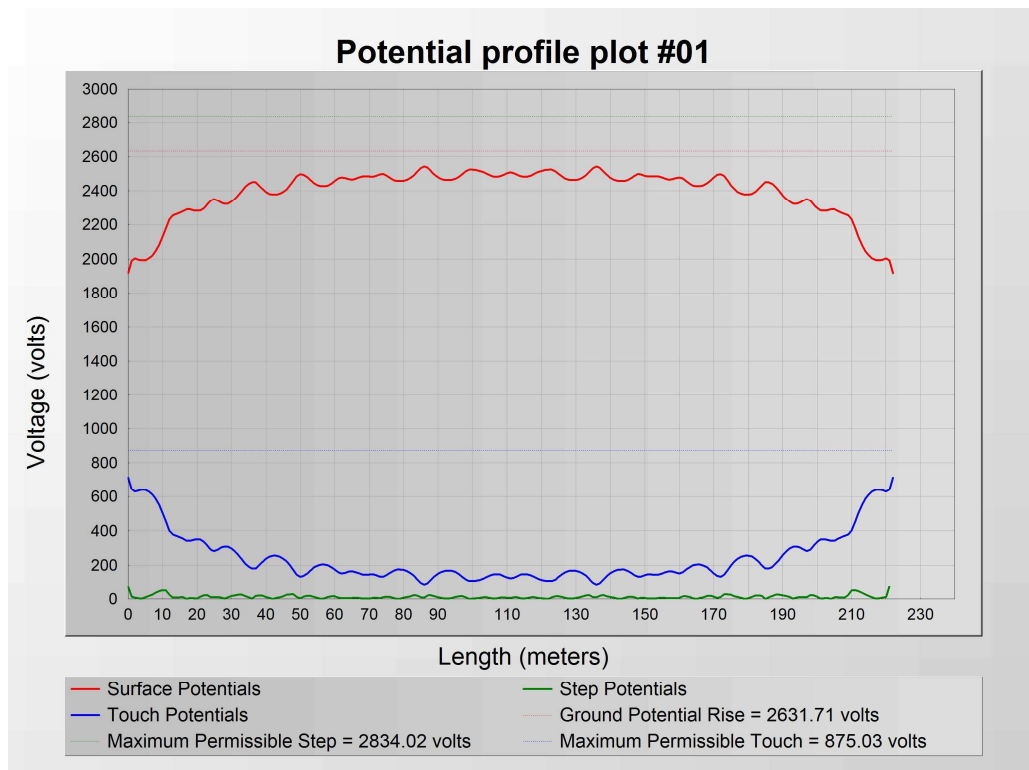


Figure 5.5: Real and Maximum Permissible Potentials Profile Plot for Case Study

Touch voltages contours and two dimensions graphs for touch and step voltages are seen in Figure 5.4 and Figure 5.5 as above.

6. CONCLUSION AND RECOMMENDATIONS

The design of grounding system in practice is presented by using a computer program. Since the output is observed on the screen of computer, in case if the voltage values are not within the limits, it is possible to adjust the design parameters such as the number of mesh, the depth of burial grounding grid, the space between parallel conductor, the length of conductor, the thickness of crushed rock and etc. The characteristic of asymmetry mesh grounding grid to the design of substation grounding system is used in the program, which makes the system more economical and more safety.

For some of cases including uniform and two-layer soils, the effects of ground grid structure on the performance of a grounding system is investigated. In order to concentrate as soon as possible on optimum design structure regarding to soil type, this study suggests a preliminary method to grounding system engineers to execute their design process.

If the results of this study are summarized as below, it shows that:

1. The safety level for equipment and people can be enhanced using unequally spaced grounding grids by decreasing earth surface potential gradients and making conductor leakage current distribution more uniform,
2. A non-uniform conductor spacing, having more conductors at the edges of the grids, provides the most efficient design in uniform or two-layer soils with a low resistivity top layer,
3. An unequally spaced grounding grid is an economical and reasonable technique as shown in simulation,
4. When the top layer thickness is small compared to the grid dimensions and the resistivity contrast between the layers is high, uniform or quasi-uniform conductor spacings provide the most efficient designs in soil structures with a high resistivity top layer [24],

5. The design of rectangular grids buried in uniform soil without ground rods could be adjusted and applied to any practical substation grounding grid design,
6. The grid resistance or ground potential rise is quite dependent on the top layer thickness,
7. The design procedure block diagram required for the grounding grid is given in order to be easily understood by the users,
8. If ground rods go through a low resistivity bottom layer to a significant depth relative to rod length, then they are also effective on the design,
9. Each design step represents an information about the grounding grid design and it is possible to add or remove a step when more experience is gained during the construction and testing,
10. By averaging the resistivities of stratified layers which are not in contact with the grid, multilayer soils act as two-layer or uniform soils. This conclusion is used as a starting point in a computerized design process due to the limited number of cases for multilayer soils,
11. Each design step is decided under a certain situation so that the user is able to learn from the previous experience in a systematic way.

Tracking the basic rules suggested by IEEE Std 80-2000, IEEE Std 142-2007 [25] and many computational algorithms to obtain safe grounding system, an expert system methodology for analysis and design of the substation grounding systems is given. Step by step design technique with necessary explanations is used to represent the required information. The developed expert system can be very useful tool in analysis and design of the substation grounding systems.

When designing earthing grid systems for large electrical substations, calculations performed in this study shows that IEEE Std 80-2000 is the most conservative since it predicts the lowest level of tolerable voltage and also the body current formulas provide adequate margins of safety for modern transmission and distribution systems. The safety criterion is compared and their differences is shown to prove that IEEE Std 80-2000 provides the most useful procedures for grounding system safety assessment.

The most critical touch voltages are found in the corners of grounding grid cases as shown in simulations. For the analysis of substation earthing systems, a boundary element approach is presented. This approach can be used in testing and designing the ground systems of power substations for system studies and applications or by university laboratories for education purposes.

To achieve more accurate results, computer aided design programs are needed for complex algorithms of calculations requiring the use of computational tools [26-33]. Since it offers the possibility of making a closest to the reality detailed analysis, the finite elements method [34] is the best way to represent the grounding systems study nowadays.

More accurate computer results are compared with several equations for E_s and E_m from cases with various mesh sizes, grid shapes, lengths and numbers of ground rods and they are found to be better than the equations. The cases include square, rectangular, L-shaped, equally and unequally spaced grids. They are run without and with ground rods. The total ground rod length is varied with different numbers of ground rod lengths and locations. Two-layer and uniform soil model cases are assumed with different conductor spacing. Most practical examples of grid design are considered. The comparisons show that it is possible to track the computer results with acceptable accuracy.

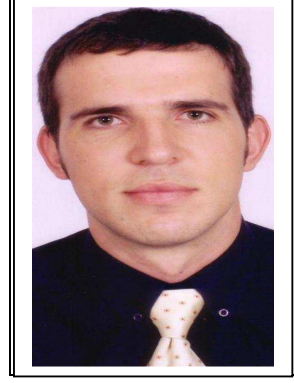
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