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Design Optimization Analysis of Ground Grid in Extra High Voltage Substation using ETAP Software

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Abstract

The power system of Myanmar relies on the 500 kV substations. They provide the power needs of the entire power system while covering a huge region. Examining the substation's ground grid system thoroughly is necessary to safeguard the grid and maintain its functionality. The grounding system of the substation is thoroughly examined, incorporating practical data collection for detailed analysis. Special emphasis is placed on the application of the latest IEEE 81-2013 standards during the data collection phase. The analysis and modeling of the network are conducted using ETAP software version 19. Specifically, the Ground Grid System (GGS) module, available in the latest version of ETAP (version 19), is utilized for the study. The substation is planned for an extension, which includes the installation of a new power transformer. The addition of the new power transformer is anticipated to elevate the overall fault level of the substation. This increase in fault level is analyzed in a dedicated case study, and a potential solution is proposed. A new ground mesh is also designed for this area, serving as a benchmark for future substations in the region, ensuring that essential parameters are carefully considered. Additionally, a new ground mesh is designed for a 500 kV substation, as it is expected to become part of the national grid in the near future. This aligns with the ongoing feasibility study conducted by NCC in Myanmar for the establishment of the first 500 kV substation in the area. The impact of variations in ground grid resistance and key safety parameters, influenced by changes in ground grid mesh shape, depth, and size, is thoroughly explained using results derived from various scenarios.

A. Introduction

The ground mesh of a substation is a critical component of its overall infrastructure. Its proper functionality is essential for ensuring the safety of personnel and equipment [1, 2]. The primary purpose of the ground mesh is to safely dissipate high fault currents that arise in the substation due to internal faults or external faults propagating through transmission lines. During a fault, the fault current must be efficiently directed to the ground; otherwise, it can damage substation equipment and potentially disrupt the entire interconnected power system. To achieve this, a low-resistance path for current dissipation is crucial. A well-designed, low-resistance ground grid mesh is installed to safeguard equipment and maintain system stability [5, 6]. If the ground grid resistance is too high, it can lead to significant voltage drops across the mesh, resulting in elevated mesh potentials. Therefore, the design of the ground mesh must strike a balance between cost-effectiveness and efficiency. Insufficient or poorly designed ground grids have been responsible for numerous hazards worldwide, underscoring the importance of robust and reliable grounding systems. One common issue, particularly in extra-high voltage (EHV) substations, is the rise in potential gradients around the ground grid mesh. These challenges are tackled using various methodologies, as discussed in the research presented below. The primary objective of this study is to address the deficiencies related to the ground grid mesh of a practical 500 kV substation. Ground grid mesh data is collected on-site using the latest IEEE 81-2013 standards. The modeling, analysis, and optimization of the ground grid mesh are conducted using IEEE 80-2000 guidelines, facilitated by ETAP-19 software. Through scenarios, the effects of increasing the ground grid mesh area, adding more horizontal or vertical conductors, and reducing the spacing between conductors on various potentials and ground resistance are examined using IEEE 80-2000 methods. The study highlights issues such as elevated potentials and temperatures exceeding safety limits. A potential design solution is proposed based on analytical methodologies to resolve these problems, and a new ground mesh is designed to accommodate the substation's expansion to meet increased power demands. Additionally, a new ground grid mesh for a 500 kV substation has been designed. Figure 1 illustrates the HGIS substation layout.

Figure 1. HGIS 500kV Substation

B. Ground SystemTerminologies

Various terminologies related to safety indices and potential gradients have been developed [1, 2, 7, and 8]. These terms are defined below and illustrated in Figure 2.

a. Ground Potential Rise (GPR)
   GPR is calculated by multiplying fault current with ground resistance given in equation 1:

$$GPR = I_g.R_g \tag{1}$$

   I_g is defined as maximum ground current, R_g is defined as Ground Resistance.

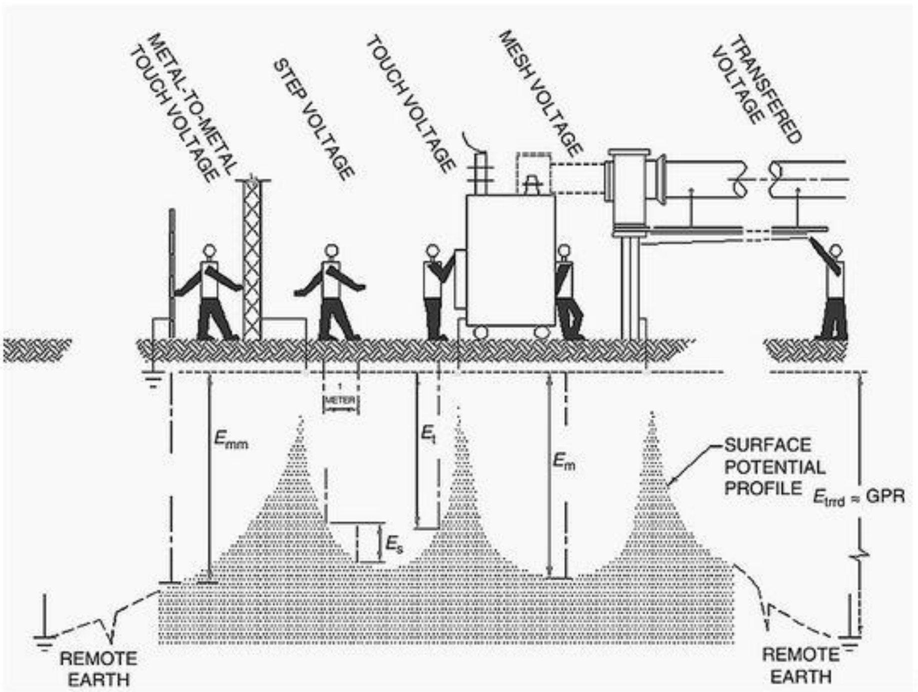

Figure 2. Demonstration of Ground Grid Parameters[8]

b. Touch Voltage (V_t)
   Touch voltage is defined as the potential difference between the Ground Potential Rise (GPR) and the potential at the earth's surface where a person is standing while simultaneously touching a structure connected to a solid grounding point. This concept is critical for evaluating the safety of personnel in substations. The mathematical expression for touch voltage is provided in Equation 2.

$$E_{step70} = \frac{1000 + 1.5Cs\rho_s}{\sqrt{t_f}} \tag{2}$$

   C_s=1 for analysis, ρ_s= Resistivity of surface n.m
   t_s =Fault /Short Circuit duration seconds.

c. Step Voltage (V_s)
The step voltage is defined as the potential difference experienced by a living being standing with their feet spaced one foot apart, without any part of their body making contact with a solidly grounded structure. The formula is provided in Equation 3.

$$E_{step70} = \frac{1000 + 6Cs\rho_s}{\sqrt{t_f}} \tag{3}$$

d. Mesh Voltage (V_m)
The mesh voltage is defined as the potential difference between the center of the ground grid mesh and a solidly grounded structure that is connected to a remote earthing electrode buried at a sufficient depth below the ground surface.

e. Earth Surface Potential (ESP)
Earth surface potential is defined as the difference between the mesh voltage (V_m) and the touch voltage (V_t). In the worst-case scenario, it has been observed that the mesh voltage is essentially equal to the touch voltage.

f. Ground Resistance (R_g)
Ground resistance is defined as the resistance of the entire ground grid mesh through which the fault current flows and is efficiently dissipated into the earth. It is essential to maintain the ground resistance at a low level to ensure proper dissipation of fault current without causing a significant rise in grid potential.

g. Fault Current (I_f)
The fault current is defined as the maximum current that flows along the ground grid mesh. The design of the ground grid mesh is based on the worst-case fault current that may occur in the substation, taking into account all design constraints.

h. Short term temperature rise
It is defined as the temperature increase that may occur along the horizontal conductors and vertical rods of the ground grid mesh. Proper analysis of the temperature rise is essential to prevent arcing, which could lead to hazardous situations across the ground grid mesh.

i. Weight of Person (Kg)
It is defined as the reference weight of a person, upon which all calculations related to the aforementioned parameters are based. The calculation can be performed for a person with a body weight of either 50 kg or 70 kg.

C. Measurement of Soil Resistivity

Various methods have been developed to calculate soil parameters, however, the resistivity of soil is determined using the methods outlined below:

1. Four Point Method
2. Wenner Method
3. Schlumberger Method

The resistivity of each soil layer can be accurately determined using any of these three methods [2, 3]. However, the third method, the Schlumberger method, is preferred over the other two due to its simpler testing procedure. Additionally, this method allows for easy identification of the soil's stratification type, whether it is horizontally or vertically stratified.

IEEE Methods

The 80-2000 methods consist of four techniques based on which the ground resistance (R_g) is calculated [3]. These methods are outlined as follows

- Laurent Newman Method
- Sevrak Method
- Schwarz Method
- Thapar - Gerez Method

It is worth noting that the Schwarz and Thapar-Gerez methods incorporate the fundamental principles of the first two methods listed. Therefore, for calculating ground resistance, the Schwarz and Thapar-Gerez methods are preferred.

Schwarz Method

Schwarz developed a set of three equations to determine ground resistance, along with a primary equation that combines the three into one [3, 4]. The central equation for calculating the ground mesh resistance is given by the formula in Equation 4:

$$R_1 = R_a . R_b - R_m . \frac{R_m}{R_a} + R_b - 2R_m \quad (4)$$

R_a and R_b represent the combined resistance of all horizontal and vertical conductors, respectively, while Rm is the mutual resistance between the horizontal and vertical conductors.

Thapar-Gerez Method

In this method, computer algorithms or programs are used to evaluate ground grid resistance. These algorithms/programs assist in designing a ground grid mesh by incorporating various grid shapes, which are selected based on the specific requirements. The conductors and rods are then arranged within the grid mesh. The different types of grid shapes are outlined as follows

- Rectangular Grid
- L-Shaped grid
- T-Shaped Grid
- Triangular Grid
- Square Grid

The value of ground grid resistance is calculated using the formula given equation (5).

$$R_g = \rho \left[\frac{1}{L_t} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h\sqrt{\frac{20}{A}}} \right) \right] \quad (5)$$

IEEE 81-2013 Method

IEEE has provided a standard for the practical measurement of ground resistance, resistivity, and potentials [2, 3]. The methods include the latest improvements to the previously mentioned measurement techniques. The updates were introduced after extensive discussions and work by a committee formed by the IEEE council to address flaws in the earlier methods.

In the current project, all measurements are conducted using IEEE 81 methods, and the data is modeled using intelligent software, such as ETAP-19, to evaluate the results.

D. Summary of Practical Data

Practical data has been collected from the Rawat substation, where the ground grid system is already installed and operational. The existing data is analyzed to determine whether all key parameters fall within the specified limits [5, 6].

- Voltage Level =500 kV
- Fault Current Level = 40 kA
- Dimension of Ground Grid = 292 x 334 m^2 (meter square)
- Ground grid mesh Length in Horizontal-direction =292 (meters)
- Ground grid mesh Length in Vertical-direction = 334(meters)
- Conductors used in Horizontal direction=21
- Conductors used in Vertical direction = 23
- Area of Conductor= 150 mm^2 (millimeter square)
- Type of Conductors=Copper annealed Soft Drawn
- Conductors Temperature = 46 C ∘
- Vertical Rods installed =464
- Vertical Rod Diameter =0.016 m (meter)
- Type of Rods=Copper clad steel Rod
- Duration of Fault t_c, t_f & t_s =1s (seconds)
- Ambient Temperature = 45C ∘
- Rod Temperature=45 C ∘
- Reactance over resistance ratio X/R ratio= 50
- Weight of Person =50 or 70 kg
- Type of soil surface layer = Gravel is used
- Resistivity of soil surface layer = 5000 Ω.m
- Height of soil surface layer = 0.5 m (meters)
- Type of soil top layer = Moist soil
- Resistivity of soil top layer = 24.66 Ω.m
- Height of soil top layer = 2 m (meters)
- Type of soil bottom layer =Semi Moist soil
- Resistivity of soil bottom layer = 200 Ω.m
- Height of soil bottom layer = infinity
- Magnitude of fault relative to current passing between remote earth and ground grid (S_f)=70
- Relative Increase of Fault Current during substation life span (C_p) =69

E. Scenario for IEEE 80-2000 Methods

The data for the 500kV substation ground grid mesh is modeled using the GGS Module of intelligent software [7, 8]

Ground Grid System Module

The latest version of Ground Grid Systems is integrated into ETAP-19, which allows engineers to accurately design, analyze, and validate protection schemes for ground grid meshes installed in high and extra-high voltage substations. The inclusion of advanced 3D technology, alongside one-line diagrams, enables researchers to visualize the designed ground systems and effectively assess the short-circuit effects. The design methods offer flexibility for ground grid mesh design based on IEEE 80-2000 standards. The GGS module calculates key parameters such as Ground Potential Rise (GPR), ground system resistance (Rg), comparison of potentials to tolerable limits, and step, touch, and absolute potentials both inside and outside the grid.

Scenario-I

In Scenario-I, the data gathered during the design phase is first modeled using ETAP-19 software. The Ground Grid System (GGS) module in ETAP is utilized to model and analyze the entire ground grid mesh. This module includes a feature for performing the analysis according to the IEEE 80-2000 standards. The potential gradients generated during the design phase are calculated and highlighted based on the analysis results. Suggested remedial actions for rectification will be provided in the subsequent Scenario (Scenario-2). Table I presents the input parameters for the ground grid, which were used for modeling, while Figure 3 illustrates the mesh modeling.

Table 1. Scenario-I Input Ground Grid Parameters

Grid Size (m)		Number of Conductor		Type of Conductor	Depth of Conductor (m)	Size of Conductor (sq.mm)	No of Rods	Type of Rods	Rod Dia. (m)	Rod Length (m)
Length X,Y direction		X,Y direction								
X	Y	X	Y							
292	334	16	24	Copper annealed Soft Drawn	0.5	150	292	Copper clad steel Rod	0.014	1.2

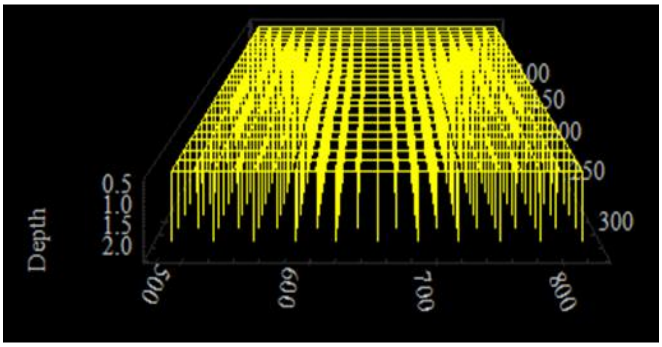

Figure 3. Scenario-I Modeling of Grid Mesh using ETAP-19

The results of analysis using IEEE 80-2000 methods are shown in figure 4.

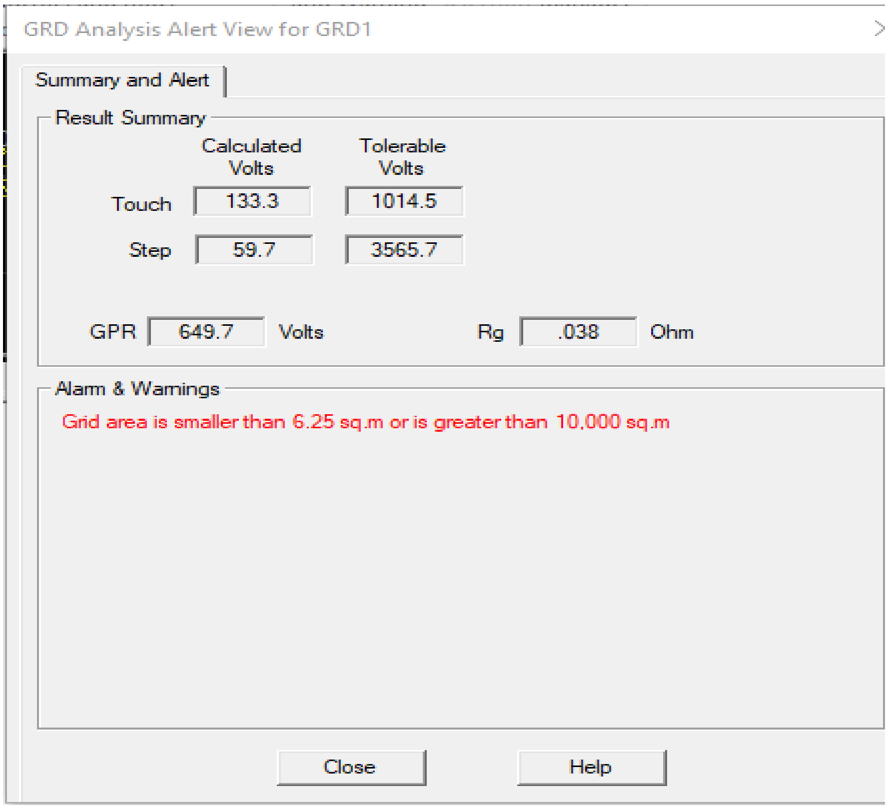

Figure 4. Results of Scenario-I Analysis

The results indicate that the Touch Potential, Ground Potential Rise (GPR), and short-term temperature rise of the conductors/rods exceed the defined safety limits. In conclusion, the ground grid mesh is not functioning as expected, which could pose a potential hazard.

Scenario-II

In Scenario-II, the shortcomings identified in Scenario-I are addressed by first modifying key parameters, followed by remodeling using the IEEE 80-2000 methods for analysis and result generation. Table 2 presents the input parameters for the ground grid, which were used in the modeling process, while Figure 5 illustrates the ground grid mesh in the x-y direction.

Table 2. Scenario-II Input Ground Grid Parameters

Grid Size (m)		Number of Conductor		Type of Conductor	Depth of Conductor (m)	Size of Conductor (sq.mm)	No of Rods	Type of Rods	Rod Dia. (m)	Rod Length (m)
Length X,Y direction		X,Y direction								
X	Y	X	Y							
292	334	21	23	Copper annealed Soft Drawn	0.5	185	464	Copper clad steel Rod	0.016	1.8

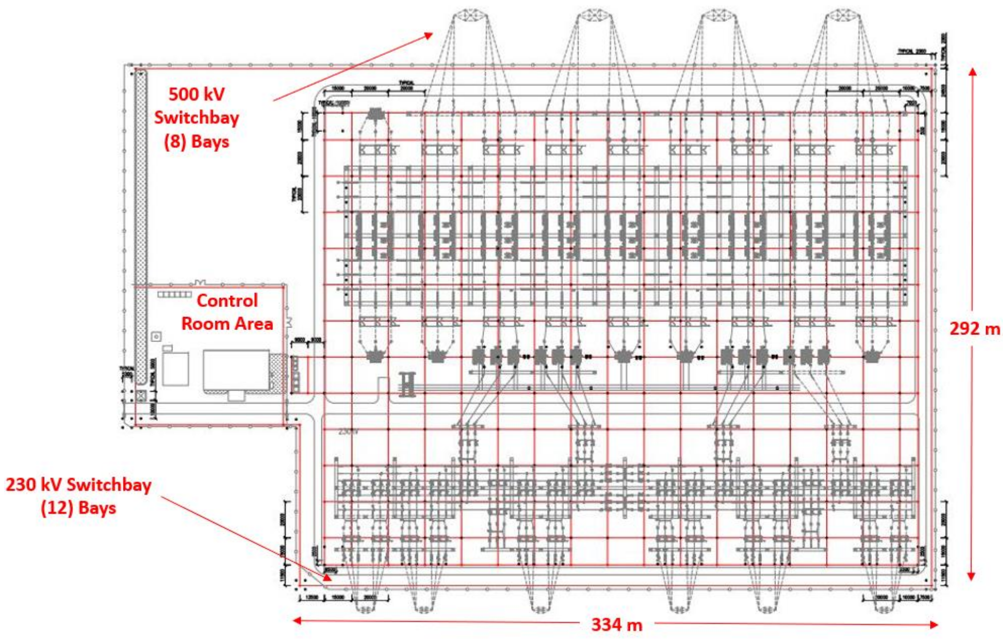

Figure 5. Scenario-II Ground Grid Mesh in X-Y direction for 500 kV HGIS Substation

The results of the Scenario-II analysis using IEEE 80-2000 methods are shown in figure 6.

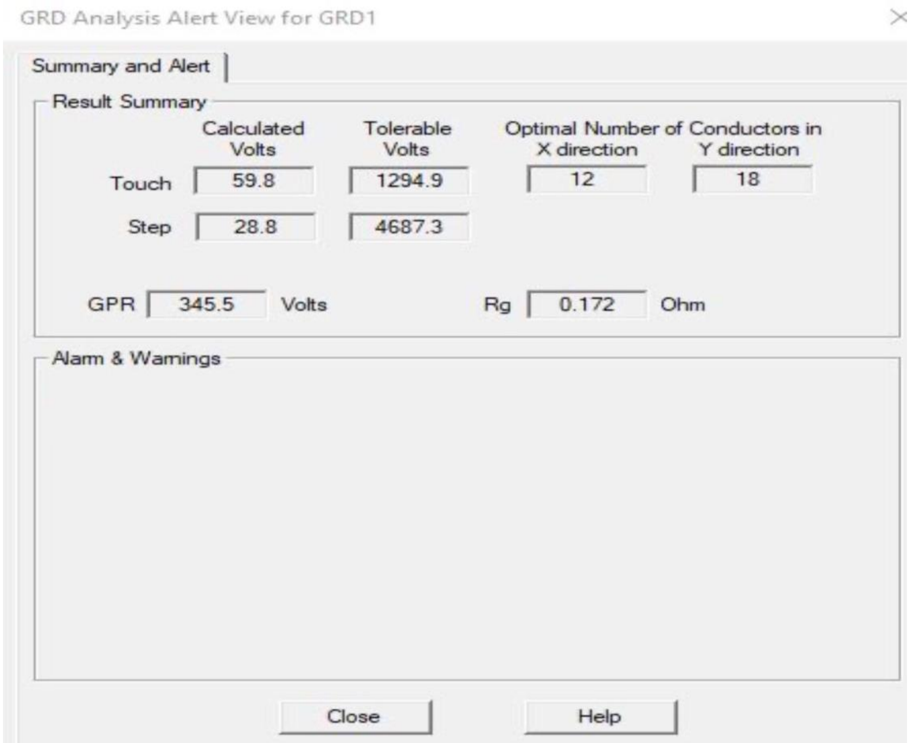

Figure 6. Results of Scenario-II Analysis

The results demonstrate that the values, which previously exceeded the prescribed limits, now fall within the defined range following the incorporation of the necessary changes [9].

Scenario-III

The third scenario is designed with the consideration of an extension to the substation. This extension involves replacing the old power transformer with a new, larger capacity transformer, which will increase the fault current from 40 kA to 45 kA. As a result, the existing ground grid will be inadequate to meet the new requirements. Therefore, modifications to the ground grid mesh are necessary.

Table 3 presents the input parameters for the ground grid, which were used in the modeling process.

Table 3. Scenario-III Input Ground Grid Parameters

Grid Size (m)		Number of Conductor		Type of Conductor	Depth of Conductor (m)	Size of Conductor (sq.mm)	No of Rods	Type of Rods	Rod Dia. (m)	Rod Length (m)
Length X,Y direction		X,Y direction								
X	Y	X	Y							
292	334	34	29	Copper annealed Soft Drawn	0.5	185	990	Copper clad steel Rod	0.018	2

The data collected regarding soil characteristics is modeled using ETAP-19, as shown in Figure 8. The results of the analysis, conducted using the IEEE 80-2000 method, are presented in Figure 7.

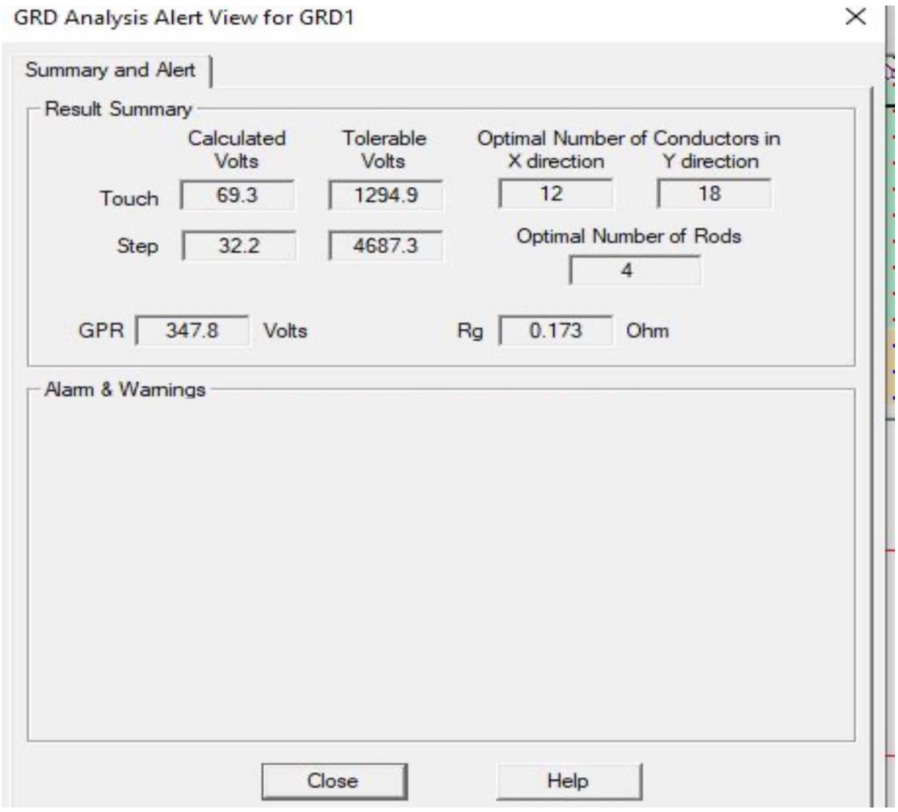

Figure 7. Results of Scenario-III Analysis

The results indicate that the parameters, which were previously exceeding the prescribed limits, are now within the acceptable range after the necessary changes were implemented.

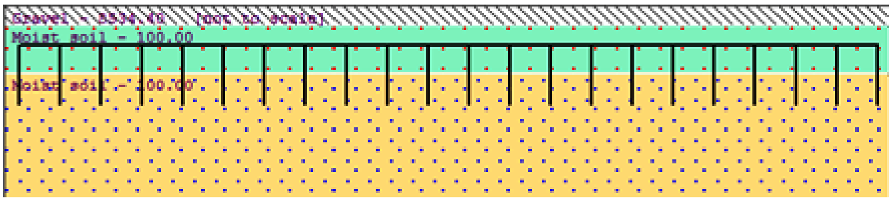

Figure 8. Scenario-III Modeling of Soil

F. Comparison of Scenarios Analysis

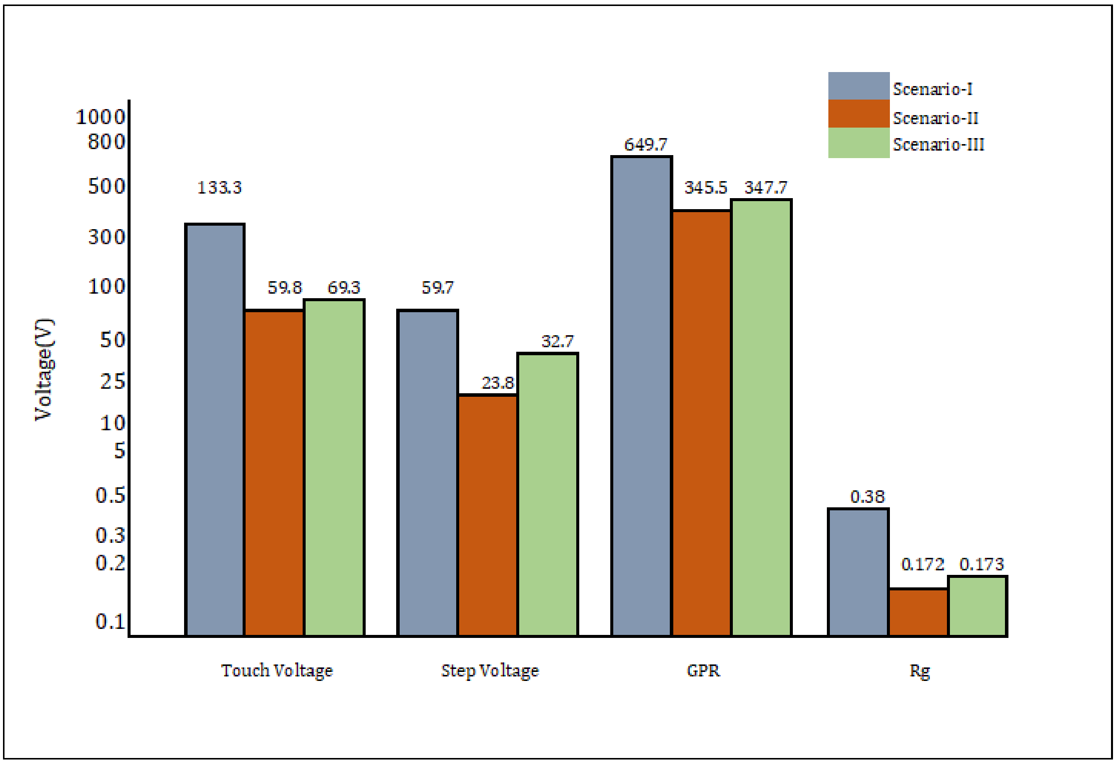

Figure 9. Comparison Ground Grid Parameters Across Scenarios Analysis

The comparison chart for the three scenarios (Scenario-I, Scenario-II, and Scenario-III). It shows the differences in Touch Potential, Ground Potential Rise (GPR), and Temperature Rise across the three Scenarios.

- Scenario-I: Parameters exceed the limits, indicating the ground grid mesh is not functioning properly.
- Scenario-II: Corrective actions bring the values within safe limits.
- Scenario-III: With the planned extension and increased fault current, parameters rise slightly but remain within acceptable ranges.

G. Discussion

The analysis was conducted to evaluate performance indices related to the ground grid mesh. The results from various scenarios have been presented, and based on these findings, the following new aspects can be inferred:

a. Effect of increase in Area on potentials

The step potential, touch potential, mesh potential, absolute potential, Ground Potential Rise (GPR), and ground impedance all decrease with the increase in the ground grid mesh area. The GPR value in Scenario-I is 645.7 V, in Scenario-II it is 345.5 V, and in Scenario-III it is 347.8 V, as verified by the results from the above scenarios. This improvement is achievable in areas where land costs are economical. However, in populated areas where land is expensive, the solution of increasing the mesh area to reduce impedance may not be feasible.

b. Effect of Reducing spacing between Conductors

Reducing the spacing between conductors from 30m to 10m significantly reduces the mesh potential; however, it may cause an increase in step potential. Despite the increase in step potential, the reduction in mesh potential proves to be more effective, offering an overall improvement in the grounding system's performance.

c. Effect of Increasing the Conductors

In Scenario-I, where 150 conductors are used, and in Scenario-II, where 185 conductors are used, the touch potential decreases significantly with the installation of more horizontal conductors. This improvement can be verified from the results of the scenarios presented above.

d. Effect of Increasing the Vertical Rods

The installation of additional vertical rods leads to a significant reduction in mesh potential, ground impedance, and short-term temperature rise of the conductor's rods, as demonstrated by the scenarios above.

H. Conclusions

The main focus of our project was to identify potential issues in the ground grid mesh of a 500kV substation. To achieve this, comprehensive data was collected from the substation using the latest IEEE 81 Methods, which served as the foundation for the modeling process. The results were then compared with IEEE standard limits. A potential solution was proposed to address the deficiencies in the ground grid mesh, involving a series of amendments to ensure that all safety parameters are within the prescribed limits. Additionally, the impact of factors such as ground grid mesh conductors, vertical rods, mesh area, and conductor spacing on various potentials was highlighted and verified through different scenarios.

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