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Optimization design of ground grid mesh of 69/13,8 KV substation using ETAP

Projeto de otimização de malha do sistema de aterramento em uma subestação 69/13,8 kV utilizando ETAP

Diseño de optimización de malla de sistema de puesta a tierra en subestación de 69/13,8 kV usando ETAP

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ABSTRACT

This scientific document presents the analysis and optimization of the mesh of the grounding system of a 69 / 13.8 kV substation in Ecuador. The mesh is made up of horizontal and vertical conductors connected with vertical electrodes buried under the ground of the substation. The function of the structure is to effectively dissipate the high short-circuit currents generated in the system. The objective is to determine the safety parameters of the ground mesh by comparing the mesh design analysis using the IEEE method and the Finite Element Analysis (FEM) method. These two methods are used differently to determine the electrical parameters of the ground mesh, the step voltage and touch voltage, the number of horizontal conductors, the number of vertical conductors, the number of electrodes, and the earth resistance of the Substation. ETAP 16.0 software is used for analysis. First, the maximum short-circuit current of the substation of 69 / 13.8 kV is determined. Second, the analysis is performed to determine the input and output parameters of the ground mesh structure using the IEEE and FEM methods. It ends with the results of the optimization of each of the specific methods, making a comparison of the two methods used and giving a recommendation regarding the best method for the design of the ground mesh.

Keywords: Grounding Mesh, ETAP, Optimization, Short circuit current, Finite element analysis.

RESUMO

Este documento científico apresenta a análise e otimização da malha do sistema de aterramento de uma subestação 69/13,8 kV no Equador. A malha é composta por condutores horizontais e verticais conectados com eletrodos verticais enterrados abaixo do solo da subestação. A função da estrutura é dissipar efetivamente as altas correntes de curto-circuito geradas no sistema. O objetivo é determinar os parâmetros de segurança da rede terrestre comparando a análise do projeto da rede utilizando o método IEEE e o método de Análise de Elementos Finitos (FEM). Esses dois métodos são utilizados de forma diferente para determinar os parâmetros elétricos da rede de aterramento, a tensão de passo e a tensão de toque, número de condutores horizontais, número de condutores verticais, número de eletrodos e resistência de terra da Subestação. O software ETAP 16.0 é utilizado para a análise. Primeiramente é determinada a corrente máxima de curto-circuito da subestação 69/13,8 kV. Em segundo lugar, a análise é realizada para determinar os parâmetros de entrada e saída da estrutura da rede terrestre utilizando os métodos IEEE e FEM. Termina com os resultados da otimização de cada um dos métodos apresentados, fazendo uma comparação dos dois métodos utilizados e é feita uma recomendação quanto ao melhor método para o dimensionamento da malha terrestre..

Palavras chave: Malha de Aterramento, DWTP, Otimização, Corrente de Curto-Circuito, Análise de Elementos Finitos..

RESUMEN

El documento científico presenta el análisis y optimización de la malla del sistema de puesta a tierra de una subestación del Ecuador de 69/13,8 kV. La malla está compuesta por conductores horizontales y verticales conectados con electrodos verticales enterrados debajo de la tierra de la subestación. La función de la estructura es disipar de manera efectiva las elevadas corrientes de cortocircuito generadas en el sistema. Se tiene como objetivo el determinar los parámetros de seguridad de la malla de tierra comparando el análisis del diseño de la malla usando el método IEEE y el método de Análisis de Elementos Finitos (FEM). Estos dos métodos son utilizados de manera diferente para determinar los parámetros eléctricos de la malla de tierra, el voltaje de paso y voltaje de toque, número de conductores horizontales, número de conductores verticales, número de electrodos y resistencia de tierra de la Subestación. El software ETAP 16.0 es usado para el análisis. En primer lugar, se determina la máxima corriente de cortocircuito de la subestación de 69/13,8 kV. En segundo lugar, se realiza el análisis para determinar los parámetros de entrada y salida de la estructura de la malla de tierra usando los métodos de IEEE y FEM. Se finaliza con los resultados de la optimización de cada uno de los métodos presentados, realizando una comparación de los dos métodos utilizados y se da una recomendación con respecto al mejor método para el diseño de la malla de tierra.

Palabras clave: Malla de Puesta a tierra, ETAP, Optimización, Corriente de Cortocircuito, Análisis de Elementos Finitos.

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Main topic:
Grounding mesh optimization
Main practical implications:
The results presented can serve as a guide for the design of future public policies involving the improvement and design of grounding mesh in substations.
Originality/value:
The article addresses in detail a subject that has been little explored by applied sciences research in the Ecuadorian context.

INTRODUCTION

Grounding systems are a fundamental part of transmission substations for the stabilization of the power system. The grounding system is a system that consists of the grounding interconnection of an electrical power system. The system provides safety to personnel, equipment and structures within the substation area, so it must have a low impedance to conduct high short-circuit currents under normal and fault conditions, without affecting the operating limits of the substation and without affecting the continuity of service. (IEEE Standard 80-2000, 2000).

The design of the grounding system is complex, the soil acts as a semiconductor and the electrodes act as conductors, leading to more complex calculations. Due to the difference of soils in the different substations, the design of the grounding grid must be done with great precision and care, in order to have acceptable safety limits for all parameters. (Nandhini et al., 2022).. A thorough evaluation of the soil conditions is required to determine the soil structure, soil type, depth and resistivity of each soil layer.

The values of short-circuit currents produced in 69 kV systems are 8 -15 kA. Due to these currents, voltage drops are generated and distributed along the grounding grid, the potential difference must be kept under the limits of the IEEE80-200 standard (Padilla & Herrera, 2020). (Padilla & Herrera, 2020).

The vital factors for ground grid evaluation are step voltage, touch voltage, ground potential rise, ground resistance, grid voltage and absolute potential. There are several methods available for substation grid design. The IEEE and FEM methods are the most commonly used methods in recent research due to their reliability. The mesh modeling and analysis is performed by these two methods. The GGS module of the ETAP 16.0 software is used to perform the mesh modeling (Cheema, Cheema, B., Cheema, B., Cheema, B., Cheema, B., Cheema, B.). (Cheema, Cheema, Bashir, & Aslam, 2015)..

Comparison between the results of the IEEE 80 & FEM method is made with case studies of existing substation ground grids to establish the cost effectiveness and efficiency of each method. Recommendations are made with respect to the methods, upon which future ground grid design can be based.

DETERMINATION OF SOIL RESISTIVITY

Several procedures are used to determine soil resistivity. The most widely used is the "four electrodes" method which presents two methods. (Chauvin Arnoux Group, 2015)..

WENNER's method: appropriate in the case of a single depth measurement.

SCHLUMBERGER method: suitable for measurements at different depths to create geological profiles of soils.

In the research project, only Werner's method was used, so only this method will be described.

The measuring instrument used is a classic earth tellurometer that allows the injection of a current and the measurement of ΔV (Chauvin Arnoux Group, 2015, p. 4)..

Wenner's method

Wenner's 4-point method is the most commonly used technique. It basically consists of 4 electrodes buried within the soil along a straight line, at a distance A apart, buried to a depth B. The voltage between the two inner electrodes potential is measured and divided by the current flowing through the other two outer electrodes to give a value of resistance R in Ω (Zhang et al., 2020)

Between the two outer electrodes (E and H) a measuring current I is injected by means of a generator; between the two central electrodes (ES, S) the potential ΔV is measured thanks to a voltmeter, the value of R measured on the tellurometer allows to calculate the soil resistivity (Chauvin Arnoux Group, 2015) Now the resistivity ρ as a function of unit length in which a and b are measured in m is calculated with the following formula (IEEE, 1992).

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

Where:

$\rho =$ Apparent soil resistivity in $\Omega m.$

$a =$ Electrode spacing in m.

$b =$ Electrode depth in m.

$R =$ Resistance measured in Ω.

It should be noted that this does not apply to ground rods driven to depth b; it applies only to small electrodes buried at depth b, with insulated connecting wires. However, in practice, four rods are usually placed in a straight line at intervals a, driven to a depth b not exceeding 0.1 a. We then assume that b = 0 and the formula becomes (Oputa & Madueme, 2019):

$$\rho = 2\pi aR$$

Where:

$\rho =$ Apparent soil resistivity in $\Omega m.$

$a =$ Electrode spacing in m.

$R =$ Resistance measured in Ω.

Only if,

$$b \leq \frac{a}{20}$$

$b =$ Electrode depth in m.

The most accurate method in practice for measuring the average resistivity of large volumes of undisturbed soil is the four-point method (Genin et al., 2012).

ANALYSIS OF GROUNDING NETWORKS USING ETAP SOFTWARE

The module for grounding networks allows fast and efficient design and analysis of grounding systems. The 3-D design-based technology is integrated with the single-line representation achieving a virtual visualization of the design and verification of results by the application of previously calculated short-circuit currents (Hardi et al., 2019)

Uses the standards and methods of:

IEEE 80-1896

IEEE 80-2000

IEEE 665-1995

Finite element calculation.

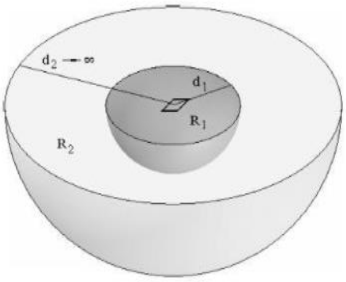
Finite Element Grounding (FEM).

The most recent studies on grounding analysis are based on Finite Element Method (FEM). It is used to determine the grounding resistance of a design or grounded region(Bugaliya et al., 2021)..

FEM is one of the most reliable methods to find the grounding resistance in the grids. The resistance found is very close to the actual value, compared to that calculated using conventional measurement methods.

FEM includes current analysis, making a mesh array in a specific area of the network. After determining the current, the ground resistance is calculated by dividing the known voltage with the calculated current value in the grid array. The main advantage of this method is to select the size of the grid model, as the distance of the ground under consideration starting from the ground grid, since the analysis of each potential in the ground for a selected point is considered from the grounding system to the point. The FEM model starts from the following steps. (Uma, Uzoechi, & Robert, 2016). First, it is assumed that the ground resistance is a parameter that does not depend on the potential or current in the grid. Second, the entire region is assumed to be an infinite flat surface.

Figure 1. Finite element modeling of soil.



Source: (Nandhini et al., 2022)

R1: is the resistance within a hemispherical surface.

R2: is the resistance outside the hemispherical surface.

$d_2$is the distance from the grid to the points where the electric potential goes to zero.

d_1:It is the distance from the mesh to the points where the equipotent surface hemisphere model is perturbed.

The resistance of the grounding grid is calculated from the equation:

$$R = R1 + R2$$

The resistance outside the hemispherical surface is calculated using the equation:

$$R2 = \frac{\rho}{2\pi d_1}$$

$$d_1 = \frac{D}{2} + 30$$

D: It is the diagonal distance of the ground grid, it is calculated with the equation:

Where the finite element analysis takes place is when determining R1, which is given by the equation:

$$R1 = \frac{V^2}{Potencia\ Disipada}$$

Replacing terms:

$$R1 = \frac{(V_G - V_B)^2}{\int_V \frac{E^2}{\rho}}$$

V_G: Potential in the mesh

V_B: Potential in the perimeter

E: Energy consumed

The earth resistance is calculated with the final formula:

$$R_g = \frac{(V_G - V_B)^2}{\int_V \frac{E^2}{\rho}} + \frac{\rho}{2\pi d_1}$$

Finite element analysis can be used to calculate the step voltage and touch voltage.

$$V_{AG} = R_g I_G$$

$\mathrm{V_{AG}}$: Step voltage

$\mathrm{I_G}$: Fault current

$$V_{AB} = R_2 I_G$$

$\mathrm{V_{AG}}$: Contact voltage

IEEE Method

IEEE 80-2000 describes 4 different methods for determining the ground resistance Rg. The methods will be discussed in the following section (Maria Alvarado et al., 2021)..

Laurent-Niemann Method

The ground resistance is a function of the area covered by the substation and the resistance of the soil in the substation. Rg is calculated with the following equation:

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

Where,

Rg: The resistance of the earth in the substation in Ω.

ρ: It is the resistivity of the soil in Ω.m

A: This is the area occupied by the earthen mesh in m^2

L_T: It is the total length of buried conductors in m.

$$L_T = L_t + n_R h$$

L_t: The total length of conductors in m.

n_R: Number of spades

h: The depth of the mesh in m.

Sverak's method

It is an integrative form of the Laurent-Niemann method. The earth resistance above the soil surface is modified to improve the approximation of the calculated soil resistance.

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

Where,

Rg: The resistance of the earth in the substation in Ω.

ρ: It is the resistivity of the soil in Ω.m

A: This is the area occupied by the earthen mesh in m^2

L_T: It is the total length of buried conductors in m.

h: It is the depth of the mesh in m.

Schwarz Method

This method is composed of 3 equations and an equation that merges the 3 equations.

$$\mathrm{R} = \frac{R_1 R_2 - R_m}{R_1 + R_2 - 2R_m}$$

$$R_1 = \frac{\rho}{\pi L_t}\left[\ln\left(\frac{2L_t}{a'}\right) + \frac{K_1 L_t}{\sqrt{A}} - K_2\right]$$

2a: Conductor diameter in m.

a': $\sqrt{2ah}$ *for conductors buried at a depth h.*

K_1 *y* K_2 *are the coefficients found in equations according to the depth of the mesh.*

$$R_2 = \frac{\rho}{2\pi n_R L_r}\left[\ln\left(\frac{4L_r}{b}\right) - 1 + \frac{2K_1 L_r}{\sqrt{A}}\left(\sqrt{n_R} - 1\right)^2\right]$$

L_r: The length of each spike in m.

b: Pick diameter in m.

n_R: Number of spades

The third equation is R_m which is the combination of the ground resistance of the grid and the stakes.

$$R_m = \frac{\rho}{\pi L_r}\left[\ln\left(\frac{2L_t}{L_r}\right) + \frac{K_1 L_t}{\sqrt{A}} + 1 - K_2\ \right]$$

Schwarz Method

This formula is the integrated version of the Svrak equation. In detail, an extra multiplication is added to include the effect of resistance in the mesh configurations.

$$\mathrm{R} = \ \rho\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{\frac{20}{A}}}\right)\right] \times 1{,}52\left[2\ln\left(L_p\sqrt{\frac{2}{A}}\right) - 1\ \right]\frac{\sqrt{A}}{L_p}$$

$\mathrm{L_p}$:Peripheral length of the mesh in m.

DESIGN PARAMETERS

The 69/138kV substation is fed from the 138/69kV SNI Slack Bus, as shown in Figure 3. ETAP 16.0 software is used to perform the network modeling, in addition to calculating the maximum short circuit current, at the high and low voltage busbar of the substation using the IEC 60909 Standard, included in the software extensions.

From Figure 3, the maximum short circuit current at the 69/13.8 kV substation busbars is 9.246kA. The modeling of the grounding grid will be verified using the software.

SIMULATION OF THE GROUNDING SYSTEM USING ETAP 16.00 SOFTWARE.

Grid input data is generated from ETAP 16.0 software, detailing system data, soil data, material constants, electrode data, grid configuration and design cost.

Simulation by the IEEE method.

For the simulation a grid mesh is available, which has the perimeter of the 3 castles that the substation has, 2 castles of 69kV and 1 castle of 13.8kV, the mesh has electrodes along the perimeter of the mesh. The grounding system module in ETAP 16.00 has the possibility to calculate 3 methods using the IEEE 80-2000 standard and each one generates different parameters, explained above. Shown here is the design of the 69/13.8 kV substation grid arrangement, with a short circuit current of 9.246kA. Table 1 shows the input parameters on which each model was performed, showing the mesh arrangement data for a normal simulation, optimized number of conductors and optimized number of picks and conductors. Figures 4, 5 and 6 show the results of each simulation.

Simulation by the FEM method.

Shown here is the design of the 69/13.8 kV substation mesh arrangement, with a short-circuit current of 9.246kA, using the Finite Element Analysis method.

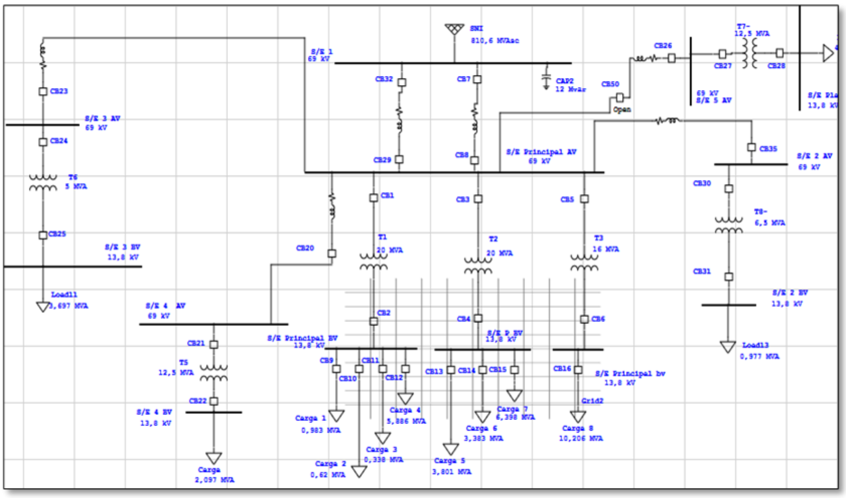
Table 1. Ground grid arrangement for normal simulation, optimized number of conductors and optimized number of picks and conductors

Parameters		Mesh configuration for normal simulation	Mesh configuration for optimized number of conductors	Mesh configuration for optimized number of conductors and spikes
Depth of conductors (m)		1,5	1,5	1,5
Mesh length (m)	**Lx**	30	30	30
	Ly	30	30	30
No. of drivers	**X**	10	3	3
	Y	10	3	3
Total number of drivers		20	6	6
Driver Type		Copper, soft drawn annealed, 1/0 AWG	Copper, soft drawn annealed, 1/0 AWG	Copper, soft drawn annealed, 1/0 AWG
No. of electrodes		20	20	4
Electrode length (m)		2.5	2.5	2.5
Electrode diameter (cm)		1,9	1,9	1,9
Earth resistance		0,121	0,176	0,188
Total design cost		$2856,00	$1346,80	$786,80

Source: own elaboration (2023)

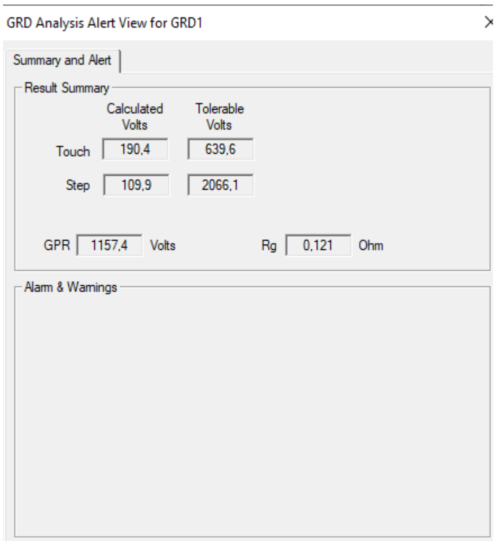
Table 2 shows the input parameters of the grounding on which the model was performed. Figures 7, 8 and 9 show the touch, step and absolute voltages after simulation using the FEM method.

Figure 2. 69/13.8 kV Substation Power Grid



Source: Obtained from Simulation in ETAP 16.00 Software.

Figure 1. Normal Simulation



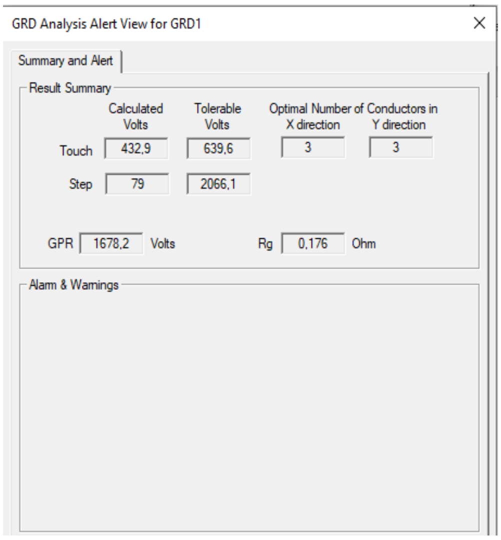
	Calculated Volts	Tolerable Volts
Touch	190,4	639,6
Step	109,9	2066,1

GPR 1157,4 Volts

Rg 0,121 Ohm

Source: Obtained from Simulation in ETAP 16.00 Software.

Figure 2. Simulation with optimized number of conductors.



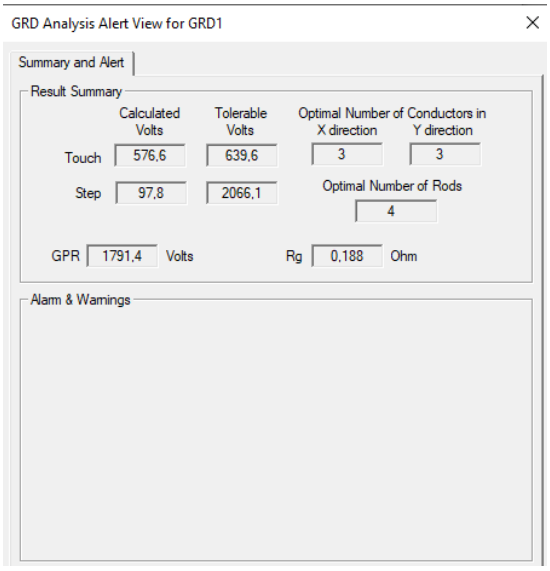
	Calculated Volts	Tolerable Volts	Optimal Number of Conductors in X direction	Optimal Number of Conductors in Y direction
Touch	432,9	639,6	3	3
Step	79	2066,1		

GPR 1678,2 Volts

Rg 0,176 Ohm

Source: Obtained from Simulation in ETAP 16.00 Software.

Figure 3. Mesh configuration with optimized number of conductors and spades.


GRD Analysis Alert View for GRD1

Summary and Alert

Result Summary

	Calculated Volts	Tolerable Volts
Touch	576,6	639,6
Step	97,8	2066,1

Optimal Number of Conductors in X direction: 3 Y direction: 3

Optimal Number of Rods: 4

GPR 1791,4 Volts

Rg 0,188 Ohm

Alarm & Warnings

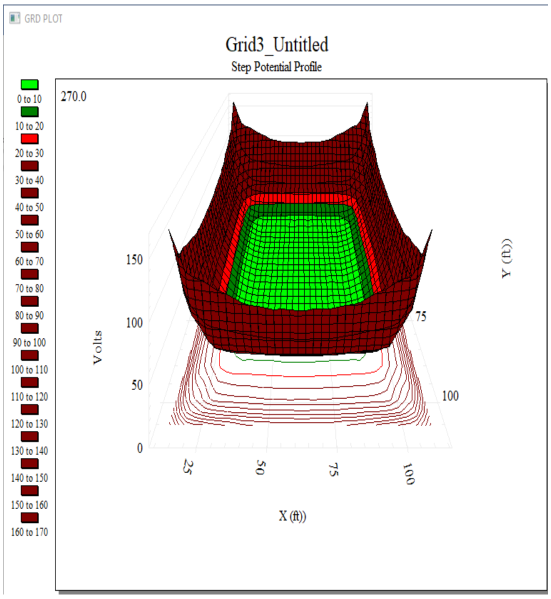
Source: Obtained from Simulation in ETAP 16.00 Software.

Table 2. Input Data

Parameters		**FEM**
Depth of conductors (m)		1,5
Mesh length (m)	**Lx**	30
	Ly	30
No. of drivers	**X**	10
	Y	10
Total number of drivers		20
Driver Type		Copper, drawn soft annealed, 1/0 AWG
No. of electrodes		36
Electrode length (m)		15
Earth resistance		0,625
Total design cost		$1700,00

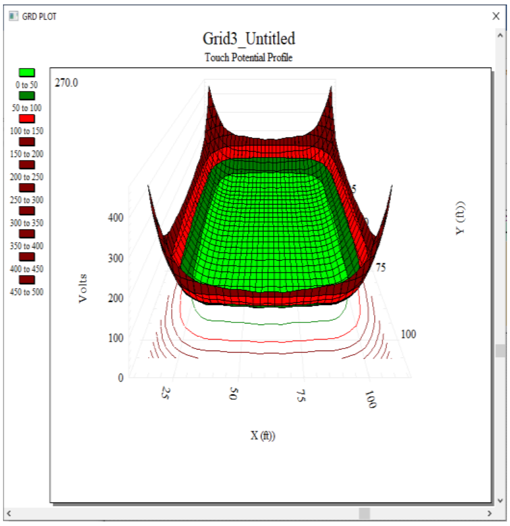
Source: own elaboration (2023)

Figure 4. Step Voltage



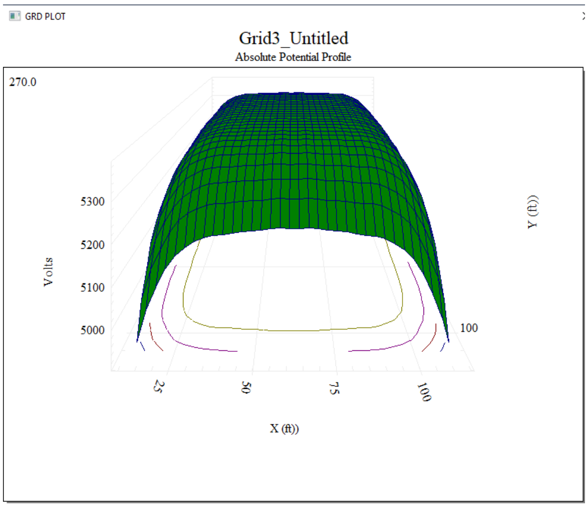
Source: Obtained from Simulation in ETAP 16.00 Software.

Figure 5. Touch Voltage



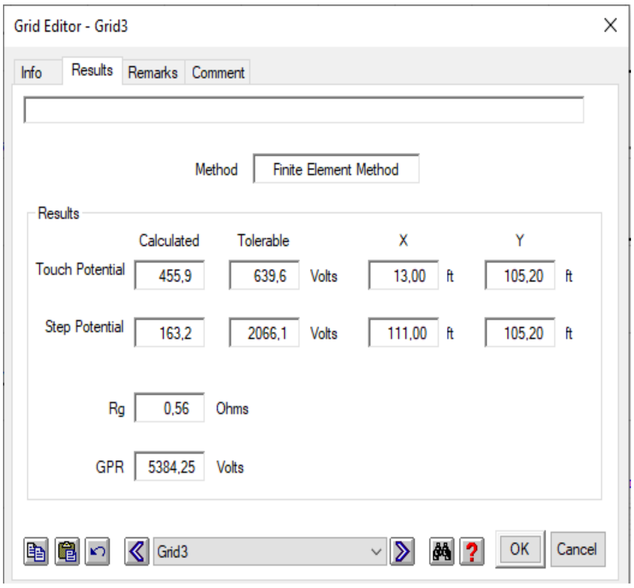
Source: Obtained from Simulation in ETAP 16.00 Software.

Figure 6. Absolute Voltage



Source: Obtained from Simulation in ETAP 16.00 Software.

Figure 7. Output parameters, FEM method.



Method: Finite Element Method

Results

	Calculated	Tolerable		X		Y	
Touch Potential	455,9	639,6	Volts	13,00	ft	105,20	ft
Step Potential	163,2	2066,1	Volts	111,00	ft	105,20	ft

Rg 0,56 Ohms

GPR 5384,25 Volts

Grid3

Source: Obtained from Simulation in ETAP 16.00 Software

The analysis is performed to evaluate the best effectiveness in terms of cost and efficiency of the ground grid design using the IEEE method and the FEM method. The results have been presented in detail in the figures and tables shown above and based on the comparison, it is determined which method is more effective and more efficient for the ground grid design.

In terms of cost, the lowest is the IEEE method with optimized number of conductors and picks.

Conductors required: The simulation shows that a greater total length of conductors is required in the FEM method (597.4 m) than in the IEEE method (179.22 m).

Required pikes: There is a higher number of pikes used in the FEM method compared to the IEEE method. The length of each stake required in the IEEE method is 2.5m while in the FEM method it is 15m.

Design Cost: The results show that the lowest cost is handled by the IEEE method with $786.80 USD and the FEM method requires $1700.00 USD. This is due to the fact that there is a greater use of material resources in the FEM method compared to the IEEE method.

Technical Effectiveness: In terms of resistance the IEEE method calculates a lower resistance of 0.18Ω while the FEM method calculated a resistance of 0.56Ω, which determines a lower GPR, however, the current dissipation along the ground grid is better in the FEM method presenting a lower touch voltage (455.9V) than the IEEE method (576.6V). It was found that for this particular case the grounding grid design is more financially optimal using the IEEE method for optimized conductors and grounding rods. It is presented that the most technically efficient method is FEM.

CONCLUSIONS AND RECOMMENDATIONS

The result of this scientific publication shows the mesh design of a grounding system for a short circuit current of 9.246kA in a 69/13.8 kV substation. Two different design methods used for the analysis were simulated through the grounding system module of ETAP 16.00 software to determine the design evaluation parameters (Grounding Resistance, GPR, Grid Voltage, Step and Touch Voltage). The FEM method presents better capabilities in terms of technical efficiency, the grounding resistance is higher than IEEE, but the current dissipation through the grid is better, $(Vtoque_{FEM} < Vtoque_{IEEE})$ The ground grid structure in FEM is more expensive compared to IEEE. The ground grid structure deteriorates with time, influencing its safety limit values, GPR, V_{toque}, V_{paso} y R_g. Therefore, it is recommended to use the FEM method for future designs because it presents results closer to reality.

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B. data research and statistical analysis:	33%	33%	33%
C. elaboration of figures and tables:	33%	33%	33%
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