

Analysis of the Grounding System of the Glugur Substation with Grid Construction

Adhi Sulaksono, Pristisal Wibowo, Adi Sastra P Tarigan

Abstract

The grounding system at the Glugur substation is one of the most important parts in the distribution of continuous, high-quality electricity. This is because the Glugur substation must work well with large disturbances that affect computer equipment, which is the main cause of damage to substation equipment. This is caused by the grounding system not functioning properly, namely due to the grounding resistance being greater than the standard limit of 0-1 ohm. Therefore, it is necessary to analyze whether the Glugur substation grounding system still meets the above standards. In this study, a specific analysis of the Glugur substation system was conducted using the grid construction method, taking into account mesh voltage, voltage, maximum grid, GPR, and soil resistivity. The results of the study show that the resistance value of the grounding system for substation equipment meets the standard of 0.10 Ω to 0.8 Ω , compared to the calculation results, namely a grounding grid without a grounding grid resistance rod ($R_g = 0.47 \Omega$) and a grounding grid with a grounding rod ($R_g = 0.18\Omega$). The maximum grounding grid current of the substation is capable of conducting power to the ground up to 9307.8 A, with a grid conductor size of 38.72 mm².

Keyword: Substation Grounding System, With Grid Construction

Adhi Sulaksono¹

¹Electrical Engineering Study Program, Universitas Pembangunan Panca Budi, Indonesia
e-mail: adhisulaksono04@gmail.com

Pristisal Wibowo², Adi Sastra P Tarigan³

^{2,3}Department of Electrical Engineering, Universitas Pembangunan Panca Budi, Indonesia
e-mail: pristisawibowo@dosen.pacabudi.ac.id², adisastra_tarigan@yahoo.co.id³

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Introduction

Substations are part of the electrical power system that are susceptible to disturbances caused by lightning strikes, namely lightning impulse voltage, open circuit impulse voltage, and truncated lightning impulse voltage and fault current. The impulse voltages and fault currents generated can damage the functionality of electrical power system equipment. Therefore, the impulse voltages and leakage currents generated must be diverted to the ground to ensure the safety limits of the electrical power system equipment and the human body in the vicinity of the substation.

The grounding system is part of the electrical power system that functions to ground any excess voltage or current, thereby minimizing any resulting interference. For ideal grounding values, the R value must be close to 0 or ≤ 1 Ohm. The above interference voltage and current do not flow into the ground due to equipment insulation failure and a sufficiently large grounding resistance value.

Because the grounding system is a device for limiting the voltage between non-electrified equipment and between these equipment parts and the ground to a certain value. The grounding system is so important for securing equipment in substations that have the function of continuously carrying very high voltage and current loads. This equipment must also be able to withstand fault currents, lightning impulse voltages, open-circuit impulse voltages, and truncated lightning impulse voltages within a matter of seconds.

The grounding of the main substation was initially carried out by planting conductor rods vertically into the ground. This was ineffective because when current and voltage appeared, they were not distributed evenly, causing the conductor rods to be damaged as they were unable to withstand the extremely high current and voltage. Therefore, a grounding design was needed for the Gelugur substation using a horizontal system relative to the ground surface and connected to other conductors to form a grid, which is then called a grid grounding system

Literature Review

2.1 Grounding System

An earthing system is a conductor connection system that connects systems, equipment, and installations to the earth/ground in order to protect humans from electric shocks and protect installation components from the dangers of abnormal voltage/current. Therefore, earthing systems are an essential part of electrical power systems

Equipment Grounding System

The equipment grounding system connects the body or frame of electrical equipment (motors, generators, transformers, circuit breakers, and other metal parts that are not normally energized) to the ground. Grounding resistance is the amount of resistance at the contact/connection between the body and the ground. Factors that affect the amount of grounding resistance are:

- a. Soil resistivity
- b. Length of grounding electrode
- c. Cross-sectional area of the grounding electrode

Grounding System Method

There are several grounding system methods, which are explained as follows:

- a. Grounding with driven ground.
Grounding with driven ground is grounding that is done by driving an electrode rod into the ground
- b. Grounding with counterpoise.
Counterpoise grounding is grounding that is carried out by planting electrode wires parallel or radially, several centimeters below the ground (30 cm – 90 cm). Counterpoise

grounding is usually used when the soil resistance is too high and cannot be reduced by driven grounding, usually because the soil resistivity is too high

c. Grounding with mesh or grid.

Grounding with mesh or grid is a method of grounding by installing longitudinal and transverse conductor wires underground, which are connected to each other at every point to form a mesh/grid. Mesh/grid grounding systems are usually installed in substations with the aim of obtaining a very low soil resistance value (less than 1 Ω)

2.2 Conductor

Each part of the grounding system, including grid conductors, connections, and all primary electrodes, must be designed so that for the expected design life of the installation, the elements will have sufficient conductivity, be able to withstand mechanical stress with a combination of disturbance magnitude and duration, have high mechanical strength, and be able to maintain their function even when exposed to corrosion

Conductor Size

Conductor size is a consideration in determining the quality of the magnitude of fault current distributed to the ground, as can be seen in the following equation:

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

Where:

- I = RMS current (kA)
- A_{mm²} = Conductor cross-section (mm²)
- T_m = Permitted maximum temperature (°C)
- T_a = Ambient temperature (°C)
- T_r = Reference temperature for material constants (°C)
- α₀ = Thermal resistivity coefficient at 0°C (1/°C)
- α_r = Thermal resistivity coefficient at reference temperature Tr (1 / °C)
- ρ_r = Resistivity of soil conductors at reference temperature Tr (μΩ-cm)
- K₀ = 1/α₀ Atau (1/α_r)- T_r(°C)
- T_c = Duration of current (s)
- TCAP = Thermal capacity per unit volume, in J/(cm³ °C)

The formula can be simplified with the following equation:

$$A_{kcmil} = I \cdot K_f \sqrt{t_c} \dots\dots\dots (2)$$

Where:

- A_{kcmil} = Conductor area (kcmil)
- I = RMS disturbance current (kA)
- T_c = Current duration (s)
- K_f = Constants for materials at various T_m values (melting temperature or limited conductor temperature based on and using ambient temperature (Ta) 40 °C

2.3 Tolerable Current Range

The most common physiological effects of electric current on the body, expressed in terms of increasing current magnitude, are threshold perception, muscle contraction, unconsciousness, cardiac fibrillation, respiratory nerve blockage, and burns. Non-fibrillation currents of magnitude I_B with a duration ranging from 0.03-3.0 s are associated with the energy absorbed by the body as described by the following equation:

$$S_B = (I_B)^2 \times t_s \dots\dots\dots (3)$$

Where:

- I_B = rms magnitude of the current passing through the bod (A)

T_s = Duration of current exposure (s)
 S_B = Empirical constant related to the electrical shock energy tolerated by a certain percentage of a given population

Tolerated Current Limit

The magnitude and duration of the current passing through the human body at 50 Hz or 60 Hz must be less than the value that can cause ventricular fibrillation of the heart. Where, in addition to the previously defined requirements for the following equation

$$K = \sqrt{S_B} \dots\dots\dots (4)$$

Dalziel discovered that the shock energy that could withstand a weight of approximately 50 kg resulted in the following equation for the permissible body current:

$$I_B = \frac{0.116}{\sqrt{t_s}} \text{ For a body weight of 50 kg} \dots\dots\dots (5)$$

Where the above equation is based, it produces alternative values of $k = 0.157$ and $S_B = 0.0246$, which apply to people weighing 70 kg (155 lb). Thus, it can be seen in the following equation:

$$I_B = \frac{0.157}{\sqrt{t_s}} \text{ For a body weight of 70 kg} \dots\dots\dots (6)$$

2.4 The Effect of Thin Surface Layers

A layer of high resistivity material 0.08-0.15 m (3-6 in) thick, such as gravel, is often spread over the ground surface above the ground grid to increase the contact resistance between the ground and human feet at substations. The relatively shallow depth of the surface material, compared to the equivalent foot radius, precludes the assumption of uniform resistivity in the vertical direction when calculating the base resistance of the foot.

$$R_f = \left[\frac{\rho_s}{4b} \right] C_s \dots\dots\dots (7)$$

$$C_s = 1 + \frac{16b}{\rho_s} \sum_{n=1}^{\infty} K^n R_{m(2nh_s)} \dots\dots\dots (8)$$

$$C_s = 1 - \frac{0.09 \cdot \left(1 - \frac{\rho}{\rho_s} \right)}{2 \cdot h_s + 0.09} \dots\dots\dots (9)$$

$$K = \frac{\rho - \rho_s}{\rho + \rho_s} \dots\dots\dots (10)$$

$$\rho = \frac{2 \cdot \pi \cdot L_r \cdot R}{\ln \left(\frac{8 \cdot L_r}{d} \right) - 1} \dots\dots\dots (11)$$

Where:

- C_s = Surface layer derating factor
- K = Reflection factor between different material resistivities
- ρ_s = Surface material resistivity ($\Omega \cdot m$)
- ρ = Earth resistivity beneath surface material ($\Omega \cdot m$)
- h_s = Surface material thickness (m)
- b = The spokes of the circular metal disc represent the legs (m)
- $R_{m(2nh_s)}$ = Mutual resistance between two similar coaxial plates, parallel, separated by a distance (2nh_s), in a medium of infinite resistivity ($\Omega \cdot m$)

Meanwhile, the voltage step limit can be seen in the following equation:

$$E_{Step50} = (1000 + 6C_S \cdot \rho_S) \frac{0.116}{\sqrt{t_S}} \text{ For a body weight of 50 kg} \dots\dots\dots (12)$$

$$E_{Step70} = (1000 + 6C_S \cdot \rho_S) \frac{0.157}{\sqrt{t_S}} \text{ For a body weight of 70 kg} \dots\dots\dots (13)$$

Similarly, the touch voltage limit can be calculated using the following equation

$$E_{Step50} = (1000 + 1.5C_S \cdot \rho_S) \frac{0.116}{\sqrt{t_S}} \text{ For a body weight of 50 kg} \dots\dots\dots (14)$$

$$E_{Step70} = (1000 + 1.5C_S \cdot \rho_S) \frac{0.157}{\sqrt{t_S}} \text{ For a body weight of 70 kg} \dots\dots\dots (15)$$

Where:

- E_{step} = Step voltage (V)
 - E_{Touch} = Touch voltage (V)
 - C_S = Surface layer derating factor
 - R_S = Surface material resistivity (Ω.m)
 - T_S = Leakage current duration (s)
- If no surface layer protector is used, then Cs = 1 and ps = ρ

2.5 Soil Resistivity Measurement

Estimates based on soil classification only produce rough estimates of resistivity. Therefore, actual resistivity measurements are very important and must be carried out at a number of locations around the substation where the soil has uniform resistivity across the entire area and sufficient depth. Typically, there are several layers, each with different resistivity.

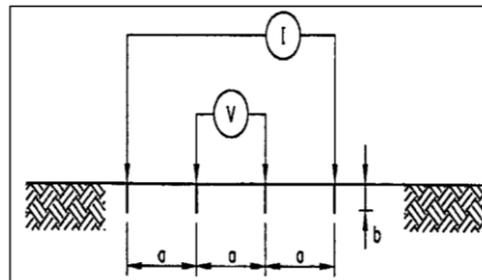


Figure 1. Four-pin Wenner resistivity measurement

The Wenner method is the four-pin Wenner method, as shown in the figure above, which is the most commonly used technique for measuring soil resistivity. In short, four probes are planted into the ground along a straight line, at equal distances apart, at a depth of b. The voltage between the two inner electrodes (potential) is then measured and divided by the current between the two outer electrodes (current) to give the resistance value R

$$\rho_a = \frac{4\pi aR}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \dots\dots\dots (16)$$

Where:

- ρ_a = Apparent resistivity of soil (Ω.m)
- R = Measured resistance (Ω)
- a = Distance between adjacent electrodes (m)
- b = Electrode depth (m)

If the small b in equation (4) can be simplified to the following equation:

$$\rho_a = 2\pi aR \dots\dots\dots (17)$$

Current tends to flow near the surface for short probe distances, while more current penetrates deeper into the ground for longer distances. Therefore, it is usually reasonable to assume that the resistivity measured for a given probe distance indicates the true resistivity of the soil to the depth of the soil layer resistivity if the contrast is not excessive. Equation (4) and Equation (5) can be used to determine the true resistivity ρ_a at depth a .

Grid rod resistance

The soil resistance between the grid and the grid rod can be seen in the following equation:

$$R_m = \frac{\rho}{\pi L_c} \left[\ln \left(\frac{2L_c}{L_r} \right) + \frac{K_1 \cdot L_c}{\sqrt{A}} - K_2 + 1 \right] \dots\dots\dots (18)$$

The combined ground resistance of the grid and rod bed will be lower than the ground resistance of the two components alone, but still higher than the parallel combination.

Table 1 Soil Resistivity Range

| Jenis Tanah (Type of earth) | Average Resistivity ($\Omega \cdot m$) |
|--|--|
| Tanah Organik Basah (Wet organic soil) | 10 |
| Tanah Lembab (Moist soil) | 10^2 |
| Tanah Kering (Dry soil) | 10^3 |
| Batuan dasar (Bedrock) | 10^4 |

2.6 Maximum grid current and fault current division factor

The factor that is the inverse of the ratio of symmetrical fault current to the portion of current flowing between the grounding grid and the surrounding earth can be seen in the following equation:

$$S_f = \frac{I_g}{3I_0} \dots\dots\dots (19)$$

Where:

S_f = Fault current divider factor

I_g = Arus grid symmetrical rms (A)

I_0 = Zero sequence fault current (A)

The maximum grid current design value, defined by the following equation

$$I_G = D_f \times I_g \dots\dots\dots (20)$$

Where:

I_G = Maximum grid current (A)

D_f = Decrease factor for the entire duration of the t_f disruption, (s)

I_g = Arus grid symmetrical rms (A)

$$GPR = I_G \cdot R_G \dots\dots\dots (21)$$

2.6 Mesh Voltage

The mesh voltage value is obtained as the product of the geometric factor, K_m ; the correction factor, K_i , which accounts for some disturbances introduced by the assumptions made in obtaining K_m ; soil resistivity ρ ; and the average current per unit length of effective drilling of the grounding system conductor (IG/LM) with the following equation:

$$E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_G}{L_M} \dots\dots\dots (22)$$

Step Voltage

The step voltage value is obtained as a result of the geometric factor (Ks); corrective factor (Ki); soil resistivity (ρ); and average current per unit of buried grounding conductor (IG / LS) using the following equation:

$$E_s = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_s} \dots\dots\dots (23)$$

Research Methodology

This research was conducted by considering the stages examined through literature review, data collection, data processing, execution/decision-making, improvement or modification, and final execution. The stages of this research can be seen in the following flowchart:

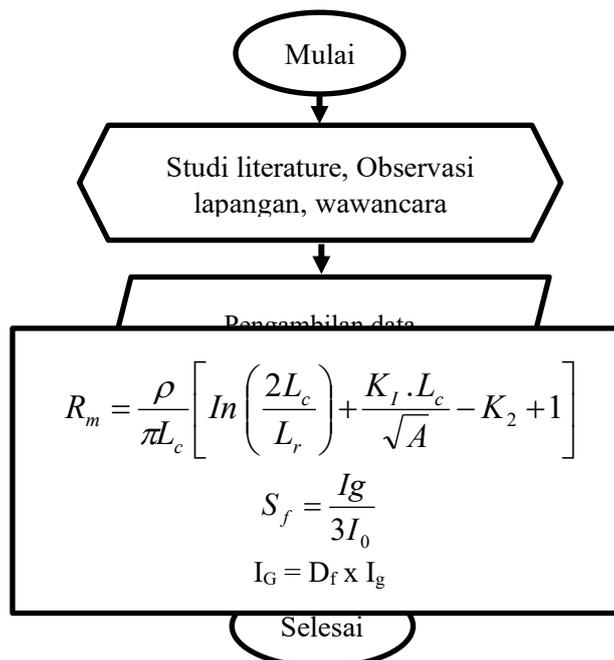


Figure 2 Research Flowchart

Results

The grounding calculation for the Glugur substation grid was calculated using two modes, namely the grounding calculation for the grid without grounding rods and the grounding calculation for the grid with grounding rods

4.1 Calculation of grid grounding without ground rods Soil resistivity

The results of soil resistance measurement at the location around the Gligur substation, so that soil resistivity can be calculated using the following equation (11):

$$\begin{aligned} \rho &= \frac{2 \cdot \pi \cdot L_r \cdot R}{\ln\left(\frac{8 \cdot L_r}{d}\right) - 1} \\ &= \frac{2 \cdot \pi \cdot 2,9,8}{\ln\left(\frac{8,2}{0,1589}\right) - 1} \\ &= 34,11 \Omega, m \end{aligned}$$

Table 2 Results of Soil Resistance Measurements in the Glugur Main Substation Area

| Depth of Grounding Rod | Measured Resistance (Ω) |
|------------------------|-------------------------|
|------------------------|-------------------------|

| | |
|------------|------|
| (m) | |
| 0,40 | 32,8 |
| 0,80 | 24,6 |
| 1,2 | 13,9 |
| 1,6 | 12,3 |
| 2,0 | 9,8 |

Table 3 Fault Current in the Glugur Substation Busbar

| Busbar GI Glugur | MAX Short Circuit Current | | |
|---------------------|---------------------------|-----------|------------|
| | Ip (kA) | Ikss (kA) | skss (MVA) |
| 3 phase | 15,513 | 6,408 | 723,6 |

Table 4 Grounding of Glugur Substation in 2025

| Bay | Substation Equipment | Resistansi (Ω) | | |
|---------------|----------------------|-------------------------|------|------|
| | | R | S | T |
| Transformer 1 | CT | 0,10 | 0,18 | 0,10 |
| | LA | 0,29 | 0,30 | 0,29 |
| | PMS | - | - | - |
| | PMT | | 0,10 | |
| Transformer 2 | CT | 0,90 | 0,30 | 0,10 |
| | LA | 0,11 | 0,10 | 0,11 |
| | PMS | - | - | - |
| | PMT | | 0,10 | |
| Transformer 3 | CT | 0,18 | 0,17 | 0,17 |
| | LA | 0,37 | 0,37 | 0,36 |
| | PMS | 0,8 | 0,8 | 0,8 |
| | PMT | | 0,15 | |

4.2 Conductor size

The size of the conductor to be used is determined by first knowing the highest fault current, which is 15.513 A. Using the typical Df value table for a fault duration of 0.5 s and a Df reduction factor of 1.0, the rms asymmetrical current is 15.513 A.

$$\begin{aligned}
 A_{Kcmil} &= I \cdot K_f \cdot \sqrt{t_c} \\
 &= 15.513 \cdot 7,06 \sqrt{0,5} \\
 &= 77,44 Kcmil \\
 &= 38,72 mm^2
 \end{aligned}$$

4.3 Touch voltage and step voltage criteria

For the thickness of the crushed rock surface layer, $h_s = 0.102$ m, with resistivity (ρ_s) = 2500 $\Omega \cdot m$ and soil resistivity (ρ) = 289 $\Omega \cdot m$, so that K can be calculated using the following equation:

$$\begin{aligned}
 E_{Step70} &= (1000 + 6C_S \cdot \rho_S) \frac{0,157}{\sqrt{0,5}} \\
 &= (1000 + 6 \cdot 0,70 \cdot 2.500) \cdot \frac{0,157}{\sqrt{0,5}} \\
 &= 2553V \\
 E_{Step70} &= (1000 + 1,5 \cdot C_S \cdot \rho_S) \cdot \frac{0,157}{\sqrt{0,5}} \\
 &= (1000 + 1,5 \cdot 0,70 \cdot 2.500) \frac{0,157}{\sqrt{0,5}} \\
 &= 804,75V
 \end{aligned}$$

Grid resistance

From the equation $L_T = 380$ m and area $A = 1500$ m², the grid resistance can be calculated using the following equation:

$$\begin{aligned}
 R_g &= \rho \left[\frac{1}{L_T} + \frac{1}{\sqrt{20 \cdot A}} \left(1 + \frac{1}{1 + h \sqrt{\frac{20}{A}}} \right) \right] \\
 &= 34,11 \left[\frac{1}{380} + \frac{1}{\sqrt{20 \cdot 1500}} \left(1 + \frac{1}{1 + 0,5 \sqrt{\frac{20}{1500}}} \right) \right] \\
 &= 0,47\Omega
 \end{aligned}$$

Maximum grid current

The maximum grid current can be calculated using the following equation and referring to $D_f = 1.0$ and current division factor $S_f = 0.6$. Then IG can be calculated as follows:

$$\begin{aligned}
 I_G &= D_f \cdot S_f \cdot 3I_0 \\
 &= 1.0 \cdot 0,6 \cdot 15.513 \\
 &= 9307,8A
 \end{aligned}$$

GPR (Ground Potential Rise)

The comparison between IG and Rg or GPR with the tolerable touch voltage $E_{touch} 70$ can be calculated using the following equation:

$$\begin{aligned}
 GPR &= I_G \cdot R_g \\
 &= 9307,8 \cdot 0,47 \\
 &= 4.374,66V
 \end{aligned}$$

Mesh voltage

E_m can be calculated using the following equation:

$$\begin{aligned}
 E_m &= \frac{\rho \cdot I_G \cdot K_m \cdot K_i}{L_C \cdot L_R} \\
 &= \frac{34,11 \cdot 9307,8 \cdot 1,09 \cdot 0,72}{160 \cdot 380} \\
 &= 461,42V
 \end{aligned}$$

Table 5 Results of Grounding Calculations for Grids Without Grounding Rods and Grids With Grounding Rod

| Indicator | Grid Landing | |
|----------------------|------------------------|---------------------|
| | Without Grounding Rods | With Grounding Rods |
| Grid resistance | 0,47 Ω | 0,18 Ω |
| Maximum grid current | 9307,8 A | 9307,8 A |
| GPR | 4374,66 V | 1675,40 V |
| Mesh Voltage | 461,42 V | 500,92 V |
| Step Voltage | 63,47 V | 63,47 V |

4.4 Grid layout

Calculations with a grid spacing of $D = 10$ m, and a grid size of 50×30 m, assume a 6×4 grid conductor pattern using 24 grounding rods, each 2 meters long. The combined length of the LT grid conductor is $(4 \times 50 \text{ m}) + (6 \times 30 \text{ m}) = 380$ m

Grid resistance

To calculate R_g as in the previous calculation, determine that L_T is $380 + (24 \times 2) = 428$ m and the area $A = 1500 \text{ m}^2$. R_g can be calculated using the following equation

$$\begin{aligned}
 R_g &= \rho \left[\frac{1}{L_T} + \frac{1}{\sqrt{20 \cdot A}} \left(1 + \frac{1}{1 + h \sqrt{\frac{20}{A}}} \right) \right] \\
 &= 34,11 \left[\frac{1}{428} + \frac{1}{\sqrt{20 \cdot 1500}} \left(1 + \frac{1}{1 + 0,5 \sqrt{\frac{20}{1500}}} \right) \right] \\
 &= 0,18 \Omega
 \end{aligned}$$

Maximum grid current and GPR

The maximum grid current is the same as before, namely 9.307.8 V and $R_g = 0.18 \Omega$, so

$$\begin{aligned}
 GPR &= I_G \cdot R_g \\
 &= 9307,8 \cdot 0,18 \\
 &= 1675,40V
 \end{aligned}$$

Mesh voltage

$$\begin{aligned}
 E_m &= \frac{\rho \cdot I_G \cdot K_m \cdot K_i}{L_C + \left[1,55 + 1,22 \left(\frac{L_r}{L_x^2 + L_y^2} \right) \right] L_R} \\
 &= \frac{34,11 \cdot 9307,3 \cdot 1 \cdot 0,72}{380 + \left[1,55 + 1,22 \left(\frac{2}{(50)^2 + (30)^2} \right) \right] 48} \\
 &= 500,92V
 \end{aligned}$$

Step voltage (E_{step})

Where

$L_c = 160 \text{ m}$, $L_R = 380 \text{ m}$

then

$$\begin{aligned} L_s &= 0,75 \cdot L_c + 0,85 \cdot L_R \\ &= 0,75 \cdot 160 + 0,85 \cdot 380 \\ &= 443V \end{aligned}$$

Therefore, ice can be determined using the following equation:

$$\begin{aligned} E_s &= \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_s} \\ &= \frac{34,11 \cdot 0,123 \cdot 0,72 \cdot 9307,8}{443} \\ &= 63,47V \end{aligned}$$

From the calculation results, several things can be analyzed that are important in determining the appropriate grounding resistance value in accordance with the standard for substations, which is 0–1 Ω . Soil resistivity is an important parameter in determining what type of grounding will be used in accordance with the soil conditions. In the calculations that have been carried out, the resistivity obtained from this study is 34.11 $\Omega \cdot \text{m}$, with a soil depth of 2 meters. The size of the conductor is important because it can determine the amount of fault current that will be distributed to the ground. From the calculation results, the conductor size is 38.72 mm². The safety of a person in a substation area depends on preventing the magnitude of electric shock energy from being absorbed under normal or fault conditions. The energy in question is touch voltage and step voltage, which have permissible criteria limits from the calculation results of $E_{\text{step}} 70 \text{ kg} = 2553 \text{ V}$ and $E_{\text{touch}} 70 \text{ kg} = 804.75 \text{ V}$.

Conclusion

From the results of the analysis and discussion, the following conclusions can be drawn:

- The resistance value of the grounding system for substation equipment meets the standard of 0.10 Ω to 0.8 Ω , compared to the calculation results, namely grid grounding without grid resistance grounding rods ($R_g=0.47 \Omega$) and grid grounding with grounding rods ($R_g=0.18\Omega$). The lower the grounding resistance value, the lower the GPR (Ground Potential Rise)
- The maximum grounding grid current of the substation is capable of conducting fault currents to ground up to 9307.8 A, with a grid conductor size of 38.72 mm²
- The mesh voltage is lower than the touch voltage criteria limit, meeting the standard of 461.42 V vs. 829.84 V and 500.92 V vs. 829.84 V
- The step voltage is lower than the touch voltage criteria limit, which meets the standard of 63.47 V vs. 2533 V
- Adding more electrode rods and grid conductors will provide a modification solution to obtain a lower resistance value

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