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Evaluation Substation Protection System From Lightning Strikes At 150kV Jatigede Substation

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***Abstract* – Grounding serves a crucial role in the field lightning protection, electric power, and electric power communications networks. The grounding system's purpose is to guide the flow of electrical charges to the ground mass as rapidly as feasible. The goal of this study is to analyze the grounding system utilized to ensure the continuity of electrical energy production and delivery. In this study, quantitative methods are used to calculate lightning parameters, substation protection by earthing wires and protection towers, earthing system, mesh voltages, touch voltages and step voltages. According to IEEE 80-2013 (latest revision) standards, an ideal earthing application should have a resistance value of <1Ω. The results of the analysis and calculation of the grounding system using the grid grounding type obtained a value of 0.28276 Ω (<1Ω), and mesh voltage 0,851314 kV. The protection system which consists of a 103.47288 M ground wire and a 55.27325 M protection tower, is capable of protecting the substation from lightning strikes with a peak current of 51.32913 kA. The touch voltage for humans weighing 50kg and 70kg is 133.39304 V and 180.54060 V, and the step voltage results in 185.5770 V and 251.1690 V. When the grounding current at touch and step voltages is considered, the values become 442.87730 kV and 616.17712 kV. Both exceed the allowed levels of 626 and 2,216 V.**

Keywords: Lightning Strike, Grounding System, Protection System, Substation.

I. INTRODUCTION

Indonesia is a tropical country that has a high lightning density each year. Lightning density in Indonesia ranges from 5 to 15 lightning strikes per kilometer annually. Power system components, especially those located in substations, are vulnerable to lightning strikes due to their relatively high intensity.[1] Substations are part of a power generation system that includes generation, transmission, and distribution. In distributing electrical energy, it is necessary to ensure the safety of each electrical part.[1] Therefore, to protect the substation from lightning strikes, a protection system is needed that can drain the surge current that arises, the protection system in question is a grounding / earthing system.

Earthing or grounding is a process of connecting an electrical element to the core of the earth, with its potential reference point being zero. The function of the grounding system is to direct the flow of electrical charges to the ground mass as quickly as possible.[2] Another purpose of the earthing system is to ensure the safety and protection of personnel exposed electrically live equipment, by utilizing a low resistance path, consisting of horizontal ground network elements, the fault current is directed to ground embedded conductors, vertically driven earth electrodes, and earthmoving equipment.[3]

This article presents an evaluation of the grounding system that has been installed in the Jatigede 150 kV Substation area using manual calculations and Ms.Excel software as a tool used for data collection and data processing that has been obtained by the researcher himself, reference for analyzing and calculating based on IEEE Std. 80-2013. This study focuses on the grounding system by analyzing the average rainfall and number of thunder days in the Sumedang area. And can inform all readers about the importance of a good grounding system as a protection system.

II. LITERATURE REVIEW

A. *Lightning Surge*

Lightning is an electrical discharge that occurs between clouds, within clouds, or between clouds and the ground. If there are positive and negative charges in a cloud, then when these charges meet there is an attractive force that can cause lightning in the cloud. Lightning currents can be offset by passing waves through the network and transmitting them to the ground.[4] The earth is a storehouse of positive and negative charges, if the discharge from lightning is close to the earth, there will be a lightning strike to the earth.[5]

B. *Grounding System*

Ground is the most effective way to protect yourself from electric shock.[6] The grounding system is a very good protection system, because it keeps the substation safe from lightning strikes. Electrical equipment at 150 kV substations must be protected from lightning strikes, because high potential differences can cause component damage.[7] Network impedance, current, and contact voltage are safety threshold parameters used to measure the performance of a grounding system. This safety threshold setting is calculated using IEEE 80 calculations.[8]

C. *Protection System*

An electric power system cannot be separated from potential disturbances that can occur at various stages, from production, transmission, to distribution.[9] A protection system is a set of protective equipment that includes the main equipment and other equipment needed to protect electrical equipment and prevent interference.[10] Generally,[11], [12] protection is a type of security for electrical equipment that helps prevent damage and maintain the stability of electrical power distribution. A protection system will operate effectively if it meets the standards of reliability, selectivity, sensitivity, and speed.[12]

D. *Lightning Parameters*

According to study by Panji A. Dwizra, the density of lightning strikes to the ground and an area's latitude coordinates affect the peak current amplitude, which determines the lightning parameters. Things that need to be considered when observing lightning include: [13]

1. Relationship between Lightning Strike Density (Fg) and IKL (T), if the effect of rain is included it can be calculated using the following equation:

$$F_g = (123x10^{-4})xP^{0,563}xT^{0,33} \qquad (1)$$

Description:

Fg = Lightning strike density to the ground (strikes/km2/year).
P = average annual rainfall in millimeters
T = Iso Keraunik Level (days / year) or the average number of thunderstorm days per year.

2. Relationship between peak current amplitude (I) and lightning strike density (Fg) and latitude (L)

$$I = f_g^{0,3420\,x} e^{(3,2585-0,004.L)} \qquad (2)$$

3. Effect cloud low level

$$I_o = 29,5143\,x\,F_g^{0,332737} x\, e^{(-4,14107x10-3.L_i)x(-2,40752x10^{-4}xHa)} \qquad (3)$$

Description:

I$_o$ = Peak lightning current (KA)
Li = Degree of latitude of the area concerned
Fg = Density of lightning strikes to the ground (strikes/km2.th)
T = Number of thunders (days/year) or IKL (Isokeraunic Level)
P = Total rainfall (mm/year)
A = Height of the lowest cloud (meter)

E. *Direct Lightning Strike*

Direct lightning strikes are strikes that strike the phase and auxiliary phase conductors (poles), although lightning strikes directly on the conductor phases of the power grid are more common. To reduce the impact of direct lightning strikes, it is important to have a proper grounding system and protect the ground wire. Earth wires (or simply earth wire) are used to protect the environment.The height of the protection tower (lightning tower) is also a crucial aspect. [14]

1. Ground Wire Protection

To make calculations with ground wire, first calculate the strike distance. To calculate the strike distance, use the equation:

$$r_g = 8xI^{0,65} \qquad (4)$$

$$r_c = \gamma_c x r_g \qquad (5)$$

$$r_s = \gamma_s x r_g \qquad (6)$$

Where :γ_c and γ_s is 1 if the ground wire ≤ 18M

Description:

rg = Strike distance to ground (M)
rs = Strike distance from ground wire (M)
rc = Conductor striking distance which is the meeting of two arcs rs (M)

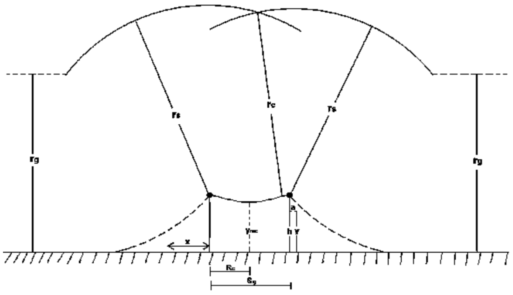

Figure 1. Protection use Ground Wire

After calculating the strike distance, the next step is to determine the length of the protection area, which may be computed using the equation :

$$a = \sqrt{r_c^2 - (r_g - h)^2} - \sqrt{r_c^2 - (r_g - y)^2} \qquad (7)$$

Description:

a = Length of protection area (M)
h = Height of ground wire or protection tower (M)
y = Height of the object to be protected (M)

The equipment in the substation must be properly protected because each has a different height, so it is necessary to calculate the minimum protection height that allows the equipment to be properly protected. To calculated the minimum height protection using the equation :

$$y_{mc} = h - r_c + \sqrt{r_s^2 + R_c^2} \qquad (8)$$

And to find value of R_c^2 can use the equation :

$$R_c^2 = {}^1\!/_2\, x\, S_g \qquad (9)$$

Description:

y$_{mc}$ = Minimum protection height (M)
R$_c$ = Half distance between ground wires (M)
S$_g$ = Distance between ground wires (M)

2. Protection Using Protected tower

The radius of the protection tower circle indicates the protected area, and the radius of the protection tower circle indicates the reachable area. With the known parameters, the protection tower circle radius value can be calculated using the equation:

$$a_0 = \sqrt{{r_s}^2 - \left(r_g - h\right)^2} \qquad (10)$$

Description :
a_0 = the radius of the protection.

F. Soil Resistivity

PUIL 2000 states that different soil types have different levels of resistance. Dry soils and rocky or sandy soils have different levels of resistance. Each soil type's resistance is listed in the table below :[15]

Table 1 Soil Resistivity

Type Of Soil	**Soil Resistivity(Ohm-Meter)**
Farmland or swamp	30
Clay or field	100
Wet Sand	200
Wet Gravel	500
Dry sand and gravel	1000
Rocky Soil	3000

Source : PUIL 2000

G. Grounding Electrodes

Ground electrodes are conductors embedded in the ground and in direct contact with the earth. The purpose of this direct contact is to achieve the best current flow in the event of a fault and direct the current to the ground.[16] According to PUIL 2000 an electrode is an introducer implanted into the ground that makes direct contact with the ground.[15]

1. Grid Electrode

Grounding electrodes are often employed in power plants, substations, and high-voltage system rooms due to high residual currents. Grounding networks can be classified into two categories: those that consider the conductor depth factor and those that ignore it. [16]

a. Concern with the conductor depth factor

$$R_g = p\left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] \qquad (11)$$

b. Not concern with the conductor depth factor

$$R_g = \frac{\rho}{4}\sqrt{\frac{\pi}{A}} + \frac{\rho}{L_T} \qquad (12)$$

Description :
ρ = Soil resistivity (ΩM)
L = Length of each electrode arm (M)
A = Area of the grounding grid (m2)
LT = Total length of the grounded conductor (M)

H. Mesh Voltage

Mesh voltage (Em) is one kind of touch voltage. Mesh voltage is the maximum voltage that can show as touch voltage in a GI earthing system. [17], [18] The equation can be calculated using the following formula:

$$E_m = \frac{\rho \; x \; K_m x \; K_i \; x \; I_G}{L_M} \qquad (13)$$

Description :
E_M = Mesh voltage (Volt)
K_m = Grid configuration geometry factor
K_i = Rectification factor
I_G = Lightning current (kA)
L_M = Grounded effective conductor length (M)

To find configure geometric grid factor :

$$K_m = \frac{1}{2\pi}\left[ln\left(\frac{D^2}{16\,hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d}\right) + \frac{K_{ii}}{K_h} ln\left(\frac{8}{\pi\,(2n-1)}\right)\right] \qquad (14)$$

Description :
D = Distance between conductors (meters)
d = Conductor diameter (meter)
h = Grid depth (meters)
n = conductor value, for a square grid n = 1
Kii = 1, with grounding along the grid
Kh = Reference grid depth (meters)
h = Depth of grounded conductor
To find the grounded effective conductor length :

$$L_M = L_C + L_R \qquad (15)$$

Description :
LC = Horizontal conductor length (M)
LR = Total length of grounded conductor (M)

I. Touch Voltage

Touch stress is the stress that exists between a touched object and a point 1 meter away. Predicting that the touched object is connected to the ground beneath it. [17], [18] The ilustration can shown on the figure below:

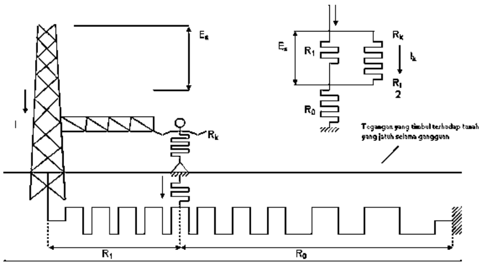

Figure 2 Ilustratrion Touch Voltage [19]
Source : IEEE 80-2013

The amount of touch voltage felt by the body with a body resistance of 1000 Ω can be made by the equation :

$$E_{touch} = (1000 + 1{,}5\,C_S\,\rho_S)\frac{k}{\sqrt{t_s}} \qquad (16)$$

C_S can also be used to compute the effective foot when there is thickness up to the material's surface. The CS value can be obtained using the equation:

$$C_S = 1 - \frac{0{,}09\left(1 - \frac{\rho}{\rho_S}\right)}{2h_s + 0{,}09} \qquad (17)$$

Description :
E_T = Touch voltage (Volts)

C_S = Surface coating factor and is affected by the thickness of the buried conductor
ρs = Resistivity of the material (Ωm)
ts = Time the current passes through the human body (Sekon)
hs = Thickness of material (meter)

A listing of the permitted touch voltage limitations will be provided below:

Table 2 Touch Voltage

Length Disturb (S)	**Touch Voltage can be allowed (volt)**
0,1	1.980
0,2	1.400
0,3	1.140
0,4	990
0,5	890
1,0	626
2,0	443
3,0	363

Source : IEEE 80-2013

J. Step Voltage

The voltage that appears when the fault current passes through the two feet of a person standing on the ground that is fed by the fault current to the ground. Assume the distance of the person is 1 meter. [17], [18] The ilustration can shown on the figure below:

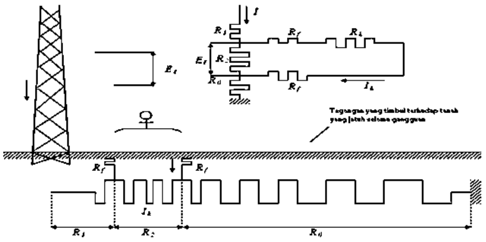

Figure 3 Ilustration Step Voltage [19]

To calculate the amount of step voltage felt by a body having a resistance of 1000 Ω, use the following equation:

$$E_{step} = (1000 + 6\, C_S\, \rho_S) \frac{k}{\sqrt{t_s}} \quad (18)$$

A listing of the permitted step voltage limitations will be provided below:

Table 3 Step Voltage

Length Disturb (S)	**Step Voltage can be allowed (volt)**
0,1	7,000
0,2	4,950
0,3	4,040
0,4	3,500
0,5	3,140
1,0	2,216
2,0	1,560
3,0	1,280

III. METHODOLOGY

To evaluate the grounding system as a substation protection system, this study employs a quantitative methodology, which is utilized to analyze and execute calculations. The first stage in doing this research is to read the literature review and make field observations for data collecting at the 150 kV Jatigede Substation. Once the data is collected, calculate the lightning parameters, substation protection system (ground wire and protection tower), grounding system, mesh voltage, touch voltage, and step voltage. Optimization parameters in this research, and use IEEE 80-2013 standard for parameters calculation. As shown in the figure below :

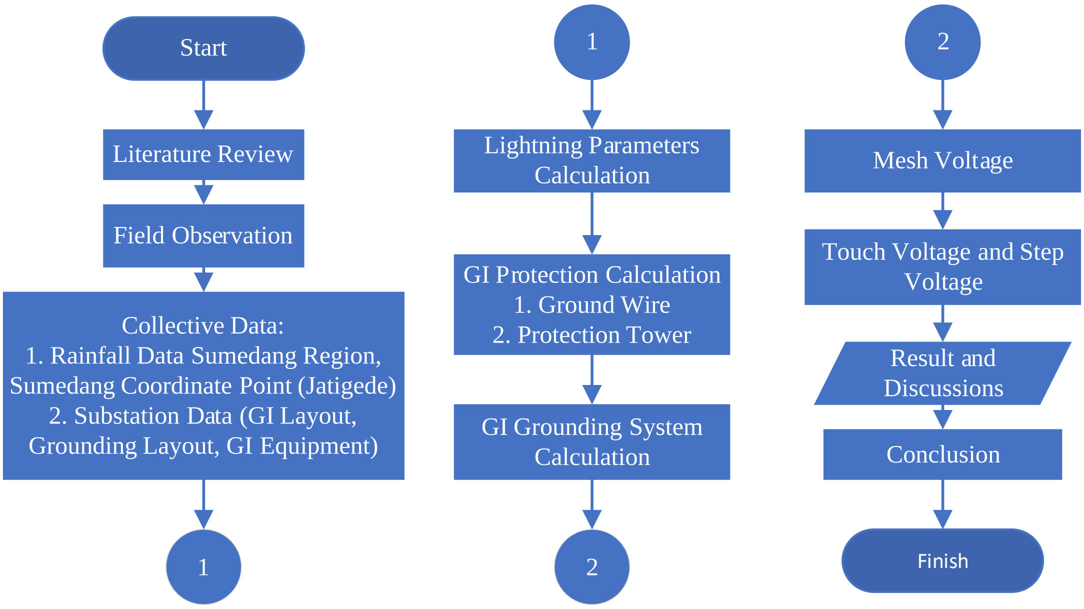

Figure 4 Flowchart Research Methods

IV. RESULTS AND DISCUSSION

A. *Calculation of Lightning Parameters*

1. Isokeraunik Level(IKL)/KM^2
   IKL = 102 Strikes km2/Year
2. Calculated the average rainfall
   $\rho = \frac{total\,rainfall}{year}$
   $= 3104{,}666667 \frac{mm}{tahun}$
3. Calculation of the Total of Lightning Strikes to the Ground.
   $f_g = 123x10^{-4} x\, p^{0{,}563} x\, (IKL)^{0{,}33}$
   $= 5{,}2329\, Strikes/km^2 - Year$

4. Calculation peak Current
   $\hat{I} = 29{,}5143\; x\; f_g^{0{,}332737} x$
   $e^{\{(-4{,}14107 \text{ x } 10^{-3}\; x\; L_i)\; x\; (-2{,}40752 \text{ x } 10^{-4}\; x\; A)\}}\; kA$
   $\hat{I} = 29{,}5143\; x\; 1{,}73441\; x\; e^{(0{,}00272)}$
   $= 51{,}32913\; kA$

B. *Substation Protection Calculations*

1. Substation Protection Using Ground Wire
   - Calculating the minimum strike distance

   $r_g = 8\; x\; I^{0{,}65}$
   $= 8\; x\; (51.32913)^{0{,}65}$
   $= 103{,}47288\; M$
   $r_s = \gamma_s\; x\; r_g$
   $= 103{,}47288\; M$
   $r_c = \gamma_c\; x\; r_g$
   $= 103{,}47288\; M$

   After obtaining the values of rg, rc, and rs, then calculate the length of the protection area drawn from the conductor height to show the protection area.

$a = \sqrt{r_c{}^2 - (r_g - h)^2} - \sqrt{r_c{}^2 - (r_g - y)^2}$
$= \sqrt{(103{,}47288\;)^2 - (87{,}47288)^2}$
$- \sqrt{(103{,}47288\;)^2 - (95{,}47288)^2}$
$= 15{,}37881$ M

   - Minimum Height Protection

   $y_{mc} = h - r_c + \sqrt{r_s{}^2 - R_c{}^2}$
   $r_c = \frac{1}{2}\, s_g = 23{,}25\; M$
   $16 - 103{,}47288 + \sqrt{(103{,}47288)^2 - 23{,}25^2}$
   $= 13{,}3541$ M

2. Substation Protection Using a Protection Tower.
   - Calculating the Radius of the Protection Circle

   $a_0 = \sqrt{r_s{}^2 - (r_g - h)^2}$
   $= \sqrt{103{,}47288^2 - 87{,}47288^2}$
   $= 55{,}27325$ M

   So, Protection using Ground Wire and Protection Tower is 103,47288 M and 55.27325 M.

C. *Substation Grounding Calculation*

Jatigede substation grounding system has a square grid shape with Stranded Bare Copper conductor type with rounded Core Copper Conductors diameter 20.25 mm, thickness 0.81 mm, resistance 120 Ω.

Table 4 Data Parameters Grounding System

No.	Data	Value
1	Lenght	146 M
2	Widht	79 M
3	Area	11534 MM²
4	Total Length of conductor	6636 M
5	Number of grid	851
6	Resistance type	100 ohm/Clay
7	Grid depth	0,4 M

1. Grid Resistance Calculation
   To calculate the grid resistance with respect to the grid depth factor, we can use the equation :
   $R_g = p\; \left[\frac{1}{L_T} + \frac{1}{\sqrt{20A}} + \left(1 + \frac{1}{1+h\sqrt{20/A}}\right)\right]$
   $= 100\; (0{,}00015070\; +\; 0.00267690)$
   $= 0.28276\; \Omega$

D. *Calculate Mesh Voltage*

$E_M = \frac{\rho\; x\; K_m x\; K_i\; x\; I_G}{L_M}$

Before the mesh voltage value can be calculated, it must first calculate the value of the grid configuration geometry factor (Km), the repair factor (Ki), and the effective buried conductor length.

$K_M = \frac{1}{2\pi}\left[\ln\left(\frac{D^2}{16\,hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d}\right) + \frac{K_{ii}}{K_h}\ln\left(\frac{8}{\pi\,(2n-1)}\right)\right]$

Where:
ρ = 100 Ohm
Kii = 1, grounding along the grid
Kh = Reference grid depth
To find the value of Kh use the equation:

$K_h = \sqrt{1 + \frac{h}{h_0}}$ where the value (h) is = 0,4M and h$_0$ = 3M
= 1.06460 M

For a grid that is square in shape then: n=1

$K_m = \frac{1}{2\pi}\left[\ln\left(\frac{D^2}{16\,hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d}\right) + \frac{K_{ii}}{K_h}\ln\left(\frac{8}{\pi\,(2n-1)}\right)\right]$
$= 0{,}15924\; [\,\ln\,(6{,}94444 + 29{,}71200 - 4{,}93830)\; +$
$0{,}93931\; \ln\,(2{,}54777)]$
$= 1{,}79041$

$K_i = 0{,}644 + (0{,}148x1)$
$= 0{,}792$
$I_G = 51.32913\; kA$
$L_M = L_C + L_R$
$= 3358 + 6636$
$= 9994$ M
Then :
$E_M = \frac{\rho\; x\; K_m x\; K_i\; x\; I_G}{L_M}$
$= \frac{85008028}{9994}$
$= 0{,}851314$ kV

The presence of current flowing into the grounding system will cause the onset of touch voltage and step voltage. To calculate the amount of current flowing into the body based on Dalziel's experiment can be calculated using the equation.

$$I_B = \frac{k}{\sqrt{t_s}}$$

- For people weighing 50kg

$$= \frac{0{,}116}{\sqrt{1}}$$
$$= 0{,}116\ A$$

- For people weighing 70kg

$$= \frac{0{,}157}{\sqrt{1}}$$
$$= 0{,}157\ A$$

- Find the value Z_{touch} :

$$Z_{touch} = 1{,}5\ x\ p$$
$$= 150\ \Omega$$

E. Calculate Touch Voltage

To calculate the value of touch voltage with human body resistance is 1000 Ω can use the equation:

$$E_{touch} = (1000 + 1{,}5\ C_s p_s)\frac{k}{\sqrt{t_s}}$$
$$C_s = 1 - \frac{0{,}09\left(1-\frac{\rho}{\rho_s}\right)}{2h_s+0{,}09}$$
$$= 0{,}83300$$

- For people weighing 50kg

$$E_{touch} = (1000 + 1{,}5\ x\ 0{,}83300\ x\ 120)\frac{0{,}116}{\sqrt{1}}$$
$$= 133{,}39304\ \mathrm{V}$$

- For people weighing 70kg

$$E_{touch} = (1000 + 1{,}5\ x\ 0{,}83300\ x\ 120)\frac{0{,}157}{\sqrt{1}}$$
$$= 180{,}54060\ \mathrm{V}$$

F. Calculate Step Voltage

To calculate the step voltage value with 1000 Ω human body resistance can use the equation:

$$E_{step} = (1000 + 6\ C_s p_s)\frac{k}{\sqrt{t_s}}$$

- For people with weight 50kg

$$E_{step} = (1000 + 6\ x\ 0{,}83300\ x\ 120\frac{k}{\sqrt{t_s}}$$
$$= 185{,}5770\ \mathrm{V}$$

- For people with weight 70kg

$$E_{step} = (1000 + 6\ x\ 0{,}83300\ x\ 120\frac{k}{\sqrt{t_s}}$$
$$= 251{,}1690\ \mathrm{V}$$

The value of the touch voltage when considering the magnitude of the fault current with the following known data:

Ground wire radius (r) = 0.00025434 m
Average height of ground wire (ht) = 16 m
Distance between ground wires (a) = 9.13 m

$$Z_{channel} = 60\ In\left(\frac{2h_t}{\sqrt{ar}}\right)$$
$$Z_{channel} = 60\ In\left(\frac{2\ x\ 16}{\sqrt{9{,}13\ x\ 0{,}00025434}}\right)$$
$$= 389{,}49840\ \Omega$$

$$V_{system} = 150000\ V$$
$$I_{system} = \frac{V_{system}}{Z_{channel}}$$
$$= 0{,}385111\ \mathrm{kA}$$

Then:

$$E_{touch} = I_g\ (R_b + Z_{touch})$$
$$= 385{,}11070\ (1000\ +\ 150)$$
$$= 442{,}87730\ \mathrm{kV}$$

The value of the current flowing into the body based on Dalziel's experiment at step voltage is the same as the touch voltage, the difference is the step impedance value (Zstep)

$$Z_{step} = 6(p)$$
$$= 600\ \Omega$$

The value of the touch voltage when considering the magnitude of the fault current is :

$$E_{step} = I_g\ (R_b + Z_{Step})$$
$$= 385{,}11070\ (1000\ +\ 600)$$
$$= 616{,}17712\ \mathrm{kV}$$

Table 5 Overall Calculation Data

No.	Parameters	Value
1.	Grid resistance	0.28276 Ω
2.	Mesh voltage	0,851314 kV
3.	Current flowing into the body:	
	a. Body weight 50 kg	0,116 A
	b. Body weight 70 kg	0,157 A
4.	Impedance:	
	a. Touch impedance	150 Ω
	b. Step impedance	600 Ω
5.	Touch voltage:	
	a. Body weight 50 kg	133,39304 V
	b. Body weight 70 kg	180,54060 V
	c. Based on grounding current	442,87730 kV
	d. Allowable limit	626 V
6.	Step Voltage:	
	a. Body weight 50 kg	185,5770 V
	b. Body weight 70 kg	251,1690 V
	c. Based on grounding current	616,17712 kV
	d. Allowable limit	2.216 V

Based on the calculations that have been carried out for the Jatigede Substation protection system using ground wire protection and protection towers, with a peak current of 51.32913 kA can be seen in the results of the ground wire with a distance of 103.47288 M and the radius of the protection tower with a distance of 55.27325 M. This proves that both are able to protect the components inside the substation, so it can be said that the protection system is working properly.

Then in the calculation of the Jatigede Substation grounding system with the grid grounding type, the resulting grid resistance is 0.28276 Ω (<1 Ohm) in accordance with IEEE 80-2013 standard, and the mesh voltage is 0.851314 kV. The touch voltages for people weighing 50 kg and 70 kg were 133.39304 V and 180.54060 V. Similarly, the step voltage for people weighing 50 kg and 70 kg was 185.5770 V and 251.1690 V. The touch voltage and step voltage are within the permissible limits of 626 V and 2,216 V.

However, when we analyze the ground current at touch voltage and step voltage, the values are 442.87730 kV and 616.17712 kV, which exceed the permitted tolerances. So, in this scenario, we infer that touch and step voltages are unsafe.

V. CONCLUSION

Based on the results and discussion, we conclude that the protection system using ground wire and protection towers can protect substation components from lightning strikes with a peak current of 51.32913 kA. The calculation results of the Grid grounding system at Jatigede Substation are in accordance with IEEE 80-2013 standards. The values of touch voltage and step voltage are within the permissible limits. However, when paying attention to the grounding current, both exceed the permissible tolerance limit with a value of 626 V and 2,216 V, so it can be said to be unsafe.

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