Economic Design of Substation Grounding Grid using ETAP Software: A Case Study of 2 x 500 MVA Galang Substation

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Abstract. Substation grounding purpose is to secure the safety of personal that are in the vicinity and provide protection of the equipment when short circuit faults. The grounding grid design is an important factor in a substation for fulfilling standard requirements formulated by IEEE Std. 80. Commonly, substation grounding is grid configuration or combination of grid and rod. This study is designing a substation economically by considering the length of rod conductor used. Some grid configuration models were used for analyzing viz. rectangular shape, T-shape and L-shape. The models were compared with the existing design in the Galang substation for finding the minimum conductor length. The grid grounding of the Galang substation is the rectangular shape. By using ETAP package software, the important parameters in design substations such as step voltage, touch voltage for 50 kg body weight can be obtained. The parameters must fulfill the IEEE std. 80-2013 as a safety requirement for designing of the substation. From various configurations were applied, all the shapes models meet the IEEE Std. 80, but T-shape is the most economical design based on the conductor length used.

1. Introduction

The purpose of substation grounding is to secure the safety of the environment for any people that are in the vicinity and provide protection of electrical equipment when short circuit faults. The faults can result from lightning strikes, animals and insulation breakdown of the equipment, etc. Generally, construction of substation grounding is grid shape. Grounding grid design in a substation is the important factor in a substation to fulfill standard requirements formulated by IEEE Std. 80. Commonly, substation grounding is grid configuration or combination of grid and rod. The objective of this combination is to reduce the ground resistance magnitude of the grid as low as possible. This is crucial to possess magnitude of a low grid resistance which is preferably around 1 ohm and 5 ohms for bulk substation and for distribution substation, respectively [1]. Low grid resistance should not provide result of step and touch voltages larger than the permissible limit.

The grounding grid design is very complex because many variables are considered. Two other crucial parameters are mesh voltage and step voltage. Other parameters in grounding grid design are considered by designer are the magnitude of grid resistance, step and touch voltages to meet according to IEEE standard. The grounding grid design can be carried out in various shapes i.e. square shape, rectangular shape, T-shape and L-shape were reported in [1]. Each model may be completed by ground rods located perimeter of the grounding grid. The grid shapes selected viz. square shape, rectangular shape, and L-shape was used as the comparison of equations found in IEEE 80-2000
Standard and Cym-GRD software [2]. These shapes influence on the conductor used for grounding grid.

Many researchers carried out studying that related to structural models of grounding grid and many software types have been used in the design of a substation. The design of the grounding grid in the rectangular shape with ground rod was documented in [3]-[5]. A substation of 132/33kV at River State of Nigeria was designed with an area (90m x 50m), with grounding rods of 22 pieces installed on the corners and perimeter of the grid [3]. Comparison of grounding grid parameters was calculated by manual calculation based on equations of IEEE Std. 80-2000 and ETAP software. Comparison of the results was analyzed for giving best design.

Substation grounding system of 400 kV EHV/HV was reported by [4] in Augrangabath Mahasrastra State India was designed with ETAP software. The optimum design was obtained by choosing the grid shape, size of ground rod conductor and location accurately which is soil has resistivity 100 to 350 Ω·m. He suggested in future research use programming MATLAB and ETAP software for designing grounding substations because ETAP software can optimize automatically design of grounding grid system. Grounding grid design used Finite Element method was published in [5]. The design used data found in IEEE Std. 80-2000 and result was verified by ETAP software.

ETAP software was used to evaluate existing grounding grid of 33kV/11kV distribution substation [6]. The grounding grid was modelled as the rectangular shape only (36m x 46m) which it consists of 12 meshes, with grounding rod installed in several location points. This paper also recommended improving the grounding grid system because the substation grounding does not satisfy standard IEEE 80-2000. A study considered non-uniform soil was presented in paper [7]. Two software programs were used i.e. MATLAB and CIDEG for two locations in Thailand. The results obtained that important parameters are similarity magnitude, but this paper did not explain the grid shape used in the design. An application modelling of Lab View graphical user interface for grounding grid designing is documented in [8].

From description previously, several of the grounding grid shapes used namely, square shape, rectangular shape and L-shape in design of substation grounding, but T-shape did not discuss. Purpose of this paper is to the design grounding grid shapes various as alternative viz. rectangular shape, L-shape and T shape is equipped by the ground rod or without ground rod as the alternative for fulfilling safety standard IEEE 80-2013 with case study is existing Galang substation, North Sumatra Province (PT. PLN-Indonesia). The grounding grid design considered is uniform soil and use ETAP Software. Result obtained is analyzed to find economic design based on the conductor length used but meet IEEE Std. 80 requirement.

2. Methodology

2.1. Grounding Grid Parameters

The design of a substation grounding system is very complex due to many parameters involved. They are grounding resistance, GPR, mesh voltage, step and touch voltages of estimate and permissible. Sverak in ref. [1] developed an equation to determine grounding resistance of the grid in uniform soil through a formula,

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

(1)

Where,

$\rho$ : The soil resistivity (Ω·m)
A : The effective area grid (m²)
h : The depth of grid (m)
L : The total length of conductor buried (m)

Equations needed for substation designing are adopted from [1]. GPR is multiplying of grounding resistance and fault current, so the equation can be wrote

\[ GPR = I_f \times R_g \]  \hspace{1cm} (2)

Where:

GPR : The ground potential rise (volt)

\[ I_f \] : The fault current (A)

\[ R_g \] : The grounding resistance of grid (Ω)

Permissible step voltage for 50 kg and 70 kg, respectively are

\[ V_{s,50} = [100 + 1.5\rho_s C_s] \frac{0.116}{\sqrt{f}} \]  \hspace{1cm} (3)

\[ V_{s,70} = [100 + 1.5\rho_s C_s] \frac{0.157}{\sqrt{f}} \]  \hspace{1cm} (4)

Permissible touch voltage for 50 kg and 70 kg, respectively are

\[ V_{t,50} = [100 + 6\rho_s C_s] \frac{0.116}{\sqrt{f}} \]  \hspace{1cm} (5)

\[ V_{t,70} = [100 + 6\rho_s C_s] \frac{0.157}{\sqrt{f}} \]  \hspace{1cm} (6)

\[ C_s \] is derating factor can be calculated by an equation

\[ C_s = 1 - 0.09 \left[ 1 - \frac{\rho_s}{\rho_t} \right] \frac{1}{2h_s + 0.09} \]  \hspace{1cm} (7)

Step and Mesh voltages calculation

\[ E_{s,cal} = \frac{\rho K_1 K_t I_G}{L_s} \]  \hspace{1cm} (8)

Mesh voltage

\[ E_m = \frac{\rho K_w K_t I_G}{L_M} \]  \hspace{1cm} (9)

where

\[ V_{s,50} \] : The step voltage for 50 kg body weight (V)

\[ V_{s,70} \] : The step voltage for 70 kg body weight (V)

\[ V_{t,50} \] : The touch voltage for 50 kg body weight (V)

\[ V_{t,70} \] : The touch voltage for 50 kg body weight (V)

\[ \rho \] : The soil resistivity (Ω-m)
\( \rho_s \): The crush rock resistivity (\( \Omega \cdot \text{m} \))

\( h_s \): The crush rock thickness (m)

\( t \): The Fault duration (second)

\( I_G \): The Maximum fault current (A)

\( L_S \): The total length of buried conductor (m)

\( L_M \): The effective length of grounding grid \((L_C + L_R)\) (m)

\( K_m, K_S \) and \( K_i \) are the spacing factors for mesh voltage, spacing factor for step voltage and correction factor for grid geometric.

Grounding grid design must to fulfil standard that has been set by IEEE Std. 80 which is the magnitude of the mesh voltage less than the tolerable touch voltage and the calculated step voltage less than the tolerable step voltage. The mesh voltage is a form of the maximum touch voltage.

2.2. Grounding Grid Model of Substation

Various models of grounding grid have been used for substation namely rectangular shape, square shape, L-shape and T-shape are shown in Figure 1.

![Square shape](image)

(a) Square shape

![Rectangular shape](image)

(b) Rectangular shape

![L-shape](image)

(c) L-shape

![T-shape](image)

(d) T-shape

**Figure 1.** Models of the grounding grid shape
The grounding grid models L-shape and T-shape as in Figure 1 have many varies, for example for L-shape of the grid area and total of rod length used are determined by sides of a, b, c, d, e and f whereas T-shape is determined sides of a, b, c, d and e. According to Thapar and Gerez [9], the values of e and f are around 180 m and 95 m and the values of a and d are around 10 to 80m. The values of L-shape have ratio a : b = 2:1 until 1:6; d : c = 4:1 until 1:8. T-shape model has ratio of it side is a : b = 3:1 to 1:4; a : d = 1 : 1 to 1 : 2; d : c = 1 : 1 and values of a and d are 5m to 100m.

2.3. Grounding Grid Design
Existing grounding grid in Galang substation is rectangular shape with four ground rod. The substation has 2x500 MVA transformers, the voltage of 150kV/275kV. The grounding grid is rectangular shape with grid area of 180m x 95m. It is equipped four pieces of the ground rod at each the corner with long of 1.5m. Spacing between parallel conductors is unequal which is 5m in axis X direction (horizontal) and 10m in direction axis Y (vertical). Four ground rods are installed at the grid corner with length of 1.5 m. Lay-out of Galang substation grounding is shown in Figure 2 and setting view in ETAP package software is shown in Figure 3. Information data of the Galang substation grounding grid is shown in Table 1.

![Figure 2. Rectangular shape of grounding grid in Galang substation](image)

The conductor total length of the grounding grid that is beneath can be calculated by an equation

\[
L = L_{\text{grid}} + L_{GR} \ (m)
\]

\(L_{\text{grid}}\) : The conductor total length of grid (m)
\(L_{GR}\) : The conductor total length of rod (m)

| Data | Legends |
|------|---------|
| Grid conductor type | Cooper Conductor–Hard 1x150mm² |
| Rod conductor type | Cooper with diameter of 17.33 mm |
| Depth of grounding grid | 0.8 m |
| Length of rod conductor | 1.5 m |
| Resistivity soil | 127.94/284.09 |
| Resistivity crush rock | 5,000 (Ω-m) |
| Thickness of crush rock | 0.2 (Ω-m) |
Current divider factor 0.6
De-rating factor 1.128 (with X/R =10)
Duration fault 0.35 second
Fault current 4,000 A

(a) Grid setting views
(b) Rod setting views

Figure 3. Setting view of grounding grid in ETAP

3. Simulation Results

Three models of grounding grid design considered to be evaluated viz. rectangular shape, L-shape and T-shape, the models were simulated using ETAP package software. In the design, parameters data such as spacing distances, grid depth, soil and crush rock of resistivity, conductor diameter and electricity parameter maintained is similar to the Galang grounding except shape models and number of rods. In the software found optimization option menu for the grid designing which gives the length conductor minimum. Simulation result for touch and step tolerable for 50 kg body weight are presented in Table 2.

| Body weight | Touch voltage (Volt) | Step voltage (Volt) |
|-------------|----------------------|---------------------|
| 50 kg       | 1899.5               | 5025.6              |

The magnitude of touch and step voltages are not influenced by grounding grid shape, they are great influence by soil resistivity, grid depth and the fault duration. The magnitudes are applied for all the shapes.

3.1. Rectangular shape design

The rectangular shape is model used in the Galang substation with grid area of 180m x 95m, the spacing distance between conductors in direction are 5 m and 10 m in direction X and Y respectively. This configuration still can be optimized by changing conductor distance so the result is shown in Table 3.
Table 3. Grounding grid parameter before and after optimization

| Model design | Conductor number X | Conductor number Y | Calculate touch | Calculate step | Grid resistance | The conductor length |
|--------------|--------------------|--------------------|-----------------|----------------|------------------|---------------------|
| Before       | 20                 | 19                 | 1075.1 V        | 636.5 V        | 0.46 Ω           | 5411 m              |
| After optimize | 11              | 21                 | 1305.1 V        | 1020.5 V       | 0.73 Ω           | 4831 m              |

Table 3 shows the length of conductor used is decreasing, the value of the step and the touch calculated increase but the values are still less than the values tolerable.

3.2. L-shape design

L-shape design of grounding grid, spacing distance between conductors in direction are 5 m and 10 m in direction X and Y respectively. The minimum conductor length for grounding grid can be obtained by setting the values of a, b, c, d, e and f. The simulation result which gives the minimum conductor length is shown Figure 4. There six ground rods installed at each the corner of L-shape with the conductor length of 1.5 m.

![Figure 4. L-shape design for the grounding grid](image)

3.3. T-shape design

T-shape model was designed to maintain spacing distance such as L-shape design and rectangular shapes. The minimum length of the conductor was obtained is similar to previous model and simulation result is shown in Figure 5. The model needs eight ground rods at each outer corner.
3.4. Important parameter in the grounding grid substation

Comparison between the grid grounding shapes viz. rectangular shape; L-shape and T-shape are given in Table 4. The grid shapes are using the conductor minimum length after though a process by setting the values of a, b, c, d, e, and f according to Thapar and Gerez [9].

| Shape model | Conductor number | Calculated touch voltage | Grid resistance | Conductor length |
|-------------|-----------------|--------------------------|-----------------|------------------|
| Rectangular | 20 19 4          | 1075.1 V                 | 636.5 V         | 0.46 Ω           | 5411 m          |
| L-shape     | 20 19 6          | 1359.7 V                 | 798.3 V         | 0.53 Ω           | 4154 m          |
| T-shape     | 20 19 8          | 1345.8 V                 | 770.3 V         | 0.56 Ω           | 3857 m          |

From Table 4, the values obtained such as the grid resistance is less than 1, the calculated step and the touch voltage are less than tolerable mesh and touch voltage. Therefore all the designs are categorized safe for person and can protect the equipment when the faults occur and finally to meet IEEE Std. 80. T-shape is the design most economist because needs minimum conductor length. T-shape design has size of $e = 180$ m, $f = 95$ m, $d = 100$ m and $a = 30$ m, so the total conductor length needed is 3857 m is presented in Figure 5.

4. Conclusion

The grounding grid system of Galang substation is combination of grid and ground rod conductor meets requirements according to IEEE Std. 80-2013 for 50 kg and 70 kg body weight. The grid is indentified as the safety substation grid grounding. All the touch and step voltage calculated considered are less than the tolerable mesh and tolerable touch voltages. The grounding resistance is less than 1 ohm. The minimum conductor length of T-shape design is most economists from the design of others L-shape and rectangular shape. Therefore the T-shape design can be considered as design alternative for the grounding grid of substation in future.
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