Safety Design Planning of Ground Grid for Outdoor Substations in MEA's Power Distribution System

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ABSTRACT

This paper analyzes the performance of a grounding system made of copper conductors and significantly influenced by soil resistivity. The grounding performance is evaluated in terms of ground potential rise (GPR), touch voltage and step voltage caused by a short circuit that generates a flow of large currents in the aboveground structures and grounding system and dissipates in the soil. These currents may cause damage to substation equipment and may be dangerous to personnel working nearby. Safety design planning for step and touch voltages for the existing fault level and future fault levels are extensively investigated for utility applications where personnel hazards may exist. Modelling and simulation is carried out on the Current Distribution Electromagnetic interference Grounding and Soil structure (CDEGS) program. The safety design planning is illustrated by a practical case of ground grid design for the 69/12-24 kV, outdoor-type Bangkrachao substation of Metropolitan Electricity Authority (MEA) with economic analysis. An effective solution to improve the performance of the substation grounding is also suggested.

Keywords: Ground Grid Design, Ground Potential Rise, Step Voltage, Touch Voltage, Safety Criteria

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1. INTRODUCTION

There are two major types of power transmission and distribution substations in Metropolitan Electricity Authority (MEA): air-insulated outdoor substations (AIS) and gas-insulated substations (GIS) in MEA. Most of the power transmission and distribution substations are of GIS type due to the restriction of space and very high cost of land in urban areas. The design of grounding system for GIS indoor substations and AIS is quite different. The main difference is that the ground grid of GIS is attached to the steel-made structure of each floor of the building, in which the GIS substation is installed, but that arrangement is not the case for AIS. The attachment is served as equipotential in floors and walls of reinforced concrete to protect the operators and maintenance personnel from substation potential rise (touch and step voltages) due to ground faults.

Based on MEA's statistical data, one of the main causes of sustain interruptions is short circuits on electrical substations. A short circuit generates large currents that flow in the aboveground structures and grounding system and dissipate in the soil. The high currents may cause damage to equipment and may be dangerous to personnel working nearby. It is therefore important to consider and incorporate safe step and touch voltage limitations into electrical designs in order to achieve a safe electrical system without potential electrical hazards after installation.

As some of the power transmission and distribution substations in MEA are of air-insulated switchgear type, ground grid design for AIS substations is essential to personal safety in the substations and areas nearby for normal operation and abnormal conditions. Safety design in substations is normally concerned with step voltage and touch voltage. Step voltage is defined as the difference in surface potential experienced by a person bridging a distance of 1 m with the feet without contacting any other grounded object. Touch voltage is defined as the potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure [1]. Although the potential loss or injury resulting from exposure to voltage hazard, particularly for those who are actively involved with hot line maintenance, may cause serious consequences, very little has been paid attention to issues of safety criteria in substations of electric power utilities in Thailand.

This paper presents a safety design of ground grid for a practical 1×10+1×20 MVA (2×20 MVA in the future), 69/12-24 kV substation grounding grid system in MEA. Modeling and simulation are carried out on the Current Distribution Electromagnetic interference Grounding and Soil structure (CDEGS) software package. Safe step and touch voltage criteria based on body weight defined in IEEE Std. 80-2000 are analyzed. These criteria are considered both in industrial applications and in general applications where personnel hazards may exist whenever short circuits occur.

2. DESCRIPTION OF BANGKRACHAO SUBSTATION

Fig. 1 and 2 show a picture of an outdoor-type 69/12-24 kV primary substation. The 69 kV power source is supplied through 2×400 mm^2 all-aluminium conductor (AAC) and 2×800 mm^2 XLPE underground cable per phase from the South Bangkok Terminal substation (SKT) and the other from the Samrong Switching substation (SRS). The power equipment at the Bangkrachao (BC) substation consists of two power transformers with a capacity of 1×10+1∓20 MVA and an air-insulated switchgear. The ability of subtransmission lines and power transformers to be electrically connected is determined by bus connections, disconnect switches, circuit breakers. These components determine the bus configuration of distribution substations. Bus configurations are an important aspect of substation reliability, operational flexibility and cost. The BC substation has a single bus single breaker configuration. They are low in cost, but must be completely de-energized for bus maintenance of bus fault. To improve reliability, the bus is often split and connected by a switch or circuit breaker [2].

Fig. 3 shows a typical installation for the grounding system of the BC grounding substation system and its grid dimension. The cross section of the ground grid conductor is 240 mm^2 and the ground rod is 2.4 m long with a diameter of 15.875 mm. All the ground rods in this substation are directly connected to the main ground grid by the exothermic welding method. The ground grid is buried at 0.5 m below the ground surface level.

3. SAFETY CRITERIA IN GROUNDING SYSTEM

Potential gradients are produced within and around a substation due to the flow of current into the earth during ground fault conditions. A grounding system has to be designed in such a way as to ensure

Fig.1: *Bangkrachao Primary Outdoor Type 69/12-24kV Substation*

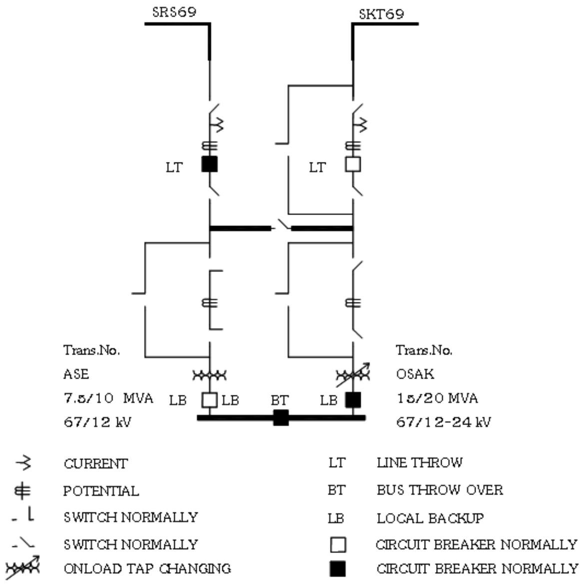


Fig.2: *Single Line Diagram of Bangkrachao 69/12-24kV Outdoor-Type Substation*

that no electrical hazards exist outside or within the substation during normal and fault conditions. Touch voltage and step voltages can be used to evaluate the safety and adequacy of the design [3, 4].

In the process of designing the ground grid system, safety criteria is firstly calculated to specify a safety level, then the maximum touch and step voltage are calculated to compare with the safety criteria to define whether it is safe to work on the area of substation. This section details the calculation of safety criteria, touch voltage and step voltage.

3.1 Touch Voltage Criteria

The potential difference between the GPR and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure.

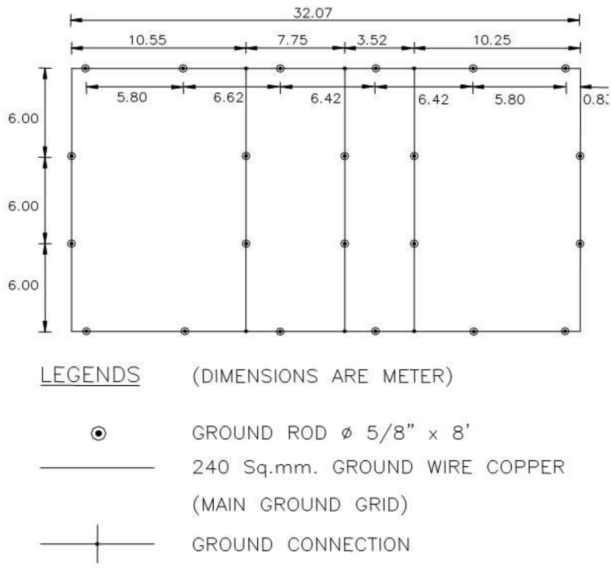


Fig.3: *Typical Installation for Grounding System*

The tolerable touch voltage in volts is defined as [4]:

$$E_{touch} = I_B \cdot (R_B + 1.5\rho_s) \quad (1)$$

where E_{touch} = tolerable touch voltage for human(V)
R_B = resistance of the human body(Ω)
ρ_s = surface layer resistivity(Ω·m)

$$I_B = \frac{k}{\sqrt{t_s}} \quad (2)$$

where I_B = current through the body (A)
k = 0.116 for 50 kg body weight
0.157 for 70 kg body weight
t_s = duration of current expose (s)

A safe grounding design has two main objectives: 1) to provide a path for electric currents into the earth under normal and fault conditions and 2) to ensure the safety of a person in the locality. The safety of a person depends on preventing the critical amount of shock energy from being absorbed before the fault is cleared and the system de-energised. To ensure safety, the magnitude and duration of the current conducted through a human body should be less than the value that can cause ventricular fibrillation of the heart. Fibrillation current is assumed to be a function of individual body weight. The tolerable body current limits for body weights 50 kg and 70 kg [3, 4].

3.2 Step Voltage Criteria

The difference in surface potential experienced by a person bridging a distance of 1 m with the feet without contacting any other grounded object.

The tolerable step voltage in volts is defined as [4]:

$$E_{step} = I_B \cdot (R_B + 6\rho_s) \quad (3)$$

where E_{step} = tolerable step voltage for human (A)

4. MAXIMUM OF MESH AND STEP VOLTAGE

The maximum touch voltage within a mesh of a ground grid [4] is calculated by

$$E_m = \frac{\rho_a \cdot K_m K_i \cdot I_G}{L_m} \quad (4)$$

where E_m = mesh voltage (V)
ρ_a = apparent resistivity of soil(Ω·m)
K_m = mesh factor defined for n parallel conductors
K_i = corrective factor for current irregularity
L_G = maximum r.m.s. current flowing between ground grid and earth (A)
L_m = effective length of for mesh voltage (m)

$$L_s = 0.75 \cdot L_C + 0.85 \cdot L_R \quad (5)$$

where L_s = effective length of $L_C + L_R$ for step voltage (m)
L_C = total length of grid conductor(m)
L_R = total length of ground rods (m)

$$E_s = \frac{\rho_a \cdot K_s \cdot K_i \cdot I_G}{L_s} \quad (6)$$

where E_s = step voltage (V)
K_s = mesh factor defined for n parallel conductors

5. SOIL CHARACTERISTIC

5.1 Resistivity Measurements

The four point method shown in Fig. 4 is one of the most accurate methods in practice for measuring the average resistivity large volumes of undisturbed earth. In the figure, four electrodes are buried in equally-spaced small holes at points C_1, C_2, P_1 and P_2. The soil resistance R in ohm is calculated from the ration of V/I, where I is an injected current between the two outer electrodes and V is the measured voltage between the two inner electrodes [4-6].

With this arrangement, the resistivity ρ_a expressed in the terms of the length units is

$$\rho_a \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2+4b^2}} - \frac{a}{\sqrt{a^2+b^2}}} \quad (7)$$

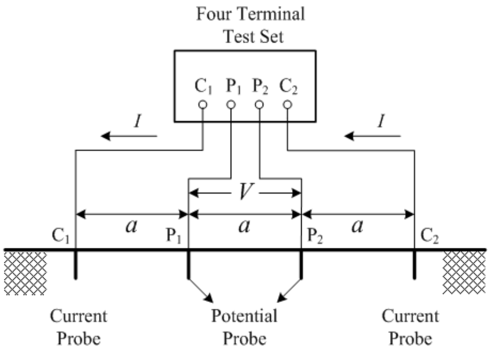


Fig.4: *Wenner Arrangement*

where ρ_a= apparent resistivity of the soil in(Ω·m)
R = measured resistance(Ω)
a = distance between adjacent electrodes(m)
b = depth of the electrodes(m)
When b is small compared to a, (7) becomes

$$\rho_a = 2\pi a R \quad (8)$$

5.2 Two-Layer Soil Apparent Resistivity

A resistivity of soil characterized with two layers shown in Fig. 5 can be determined from the Wenner method. In this method, the apparent resistivity is calculated from (9) [4-7].

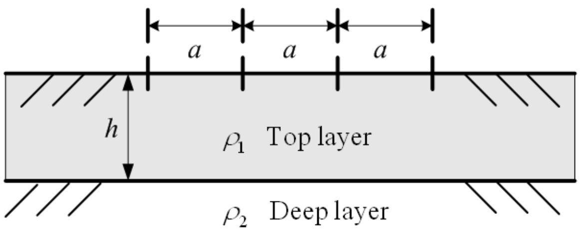


Fig.5: *Two-layer Earth Model*

$$\rho_a = \rho_1 \left(1 + 4\sum_{i=1}^{\infty} \frac{K^n}{\sqrt{1+\left(2n\frac{h}{a}\right)^2}} - \frac{k^n}{\sqrt{4+\left(2n\frac{h}{a}\right)^2}}\right) \quad (9)$$

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \quad (10)$$

Where h = first layer height(m)
K = reflection factor
ρ_1 = first layer resistivity (Ω·m)
ρ_2 = deep layer resistivity(Ω·m)

6. PROCESS OF SAFETY DESIGN

The process of safety design is described step by step as follows.

Step 1: Measure the apparent resistivity of the soil in the study area using the Wenner Arrangement method.

Step 2: Analyze the data obtained from step 1 (soil structure analysis) by the Rural Electric Safety Accreditation Program Module (RESAP)in CDEGS using the steepest method to yield the soil characteristic.

Step 3: Analyze the data obtained from step 1 to establish safety criteria by the MALT Module.

Step 4: Input an existing standard configuration of ground grid of MEA and proposed configurations(see Section 7).

Step 5: Simulate the maximum of mesh (or touch) and step voltages and compare them with the safety criteria.

Step 6: For a given configuration of step 4, if the safety criteria are met, calculate the investment cost of ground grid. Otherwise, that configuration, which fails to meet the safety criteria, needs to be redesigned by the methods described in step 7.

Step 7: The unsafe conditions can be classified into 3 cases as follows. Case 1) Only touch voltage is not satisfied. In this case, the conductor compression ratio of the ground grid should be first adjusted to have optimal spacing of ground grid conductors that can reduce GPR slightly but may decrease the maximum touch voltage to be in the criteria range. However if the maximum touch voltage still exceeds the criteria, consider the soil resistivity[8].

- If the top layer has a lower soil resistivity, lengthen the ground rods so that they are able to penetrate into the bottom layer. If the maximum touch voltage still violates the criteria, increase the number of ground rods with the updated length.

- If the top layer has a lower soil resistivity, increase the number of ground rods while keeping the length of ground rod the same to avoid GPR that is expected to rise sharply. Ground rods available in the market are in the sizes of 2.4, 3 and 6 m. with a diameter of 15.875 mm. The MEA standard configuration is 2.4 m. long with a diameter of 15.875 mm.

Case 2) Only step voltage is not satisfied. This case can be fixed by increasing the number of ground grid conductors around the boundary because short circuit currents are densely distributed at the boundary. The cross- section areas of ground grid conductor available in the market are 95, 120, 185 and 240 mm2. The MEA standard cross-sectional area is 240 mm^2, although this dimension may be safely substituted with the size of 95 mm^2 according to [1].

Case 3) Both maximum touch and step voltages are not satisfied: As this case is the combination of the two previous cases, follow the viable solutions explained in case 1 and case 2. Alternatively, a possible suggestion is given.

• If the top layer has a higher soil resistivity than the bottom layer, shift the level of the ground grid system downward until the maximum touch and maximum step voltages meet the criteria. It is possible that the ground grid and ground rods may penetrate to the bottom layer.

• If the bottom layer has a higher soil resistivity than the top layer, shift the level of the ground grid system downward until the maximum touch and maximum step voltages meet the criteria. However, the ground grid system should not be shifted to the bottom layer as the GPR will be increased. In addition, although the level of the ground grid system still stays in the top layer, the ground rods may extrude the bottom layer. In that situation, the ground rods should be removed and the ground grid system should be gradually shifted downward to the top layer [5],[9-12].

Step 8: Select the optimal configuration among all possible configurations that gives the minimum cost of installation.

The flowchart for the proposed ground grid design is shown in Fig. 6.

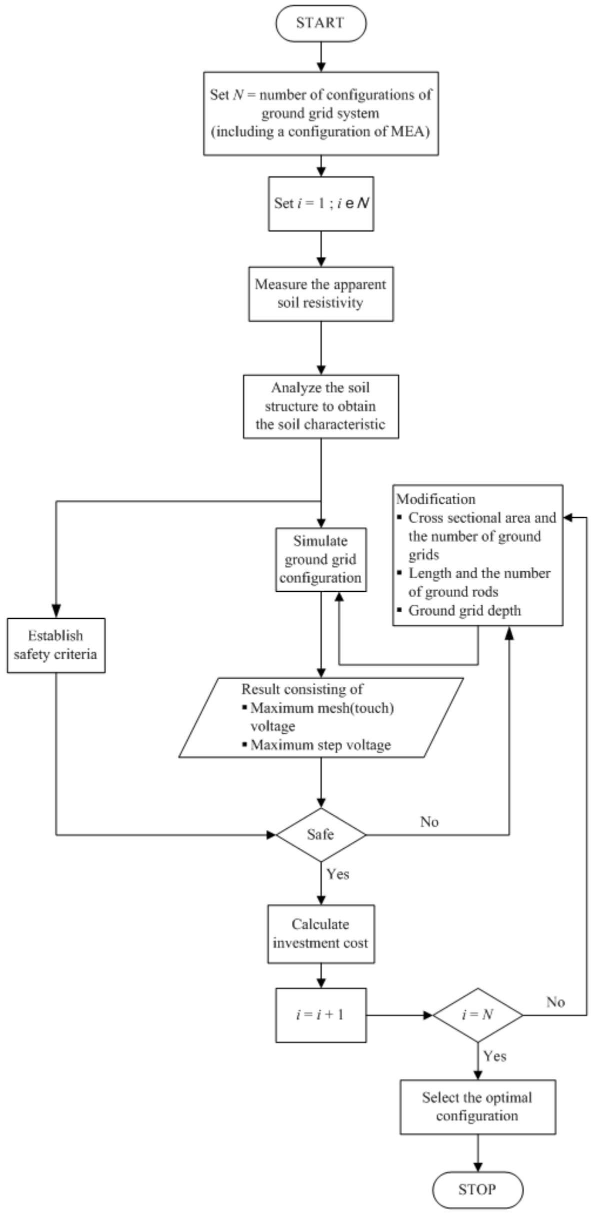


Fig.6: Flowchart of Ground Grid Design

7. CASE STUDY

The BC grounding substation system shown in Fig. 3 is analyzed in this case study. Four parameters of interest in the simulation are 1) cross section area of ground grid conductor, 2) length of ground rod, 3) depth of ground grid and 4) short circuit current and interrupting capacity of circuit breaker in the future. The ground grid system for the BC substation is modelled using the CDEGS program. The soil layer characteristics of the BC substation are analyzed by a built-in module in the CDEGS program, logarithmically shown in Fig. 7.

With the model in Fig. 7, the resistivity of the BC substation is shown in Table 1. The resistivity of the top and bottom layers is 89.22586 and 4.543867 Ω·m respectively. The thickness of the top layer is 0.6133479 m. The top layer has a more resistivity than the bottom layer (deeper layer) due to a number of factors such as moisture content of the soil, chemical composition, concentration of salts dissolved in the contained water, and grain size [13].

Table 1: Summary of Soil Resistivity

Layer Characteristic				
Layer	Resistivity (Ω·m)	Thickness (m)	Reflection Coefficient (p.u.)	Resistivity Contrast Ratio
Top	89.22586	0.6133479	-1.0000	0.89226E-18
Bottom	4.543867	infinity	-0.90308	0.50925-01

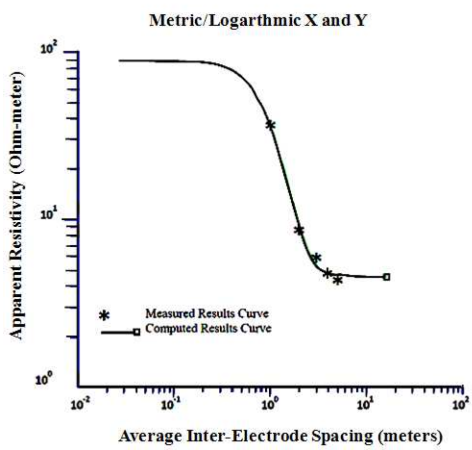


Fig.7: Soil Resistivity Model

The safety criteria of the BC substation are shown in Table 2. Taking a surface layer resistivity of 2,000 Ω·m as a safety criterion, the touch and step voltage

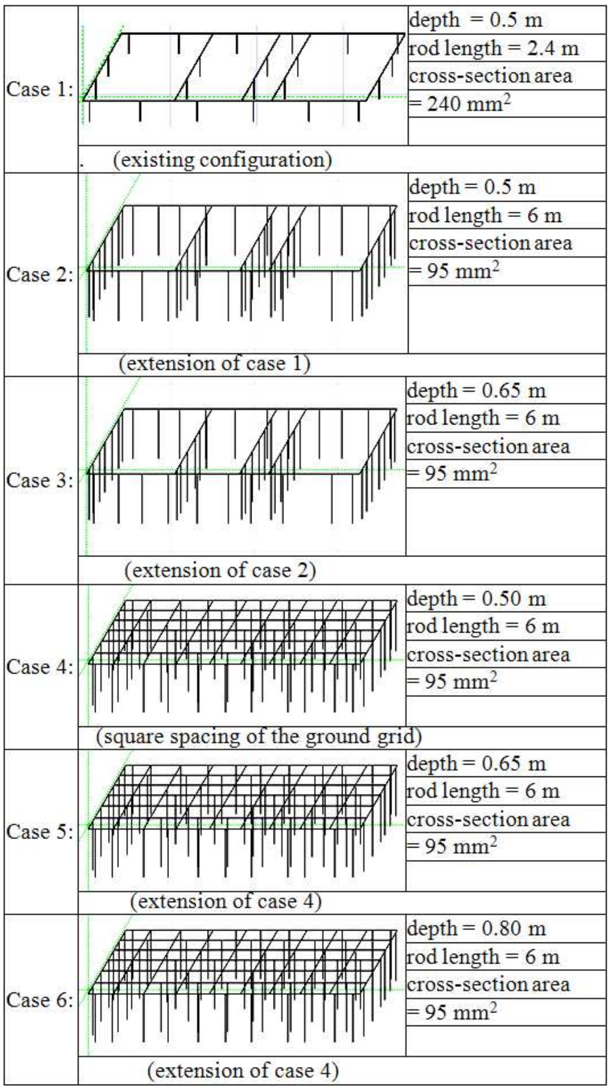
Table 2: *Safety Criteria for 50 kg Body Weight*

Surface Layer Resistivity (Ω·m)	Fault Clearing Time 0.1 sec		Foot Resistance 1 Foot (Ω)
	Touch Voltage (V)	Step Voltage (V)	
None	329.50	450.40	278.80
500	505.20	1,153.30	1,494.10
1,000	718.30	2,005.60	2,967.80
1,500	931.30	2,857.60	4,441.00
2,000	1,144.30	3,709.60	5,914.00
2,500	1,357.20	4,561.50	7,386.90
3,000	1,570.20	5,413.30	8,859.90
3,500	1,783.20	6,265.20	10,332.80
4,000	1,996.10	7,117.10	11,805.70
4,500	2,209.10	7,968.90	13,278.60
5,000	2,422.10	8,820.80	14,751.40
5,500	2,635.00	9,672.60	16,224.30
6,000	2,848.00	10,524.40	17,697.20
6,500	3,061.00	11,376.30	19,170.10
7,000	3,273.90	12,228.10	20,642.90
7,500	3,486.90	13,080.00	22,115.80
8,000	3,699.80	13,931.00	23,588.70

are 1,144.3 V and 3,709.6 V for 50 kg body weights.

7.1 Planning Criteria

MEA has power distribution improvement and expansion plans to reinforce its power distribution system to accommodate load growth in the future. The plans consist of the construction of terminal stations, distribution substations, subtransmission lines, and distribution feeders as well as the installation of new equipment (e.g., transformers, circuit breakers) in the subtransmission and distribution systems. This expansion plan will increase the effective short-circuit current at the BC substation. Therefore, such construction and equipment installation need to take into account equipment rating. At present, a three-phase fault level of 7.8 kA is used in the planning process of Expansion Plan No. 10 (years 2007-2011). It is anticipated that this amount of short circuit current will increase to 25 kA in Expansion Plan No.12 (years 2017-2021) and to the highest level at 40 kA, which is estimated based on a worst case scenario analysis. Note that the 40 kA short circuit level is the interrupting capacity (IC) of 69 kV circuit breakers in MEA. Six cases are of interest as follows:



For the existing case of ground grid design, its 3-dimension GPR is shown in Fig. 8, two-dimension spot touch voltage in Fig. 9, and two-dimension spot step voltage in Fig. 10. For Case 5 at the 40 kA fault level, its 3-dimension GPR is shown in Fig. 11, two-dimension spot touch voltage in Fig. 12, and two-dimension spot step voltage in Fig. 13. It can be seen that ground potential differences (GPD) between two points in the substations of Fig. 8 is much higher than of Fig. 11, introducing many high peak spikes; and therefore high touch voltage and step voltage. In other words, although the peak GPR of Fig. 11 is almost 2.60 times higher, only voltage difference directly counts for touch and step voltages. Such GPD could damage sensitive intelligent electronic devices if they are going to be installed in the substation in the future. Note that the same colors in these figures do not represent the same scale of voltage level.

The three indices, consisting of GPR, touch voltage and touch voltage, simulated from the CDEGS program are listed in Table 3 under the assumption that there is no surface layer resistivity. For the existing case, the maximum values for GPR, touch voltage and step voltage are 991.37 V, 706.93 V and 156.79 V respectively. It is seen from Table 3 that the touch voltage fails to meet the established touch voltage level of 329.5 V given in Table 2, whereas the constraint on step voltage of 450.4 V is satisfied.

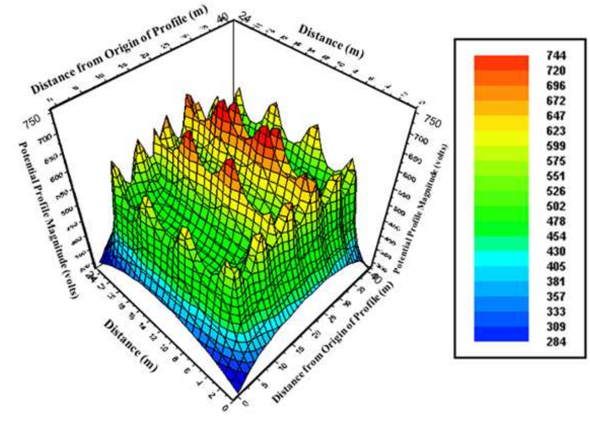


Fig.8: *Ground Potential Rise for Existing System of 7.8 kA Fault Level*

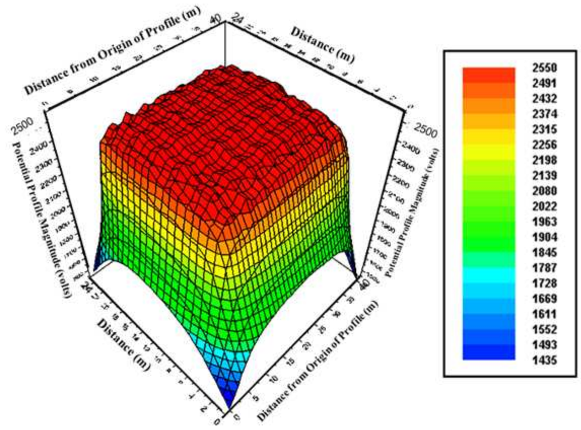


Fig.11: *Ground Potential Rise of Case 5 of 40 kA Fault Level*

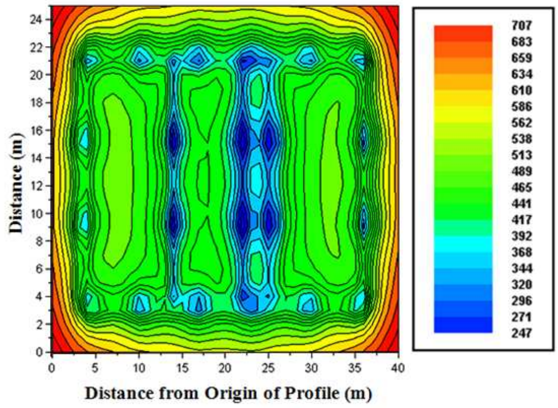


Fig.9: *Touch Voltage Magnitude of Existing System of 7.8 kA Fault Level*

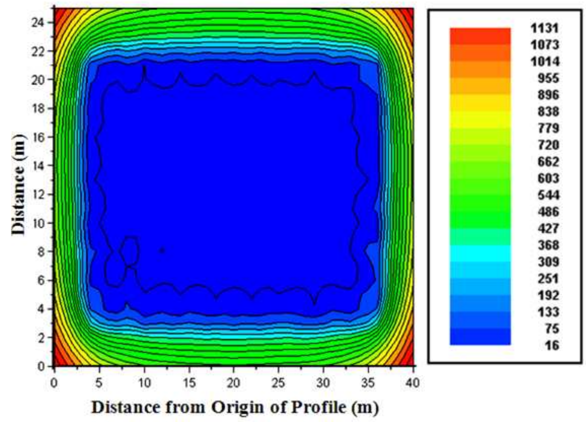


Fig.12: *Touch Voltage Magnitude of Case 5 for 40 kA Fault Level*

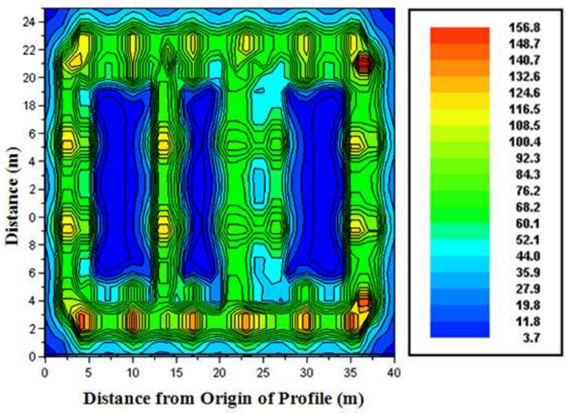


Fig.10: *Step Voltage Magnitude of Existing System of 7.8 kA Fault Level*

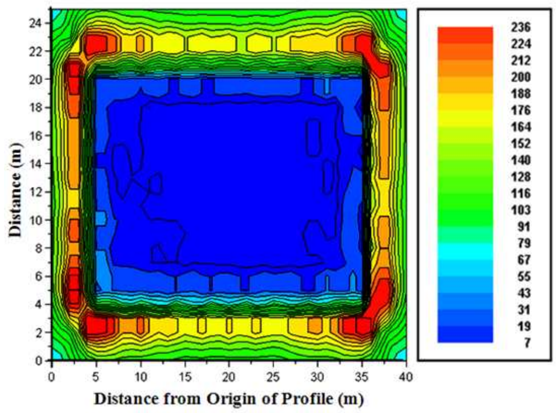


Fig.13: *Step Voltage Magnitude of Case 5 for 40 kA Fault Level*

Table 3: *GPR, Touch and Step Voltages for Six Cases*

Case	Type of Voltage	Voltage Level (V)		
		Short Circuit Current		IC at 69 kV
		7.8 kA	25 kA	40 kA
1	GPR	991.37	3,177.50	5,083.90
	Touch	706.93 ✓	2,265.80 ×	3,625.28 ×
	Step	156.79 ✓	502.54 ✓	804.06 ✓
2	GPR	531.08	1,702.20	2,723.50
	Touch	250.61 ✓	803.24 ✓	1,285.18 ×
	Step	45.79 ✓	146.77 ✓	234.83 ✓
3	GPR	513.69	1,646.40	2,634.30
	Touch	231.38 ✓	741.61 ✓	1,186.58 ×
	Step	49.84 ✓	159.73 ✓	255.57 ✓
4	GPR	511.42	1,639.20	2,626.20
	Touch	233.98 ✓	749.94 ✓	1,203.37 ×
	Step	43.46 ✓	139.30 ✓	224.11 ✓
5	GPR	500.32	1,603.60	2,565.70
	Touch	220.59 ✓	707.02 ✓	1,131.23 ✓
	Step	46.08 ✓	147.70 ✓	236.31 ✓
6	GPR	492.13	1,577.30	2,523.70
	Touch	212.64 ✓	681.55 ✓	1,090.48 ✓
	Step	43.83 ✓	140.49 ✓	224.79 ✓

✓: within range for 2,000 Ω·m safety criteria in Table 2
×: out of range for 2,000 Ω·m safety criteria in Table 2

Table 4: *Investment Cost for Different Configurations of Grounding System*

Case	Investment Cost (Million Baht)	Safety Criteria		
		Short Circuit Current		IC at 69 kV
		7.8 kA	25 kA	40 kA
1	0.1211	✓	×	×
2	0.4459	✓	✓	×
3	0.4466	✓	✓	×
4	0.6479	✓	✓	×
5	0.6501	✓	✓	✓
6	0.6516	✓	✓	✓

7.2 Short-Circuit Design

7.8 kA short-circuit current design
Based on the simulation results in Table 3, the substation is able to support the 7.8 kA short-circuit current with the configuration of ground grid construction. The existing values of touch and step voltage criteria are satisfied.

25 kA short-circuit current design
For the 25 kA short-circuit current, the configuration of ground grid in all the cases except for Case 1 can meet the criteria given in Table 2, but the cost of ground grid construction is at minimum in Case 2. Compared with Case 1, Case 2 sees decreases of 46.43% (3,177.50 V to 1,702.20 V) for maximum GPR, 64.55% (2,265.80 V to 803.24 V) for maximum touch voltage, and 70.79% (502.54 V to 146.77 V) for maximum step voltage.

40 kA short-circuit current design
For the 40 kA short-circuit current, the configuration of ground grid of only cases 5 and 6 can meet the criteria but Case 5 would be more attractive due to its slightly lower cost of ground grid construction. It is seen from Cases 1 and 5 that as much as 50% (5,083.90 V to 2,565.70 V) for maximum GPR, 69% (3,625.28 V to 1,131.23 V) for maximum touch voltage and 71% (804.06 V to 236.31 V) for maximum step voltage are decreased if the length of ground rod is changed from 2.4 m to 6 m and the substation has more ground rods scatteredly installed around the area of the ground grid.

As already seen, the ground grid system design of existing substation is not safe for a 25 kA short-circuit current for Case 1 and for a 40 kA short-circuit current for Cases 1 to 4. Therefore, an urgent solution to this problem is to apply materials (e.g., crushed rock) to the surface of the substation area in order to increase the resistivity between operators and the ground. Table 5 shows how material resistivity varies by the three levels of short circuit current for the six different configurations. For example, in Case 1, a material with a resistivity of 5,000 Ω·m and 8,000 Ω·m may be placed on top of the surface of the substation so that it is able to accommodate 25 kA and 40 kA short circuit currents respectively.

A comparison displayed by two-dimension plots for touch voltage without and with material of 2,000 Ω·m (crushed rock), and 3,000 Ω·m (crushed rock), and 5,000 Ω·m (washed granite) is shown in Fig. 15, 16 and 17 respectively. Based on Case 1 in Table 3, the maximum touch voltage is 2,265.80 V. After washed granite with 5,000 Ω·m resistivity is applied on the substation area, the operators can withstand a touch voltage of 2,422.1 V.

Table 5: *Requirement of Material Resistivity*

Case	Material Resistivity (Ω · m)		
	Short Circuit Current		IC at 69 kV
	7.8 kA	25 kA	40 kA
1	✓	5,000	8,000
2	✓	✓	2,500
3	✓	✓	2,500
4	✓	✓	2,500
5	✓	✓	✓
6	✓	✓	✓

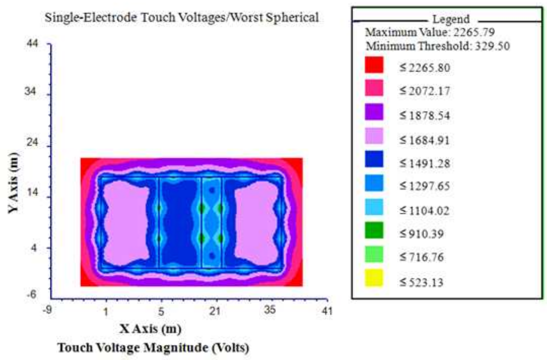


Fig.14: *Touch Voltage without Crushed Rock on Top*

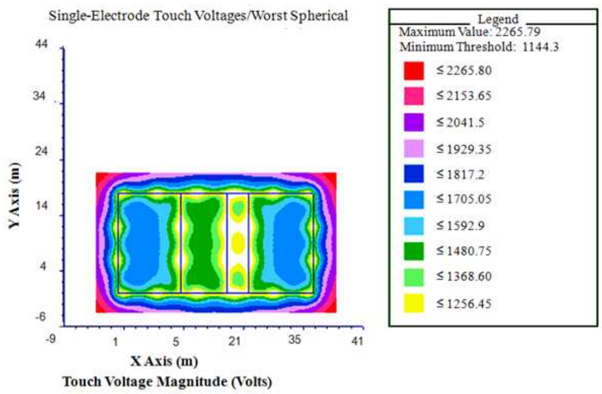


Fig.15: *Touch Voltage of Surface with Crushed Rock of 2,000 Ω·m Resistivity*

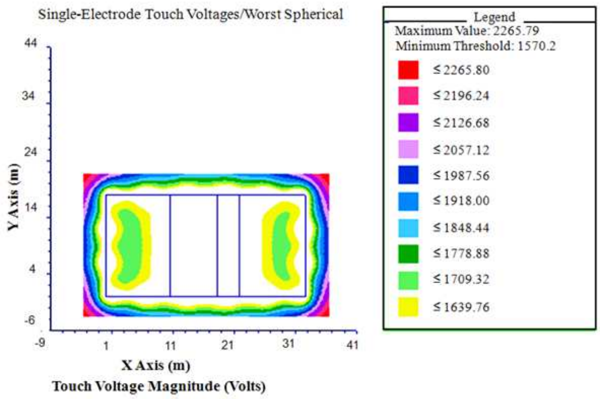


Fig.16: *Touch Voltage of Surface with Crushed Rock of 3,000 Ω·m Resistivity*

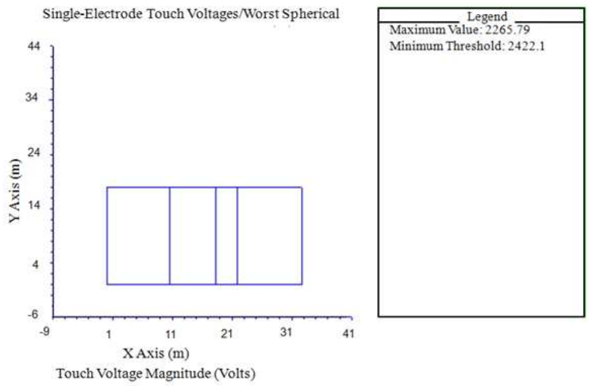


Fig.17: *Touch Voltage of Surface with Washed Granite 5,000 Ω·m Resistivity*

8. APPLICABILITY

The main achievement obtained from this research is the ability to analyze whether a grounding design for a substation is safe for those who are working inside whenever there is a short circuit. Substations with low grounding resistances do not always guarantee personal safety because touch and step voltages are also relevant factors. The new safety criteria can replace the existing ones for new substations in MEA without significant change in GPR, touch voltage and step voltage; for example, reducing the cross section area of ground grid from 240 mm^2 to 95 mm^2 or increasing the length of ground rod from 2.4 m to 6 m or adding the depth of ground grid from 0.5 m to 0.65 m or 0.8 m. Most importantly, the new criteria introduce lower installation cost for substation grounding, compared with the existing ones.

The work carried out in this paper takes into consideration the safety criteria based on IEEE-Std 80-2000 for the construction of substations in the MEA service areas covering three provinces; namely, Bangkok, Nonthaburi and Samutprakarn. Because soil characteristics in the MEA service areas obtained from several field tests are not much physically different (i.e., the soil can be characterized by two layers of which the top layer resistivity is greater than that of the bottom one), the presented method can be, to certain extent, used for substations only in the areas. However, if the method were to be applied in any other areas in Thailand, measurement of soil resistivity would be strongly recommended as it is one of the most important factors in the calculation of safety criteria.

9. CONCLUSION

The ground grid design for the Bangkrachao substation is examined with the main objective to assess its grounding system condition in terms of ground potential rise, touch voltage and step voltage. These three parameters are analyzed to ensure that they satisfy the safety criteria defined in the IEEE Std 80-2000 with three scenarios classified by fault levels: 7.8 kA for the existing configuration, 25 kA for Expansion Plan No.12 (years 2017-2021) and 40 kA for the interrupting capacity of 69 kV circuit breakers in MEA. As far as installation costs and other necessary expenses in grounding system planning is concerned, the length of ground rods, the size of conductor, the short circuit current and IC of 69 kV circuit breakers are the main factors that need to be taken into consideration and should financially reflect incremental total cost and worth for various alternatives while respecting the established safety criteria.

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