Safety Analysis for Grounding System of Two Neighbouring Substations: Case Study of Metropolitan Electricity Authority's System

A. Phayomhom, S. Sirisumrannukul, T. Kasirawat, A. Puttarach, C. Klinsopon, and P. Pearnont

Abstract— *This paper presents construction planning procedures for a new gas insulated substation (GIS) to replace an existing air insulated substation (AIS) and for a small air insulated substation that is served as a temporary substation to supply the load of the existing air insulated substation while it has not yet been removed. In the meantime when the ground grids of the two substations are electrically disconnected, the auxiliary grounding system of the existing substation can create steep ground potential rise between the ground grids of the two substations and hence introduces a risk for those who are working nearby. It is therefore important to incorporate safety criteria described in terms of step and touch voltage into electrical designs without any potential electrical hazards. The safety design planning process is illustrated by the Pathumwan (PM) substation of Metropolitan Electricity Authority (MEA). Modeling and simulation is carried out on the Current Distribution Electromagnetic interference Grounding and Soil structure (CDEGS) program. A sequential transition process from the existing air insulated substation to a new indoor gas insulated substation is suggested to comply with the IEEE standard 80-2000.*

Keywords— **Distribution Substation, Ground potential rise, Step voltage, Touch voltage.**

1. INTRODUCTION

There are two types of power transmission and distribution substations, outdoor air insulated substations (AIS) and gas-insulated substations (GIS), in Metropolitan Electricity Authority (MEA). Examples of AIS in MEA are Rasburana substation, Petchkasem substation and Pathumwan (PM) substation. Examples of GIS are Klongtoey substation and Rachaprarop substation. Due to its compactness, GIS is a preferred choice for a new substation to accommodate load growth while satisfying land constraint. In some cases where there is a need to build a temporary substation in the meantime of planning and construction of new GIS permanent substations, or renovation of existing substations, small AIS substations served as temporary substations is normally required.

This paper proposes a safety design grounding system of two neighbouring substations in MEA. The methodology is illustrated by the PM substation, a 69 kV outdoor air-insulated substation that has been operating for more than 30 years. To enhance security and reliability of the power system and also aesthetics, this substation will be replaced by an indoor GIS. All high voltage equipment of the GIS will be installed in metal–clad with SF6 insolated and the supply voltage need upgrading from 69 kV to 115 kV in 2011. In the meantime, a small AIS substation is temporarily required to help take care of the demand of the existing substation. The existing outdoor substation will then be decommissioned and replaced with a new indoor substation. Some parts of the outdoor substation, however, can still be used as spare parts. The small AIS substation will be put into operation approximately 1 or 2 years before the new indoor substation will have already been completed [1].

In this circumstance, safety analysis for designing grounding system of two neighboring substations should be taken into consideration. When there are two substations close to each other and one is operating while the other is not, if the ground grids of both substations are isolated, the idle ground grid of substation will simulate itself as an auxiliary grounding of the existing substation and can cause a huge difference of ground potential rise (*GPR*) between the two substations; in other words, the touch voltage is high. This creates ground potential rise to be steep and may harm personals while working in the area of substation. To cope with this safety issue, 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.

To renovate existing substation operating for more than 30 years, a new small AIS substation has to be constructed to temporarily supply distribution system instead of that existing substation. After that the existing substation will be removed and a new GIS substation

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A. Phayomhom was financially supported by Metropolitan Electricity Authority (MEA), Thailand.

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will be constructed. However, in the past, during purchasing and construction preparation period for the new GIS substation, ground grid connection between the small AIS substation and the existing substation was not taken into consideration. Practically, its effect can lead to any equipment and personnel damages. So it is recommended to find the solution to avoid this effect.

2. SAFETY CRITERIA

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 part will show a calculation of safety criteria, touch and step voltage.

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.

The tolerable touch voltage in volts is defined as [2]

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

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

R_B = resistance of the human body (Ω)

C_s = surface layer derating factor

ρ_s = surface layer resistivity $(\Omega \cdot \mathrm{m})$

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

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)

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 are: [2],[3].

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 [2]

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

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

3. MAXIMUM OF MESH AND STEP VOLTAGE

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

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

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

I_G = maximum rms current flowing between ground grid and earth (A)

L_m = effective length of $L_C + L_R$ for mesh voltage (m)

For grids with or without ground rods, the effective buried conductor length, L_s , is

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

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)

The step voltage is determined from

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

where E_s = step voltage (V)

K_s = mesh factor defined for n parallel conductors

To calculate both maximum touch and step voltage, apparent resistivity factor is required and it can be obtained by applying wenner arrangement method.

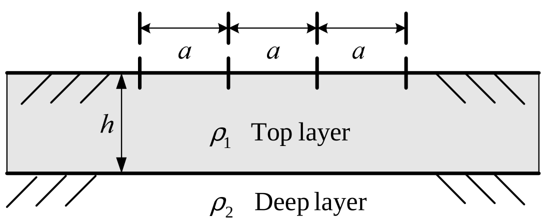


Fig.1. Two Layer Earth Model.

A resistivity of soil characterized with two layers shown in Figure 1 can be determined from the wenner method. In this method, the apparent resistivity is calculated using Eq. (7) [2], [4-6]:

$$\rho_a = \rho_1 \left(1 + 4\sum_{i=1}^{\infty} \frac{K^n}{\sqrt{1+\left(2n\frac{h}{a}\right)^2}} - \frac{K^n}{\sqrt{4+\left(2n\frac{h}{a}\right)^2}} \right) \qquad (7)$$

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \qquad (8)$$

where ρ_a = apparent resistivity of the soil in ($\Omega \cdot$ m)
h = first layer height (m)
K = reflection factor
ρ_1 = first layer resistivity ($\Omega \cdot$ m)
ρ_2 = deep layer resistivity ($\Omega \cdot$ m)

A measurement of apparent resistivity of soil within the substation area is applied with the wenner arrangement method for a purpose of calculating apparent resistivity shown in Eq.**7** . After apparent resistivity is obtained, maximum touch and step voltage then can be determined. Below is an explanation of the wenner arrangement approach to obtain apparent resistivity.

The four point method shown in Figure 2 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 [2], [4-5].

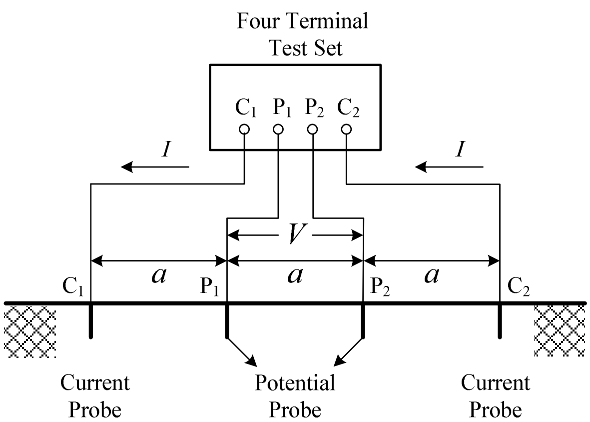


Fig.2. Wenner Arrangement.

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

$$\rho_a = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \qquad (9)$$

where R = measured resistance (Ω)
a = Distance between adjacent electrodes (m)
b = depth of the electrodes (m)

When b is small compared to a, Eq. (9) becomes

$$\rho_a = 2\pi a R \qquad (10)$$

4. PROCESS OF SAFETY ANALYSIS

The safety analysis is carried out on the CDEGS program.

The process of safety analysis can be described by the following steps.

Step 1: Measure a resistance (Ω) of soil located within the targeted substation area by using the wenner arrangement method.

Step 2: Input the value of resistance obtained from step 1 into the Rural Electric Safety Accreditation Program Module (RESAP) by using steepest method to get the soil characteristic such as soil resistivity (**Ω**.M) and the thickness of the soil layer.

Step 3: Input the value of resistance obtained from step1 into the CDEG program using the MALT module to achieve the safety criteria.

Step 4: Design the ground grid system of each substation corresponds to each ground grid study.

Step 5: Compare the potential the maximum touch and step voltage, which are simulated from each designed ground grid configuration with the safety criteria to examine whether they exceed the safety criteria level. If yes, the designed ground grid configuration needs to be revised until the maximum touch and step voltage are within the safety criteria.

5. CASE STUDY

Figure 3 shows a typical installation for the grounding system of the PM grounding substation system and its grid dimension. The existing substation has 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. The small AIS substation has the cross section of the ground grid conductor is 95 mm^2, the ground rod is 3.0 m long with a diameter of 15.875 mm and the depth of ground grid is 0.5 m.

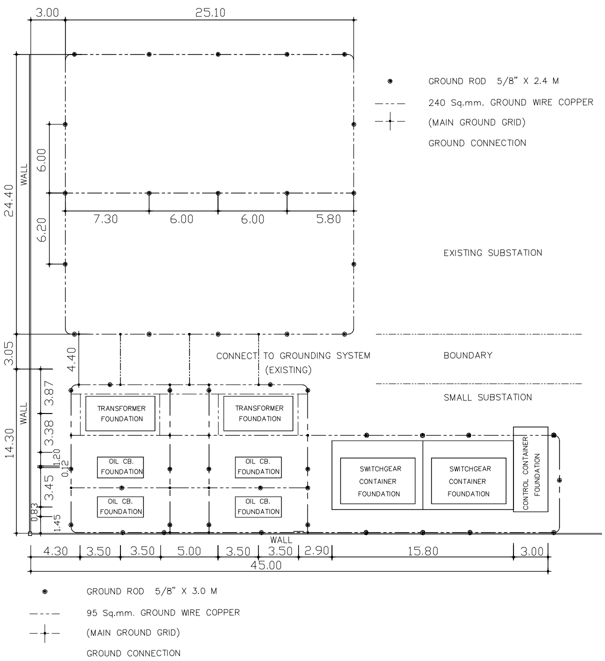


Fig.3. Typical Installation for Grounding System.

Ground Grid Simulation Model

The ground grid system for the PM substation was modelled using the CDEGS program as shown in Figure 4.

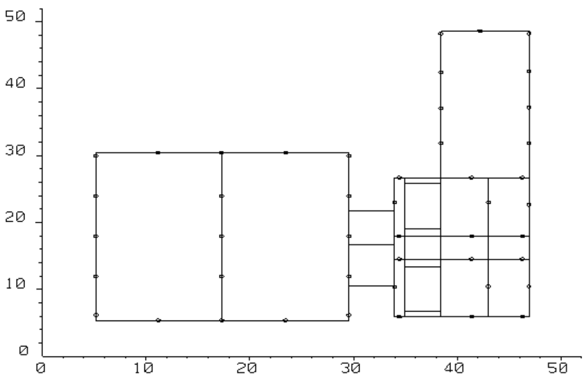


Fig.4. Ground Grid Top View Model for PM Substation.

Soil Resistivity Result

The soil layer characteristics of the PM substation were analyzed by a built-in module in the CDEGS program called Rural Electric Safety Accreditation Program module (RESAP), logarithmically shown in Figure 5.

With the model in Figure 5, the resistivity of the PM substation is shown in Table 1. The resistivity of the top and bottom layers is 22.2588 and 1.019092 $\Omega\cdot$m, respectively. The top layer has a more resistivity than the bottom layer (deep 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 [7].

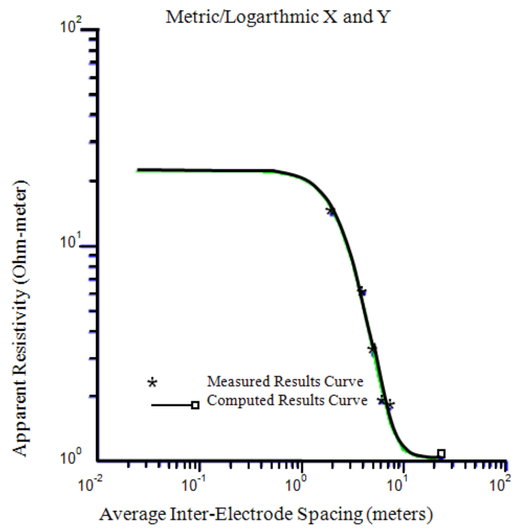


Fig.5. Soil Resistivity Model.

Table1. Summary of Soil Resistivity

Layer Characteristic				
Layer	Resistivity ($\Omega\cdot$m)	Thickness (m)	Reflection Coefficient (p.u.)	Resistivity Contrast Ratio
Top	22.2588	1.831156	-1.0000	0.22259E-18
Bottom	1.019092	infinity	-0.91244	0.45784-01

Table 2. Safety Criteria for 50 kg Body Weight

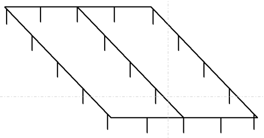
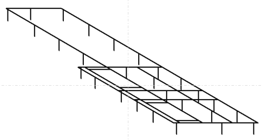
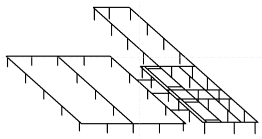
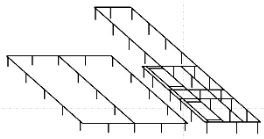
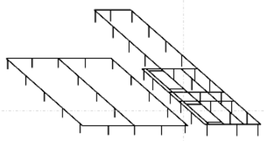
Surface Layer Resistivity ($\Omega\cdot$m)	Fault Clearing Time 0.1 sec		Foot Resistance: 1 Foot (Ω)
	Touch Voltage (V)	Step Voltage (V)	
None	371.50	618.60	69.6
500	583.3	1,465.7	1,534.3
1,000	804.9	2,352.0	3,066.7
1,500	1,026.4	3,238.3	4,599.1
2,000	1,248.0	4,124.5	6,131.5

User defined extra foot resistance: 500. Ω.
Body resistance: 1,000 Ω.

The safety criteria of the PM substation are analyzed by MALT, shown in Table 2 for 50 kg body weight. Taking a surface layer resistivity of 1,000 as a safety criterion, the touch and step voltage are 804.90 volt and 2,352 volt for 50 kg body weights.

Although there may be a number of ground grid configurations, five common configurations are of interest as given in Table 3.

Table 3. Difference Configuration of Ground Grid

<table>
<tr><td rowspan="3">Case 1:</td><td rowspan="2"></td><td>rod length of existing grid = 2.4 m</td></tr>
<tr><td>fault at existing substation</td></tr>
<tr><td colspan="2">(existing grid)</td></tr>
<tr><td rowspan="3">Case 2:</td><td rowspan="2"></td><td>rod length of temporary grid = 3.0 m</td></tr>
<tr><td>fault at small AIS substation</td></tr>
<tr><td colspan="2">(temporary grid)</td></tr>
<tr><td rowspan="4">Case 3:</td><td rowspan="3"></td><td>rod Length of existing grid = 2.4 m</td></tr>
<tr><td>rod length of temporary grid = 3.0 m</td></tr>
<tr><td>fault at temporary or existing substation</td></tr>
<tr><td colspan="2">(existing grid with connected temporary grid)</td></tr>
<tr><td rowspan="4">Case 4:</td><td rowspan="3"></td><td>rod length of existing grid = 2.4 m</td></tr>
<tr><td>rod length of temporary grid = 3.0 m</td></tr>
<tr><td>fault at small AIS substation</td></tr>
<tr><td colspan="2">(existing grid disconnected temporary grid)</td></tr>
<tr><td rowspan="4">Case5:</td><td rowspan="3"></td><td>rod length of existing grid = 2.4 m</td></tr>
<tr><td>rod length of temporary grid = 3.0 m</td></tr>
<tr><td>fault at existing substation</td></tr>
<tr><td colspan="2">(existing grid disconnected temporary grid)</td></tr>
</table>

existing grid: existing ground grid of the existing outdoor substation

temporary grid: ground grid of the small AIS substation (temporary ground grid)

Table 4. *GPR* , Touch and Step Voltages for Five Cases

Case	Voltage Level (V)		
	Type of Voltage		
	GPR	Touch	Step
1	1,166.6	1,082 ×	313 ✓
2	774.9	694 ✓	171.5 ✓
3	542.72	451 ✓	118.7 ✓
4	770.6	662 ✓	171.5 ✓
5	1,161.4	1,054 ×	312 ✓

Safety criteria: touch =804.9 volt, step=2,352 volt

✓: within range for 1,000 $\Omega \cdot m$ safety criteria in Table 2

×: out of range for 1,000 $\Omega \cdot m$ safety criteria in Table 2

The three voltage performance indices are listed in Table 4. The data in Table 4 are graphically displayed in Figures 6 to 20.

Based on the simulation results in Table 4, the substation is able to support the 25 kA short-circuit current with configuration of ground grid construction. The analysis on case-by-case basis is given as follows.

Case 1: 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. The depth of ground grid is 0.5 m. All of grid conductors are buried in the top layer. The existing values of touch voltage (1,082 volt) and step voltage (313 volt) criteria are not satisfied. Although the touch voltage exceeds the safety criteria (804.9 volt) by 25.61%, the step voltage stay within the safety limit. For the existing case of ground grid design, 3-dimension *GPR* is shown in Figure 6, from which we can see that the height of the waveform is noticeable when it is near the center of the existing substation. This indicates there is a large voltage difference between the top of the existing substation and the ground. There are many peak points on the graph. Each of these peak points represents the intensity of the voltage; namely, the higher the point is, the higher voltage will be. The area on the graph where peak points are located represents the area of the existing substation and far apart from the peak point area is the area of the temporary substation including the border, which is the area between the existing and the temporary substation. Figure 7 shows the side view perspective of 2-dimension *GPR* graph with the maximum value at approximately 16 m away from the origin. Figure 8 is the graph of the 2-dimension spot touch, which illustrates the top view of the graph to help determine the safety contour area. To conclude, the unsafe area covers a distance of 45 to 55 m away from the origin for axis x and y.

Case 2: The cross section of the ground grid conductor is 95 mm^2 and the ground rod is 3.0 m long with a diameter of 15.875 mm. The depth of ground grid is 0.5 m. All of grid conductors are buried in the top layer. The condition in case 2 has 1 to 2 years time interval for the construction of the indoor GIS substation. Therefore, the system planner must consider the safety criteria before the construction begins. In this scenario, 33.58% (1,166.6 volt to 774.9 volt) for maximum *GPR*, 35.86% (1,082 volt to 694 volt) for maximum touch voltage and 67% (313 volt to 171.5 volt) for maximum step voltage are decreased because the length of ground rod is changed from 2.4 m to 3 m. Total buried length of main electrode is 302.8 m. For case 2 of ground grid design, 3-dimension *GPR* is shown in Figure 9. The figure illustrates that the height of the waveform graph is rather high when it is the boundary of the small AIS substation, indicating there is a moderately large voltage difference between the top of the small AIS substation and the ground. However, this voltage difference is acceptable because it is within the safety criteria range. The area on the graph where many peak points are located represents the area of the small AIS substation. Figure 10 shows the side view perspective 2-dimension *GPR* graph with the maximum value at approximately 33 m away from the original. Figure 11 is the graph of the top view 2-dimension spot touch. The area contours show that all the areas within the two substations are safe.

Case 3: This case is the ground grid system of case 1 and case 2 are interconnected together with 4.40 m spacing. In this scenario, 53.48% (1,166.6 volt to 542.72 volt) for maximum *GPR*, 58.32% (1,082 volt to 451 volt) for maximum touch voltage and 62.08% (313 volt to 118.7 volt) for maximum step voltage are decreased because the total resistance of case 3 (0.021709 Ω) grounding system are less than case 1 (0.046665 Ω) and case 2 (0.030996 Ω). Total buried length of the main electrode is 485.70 m. The 3-dimension *GPR* for this case is shown in Figure 12, the waveform graph of which spreads all over the 2 substation areas. So there is a slightly voltage difference between 2 reference points (e.g. the top of the substation and the ground point). Figure 13 shows the side view 2-dimension *GPR* and Figure 14 is the graph of the 2-dimension spot touch. According to all information from the graphs, all areas within the two substations are safe.

Case 4: This case is the ground grid system of case 1 and case 2 with 4.40 m spacing. Assume that there is a short circuit at the small AIS substation site. In this case, 33.95% (1,166.6 volt to 770.6 volt) for maximum *GPR*, 38.82% (1,082 volt to 662 volt) for maximum touch voltage and 45.21% (313 volt to 171.5 volt) for maximum step voltage are decreased because the total resistance of case 3 less than case 1. For case 4, its 3-dimension *GPR* is shown in Figure 15. It is observed that the height of the waveform graph is rather high within the small AIS substation. So there is a moderately large voltage difference between the top of the small AIS substation and the ground. However, this voltage difference is acceptable because it is within the safety criteria range. The area on the graph where many peak points are located represents the area of the temporary small AIS substation. Figure 16 shows the 2-dimension *GPR* and Figure 17 is the graph of the 2-dimension spot touch. Based on safety criteria, all areas within the two substations for this case are safe.

Case 5: This case is the same as case 4 except that a short circuit assumes to occurr at the existing substation site. In this case, 0.45% (1,166.6 volt to 1,161.4 volt) for maximum *GPR*, 2.59% (1,082 volt to 1,054 volt) for maximum touch voltage and 62.08% (313 volt to 312 volt) for maximum step voltage are decreased because the total resistance of case 5 is less than that of case 1. For case 5 of the ground grid design, both 3-dimension *GPR* shown in Figure 18 and 2-dimension *GPR* shown in Figure 19 are similar to those of case 1. The areas that have orange shade in Figure 20 are unsafe.

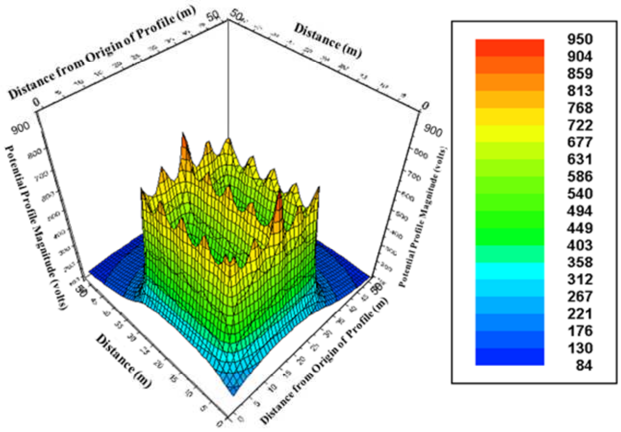


Fig. 6. 3-Dimension Ground Potential Rise for Case 1.

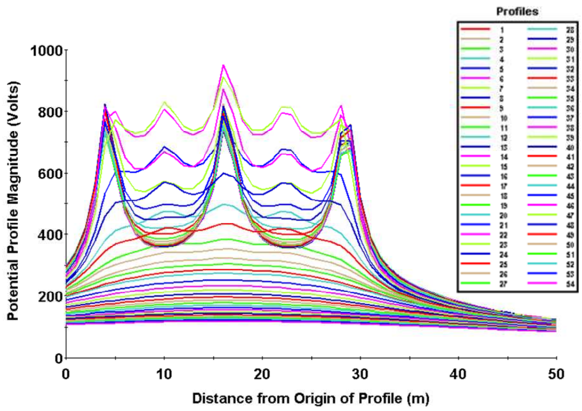


Fig. 7. 2-Dimension Ground Potential Rise for Case 1.

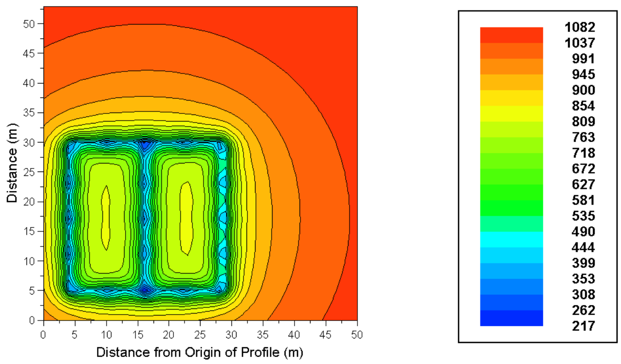


Fig. 8. 2-Dimension Spot Touch for Case 1.

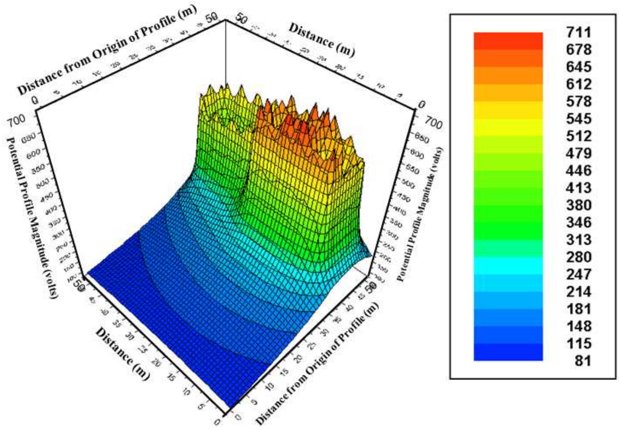


Fig.9. 3-Dimension Ground Potential Rise for Case 2.

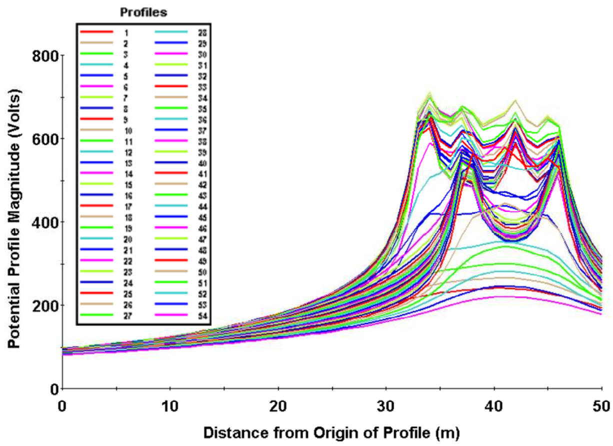


Fig.10. 2-Dimension Ground Potential Rise for Case 2.

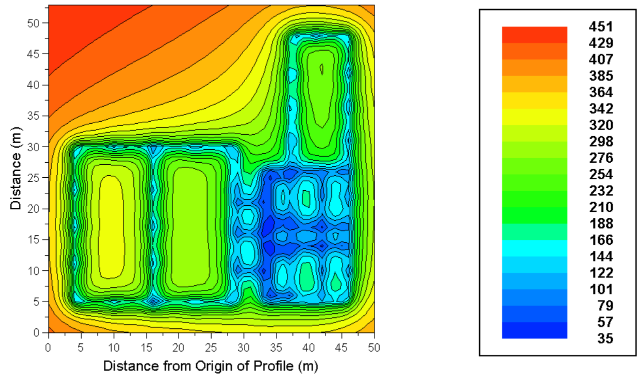


Fig.14. 2-Dimension Spot Touch for Case 3.

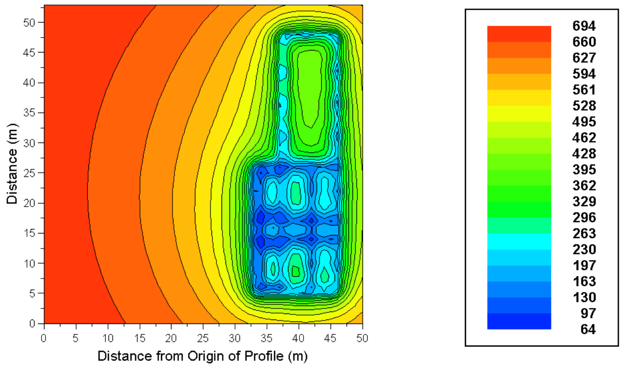


Fig.11. 2-Dimension Spot Touch for Case 2.

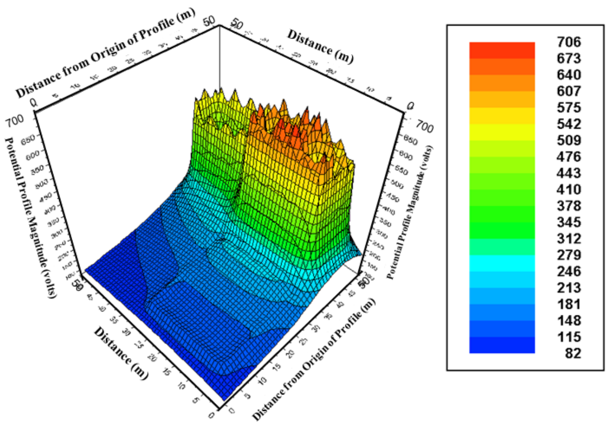


Fig.15. 3-Dimension Ground Potential Rise for Case 4.

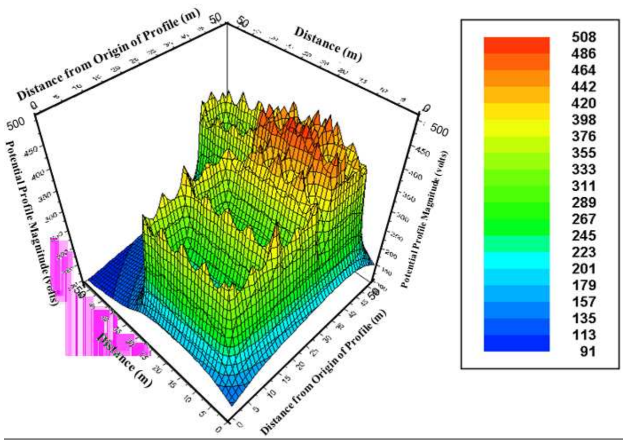


Fig.12. 3-Dimension Ground Potential Rise for Case 3.

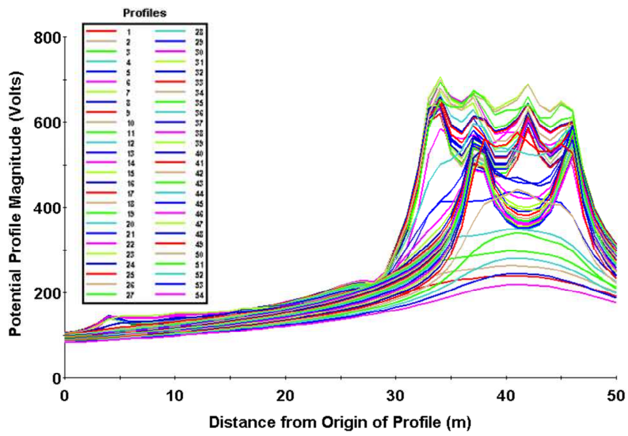


Fig.16. 2-Dimension Ground Potential Rise for Case 4

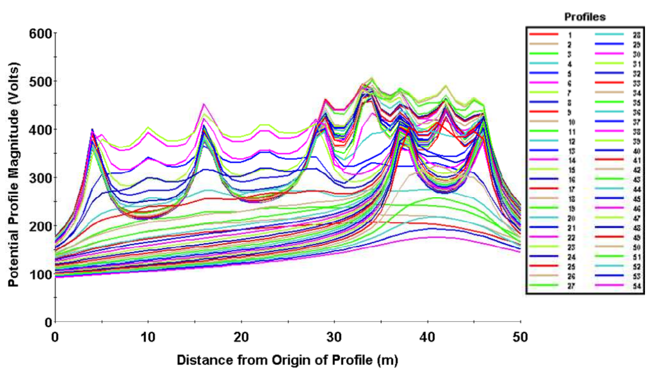


Fig.13. 2-Dimension Ground Potential Rise for Case 3.

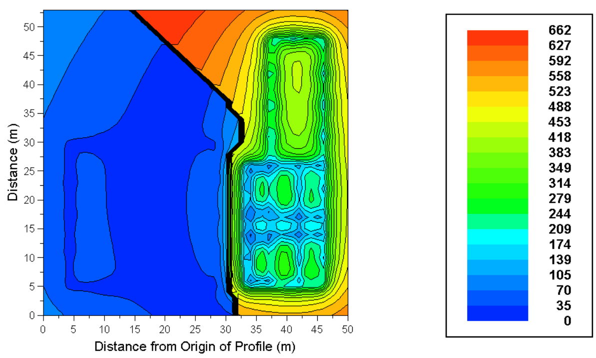


Fig.17. 2-Dimension Spot Touch for Case 4.

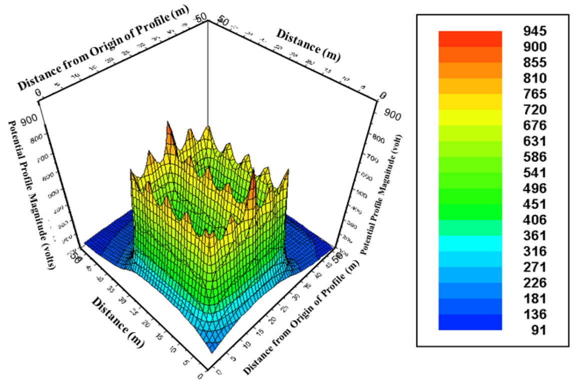


Fig.18. 3-Dimension Ground Potential Rise for Case 5.

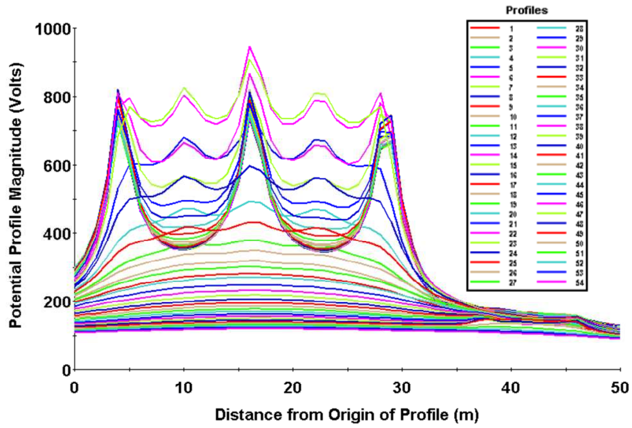


Fig.19. 2-Dimension Ground Potential Rise for Case 5.

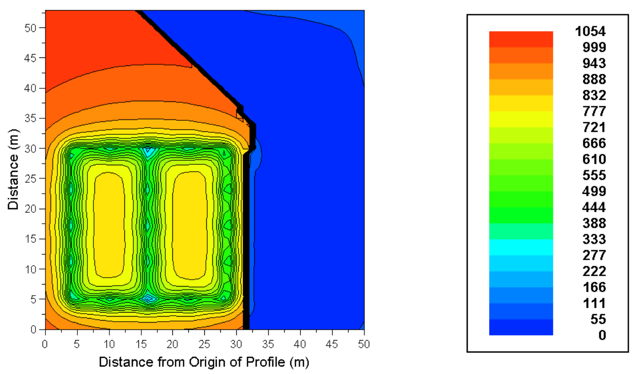


Fig.20. 2-Dimension Spot Touch for Case 5.

From the results of the 5 cases, it is found that *GPR* of cases 1, 2, 4 and 5 have a steepness characteristic. Therefore, this will generate ground potential difference (GPD). If the value of steepness is high, the touch voltage will also be high within the area of the substation. Even though GPD exists, it is still safe as long as the touch voltage does not exceed safety criteria.

For the procedure of substation construction, case 2 should be chosen for the first design. Because there is only ground grid of a small AIS substation so it is safe for the first step. The design that consists of two neighbouring substations is then processed for the next step. Despite the safety value of touch voltage in case 2, the rate of safety is increased when there is the interconnection with the ground grid system of the nearby substation. If the ground grid is separated, the status of auxiliary grounding system of the substation may create a high GPD. Hence, it has to consider the value of the maximum touch voltage within safety criteria before commencing the construction in the next step.

Based on the simulation results obtained for all cases, a sequential transition from the existing to new substation is suggested to comply with the IEEE std 80-2000, as shown Figure 21. As far as the safety is concerned for cases 1 and 5, their time interval has to be minimized, for example, by increasing the number of workers. Alternatively, it can be achieved by dropping crushed rock number 2 with a resistivity of 3,000 $\Omega \cdot$m until the thickness of rocks is approximately 10-20 cm.

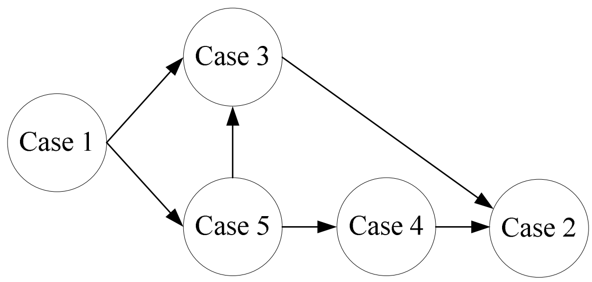


Fig.21. Step of Safety Construction.

6. CONCLUSION

The ground grid design for the PM substation has thoroughly 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 25 kA in Expansion Plan No.11 (years 2012-2016) in MEA. It is found that safety criteria should not be ignored in the meantime of ground grid isolation because the auxiliary grounding system of the existing substation can create steep ground potential rise and therefore the voltage difference can harm personals working nearby and cause damage to equipment in the vicinity of faults, particularly when the ground grid of the two neighbouring substations are not connected.

For the procedure in improving the existing distribution substation that require small distribution substation in order to supply temporary electricity, ground potential different between two separate ground grids in the distribution substation can occur when ground grids of two neighboring distribution substations are not connected together or there is only ground grid in one substation. This high GPR can damage intelligent electronic devices (IED), which will be used in distribution substation in the future or electronic controller which is currently used. This incident can occur after fault in distribution system or lightning. Moreover this high GPR is also dangerous to personnel operating in the distribution substation or nearby. The connecting ground grids of two neighboring distribution substations is a simple and economical method with effectiveness to reduce the damage of devices and danger to personnel working that can lead to power supply outage in industrial zone or densely populated area. Therefore, this method has more advantages compared with other methods e.g. installing more protection devices which needs more investment cost but cannot completely solve the problem.

ACKNOWLEDGMENT

The first author would like to express his deepest gratitude to late Assoc. Prof. Dr. Jamnarn Hokierti, Kasertsart University, Thailand and Mr. Praditpong Suksirithaworngule, ABB, Thailand, for teaching him the essential knowledge of power system. The author would like to express his sincere thanks to Provincial Electricity Authority (PEA) for CDEGS program and MEA for the technical data used in this research work. High appreciation is given to Mr. Chotepong Pongsriwat, PEA, Northern Region1, Chiang Mai, Thailand for his constructive comments. The author is deeply indebted to Mr. Worapot Krayong, Mr. Panoth Nitithumagul, Mr. Kangwarn Chareankornburi, Mr. Chukiat Yangyuenbangchan and Mr. Jatuporn Thamjaroen, MEA, for their fruitful discussions and kind assistance and Power System Planning Department for research time and strong support in this work.

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