Safety Design of Ground Grid in Distribution Substation: Case Study of Metropolitan Electricity Authority's System

A. Phayomhom, S. Sirisumrannukul and T. Kasirawat

Abstract— *Most of the power transmission and distribution substation in Metropolitan Electricity Authority (MEA) are of gas-insulated substation (GIS) type due to the restriction of space and very high cost of land in urban areas. A short circuit generates large currents that flow in the aboveground structures and grounding system and dissipate in the soil may cause damage to substation 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. In this paper, safe step and touch voltage criteria, based on body weight, are analyzed for utility applications where personnel hazards may exist. This paper presents a safety design of ground grid for a practical 120 MVA, 115-24 kV substation grounding grid system. Modeling and simulation is carried out on the Current Distribution Electromagnetic interference Grounding and Soil structure (CDEGS) program. The simulation results show the effects of the changes on the design and analysis of power system grounding and could be set as a standard in grounding system design and modification in MEA's distribution substations.*

Keywords— **Grounding grid, Ground potential rise, Step voltage, Touch voltage.**

1. INTRODUCTION

Metropolitan Electricity Authority (MEA) is an electric utility that is responsible for power distribution covering an area of 3,192 square kilometers in Bangkok, Nonthaburi, and Samutprakarn provinces of Thailand. MEA serves approximately 37 % of the whole country power demand. MEA's networks consist of transmission, subtransmission and distribution systems. Voltage level in transmission lines is 230 kV, while voltages in subtransmission systems are 69 and 115kV. 12 and 24 kV are voltages in the distribution feeders.

There are two types of power transmission and distribution substations in 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 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 fault. For this reason, GIS has an advantage over AIS in reducing the risk from touch voltage for personnel working nearby. Although the investment and operating costs of GIS are higher than those of AIS, it would still be a good option due to its compactness because the GIS indoor substation normally occupies only 10-25% of the land required for AIS. In addition, the GIS substation can reduce environment impact, safety concern and increase reliability. These benefits can compensate the higher costs in the long term [1], [2].

Based on MEA's statistical data, one of the main causes of sustain interruptions is short circuit on electrical substations. The 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.

With reference to a statistical report of Power System Control Department of MEA in the year 2008, there are in total 145 substations in MEA's network. Of these, 17 units are transmission substations, 127 units are distribution substations, and only 1 unit is a switching substation. Distribution substations are further classified as 66 unmanned substations and 61 manned substations.
This paper presents a safety design of ground grid for a practical 120 MVA, 115-24 kV substation grounding grid system in MEA. Modeling and simulation are carried out on the Current Distribution Electromagnetic

A. Phayomhom (corresponding author) is with Department of Electrical Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Thailand and with Power System Planning Department, Metropolitan Electricity Authority (MEA), 1192 Rama IV Rd., Klong Toey, Bangkok, 10110, Thailand. Phone: +66-2-348-5421; Fax: +66-2-348-5133; E-mail: attp@mea.or.th, att_powermea@hotmail.com.

S. Sirisumrannukul is with Department of Electrical Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok 1518, Pibulsongkram Rd., Bangsue, Bangkok, 10800, Thailand. E-mail: spss@kmutnb.ac.th.

T. Kasirawat is with Operation Network Department, Provincial Electricity Authority (PEA), Northern Region1, Chiangmai, Thailand. Phone: +66-53-241-486; Fax: +66-53-246-743; E-mail: tirapong.kas@pea.co.th.

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 a short circuit occurs.

2. SUBSTATION GROUNDING SYSTEM

The substation grounding system provides a means of dissipating electric current into the earth for reliable operation, human safety and equipment protection. The grounding system includes all interconnected grounding facilities, for example, ground grid, overhead ground wires, neutral conductors, underground cable, foundations, deep well, etc. The ground grid consists of horizontal interconnected bare conductors (mat) and ground rods [3].

Figure 1 shows a typical installation for grounding system of 120 MVA, 115-24 kV, Laksi grounding substation system. The cross section of the ground grid conductor is 240 mm^2, the grid dimension is 3m $\times$ 3m, and the ground rod is 2.4 m long with a diameter of 15.875 mm. All the ground rods 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.

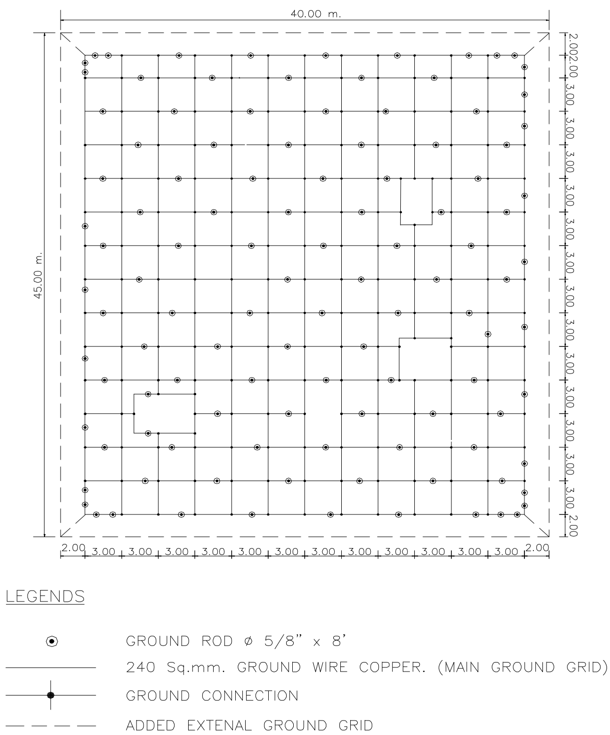

Fig.1. Typical installation for grounding system.

3. DEFINITION OF TOLERABLE VOLTAGE

According to [4], the following definitions for the voltage considered in this paper are given.

Fault Current Division Factor

A factor representing the inverse of a ratio of the symmetrical fault current to that portion of the current that flows between the grounding grid and surrounding earth.

$$S_f = \frac{I_g}{3 \cdot I_0} \tag{1}$$

where S_f = fault current division factor
I_g = rms symmetrical grid current (A)
I_0 = zero-sequence fault current (A)

Maximum Grid Current

A design value of the maximum grid current, defined as follows:

$$I_G = D_f \cdot I_g \tag{2}$$

$$I_G = D_f \cdot S_f \cdot 3I_0 \tag{3}$$

where I_G = maximum grid current (A)
D_f = decrement factor for the entire duration of fault t_f (s)

Ground Potential Rise (GPR)

The maximum electrical potential that a substation grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. This *GPR* is equal to the maximum grid current times the grid resistance.

$$GPR = I_G \cdot R_g \tag{4}$$

where GPR = ground potential rise (V)
R_g = resistance of grounding system (Ω)

Step Voltage

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

The potential difference between the ground potential rise 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.

Step and Touch Voltage Criteria

The step and touch voltage criteria are derived from the permissible body current. There is no direct change in the expressions of the permissible touch and step voltages. The permissible step and touch voltages for 50 kg and 70 kg persons are, respectively, [4]

$$E_{step50} = \left(1{,}000 + 6C_s \cdot \rho_s\right)\frac{0.116}{\sqrt{t_s}} \tag{5}$$

$$E_{step70} = \left(1{,}000 + 6C_s \cdot \rho_s\right)\frac{0.157}{\sqrt{t_s}} \tag{6}$$

$$E_{touch50} = \left(1{,}000 + 1.5C_s \cdot \rho_s\right)\frac{0.116}{\sqrt{t_s}} \tag{7}$$

$$E_{touch70} = \left(1{,}000 + 1.5C_s \cdot \rho_s\right)\frac{0.157}{\sqrt{t_s}} \tag{8}$$

where E_{step50} = tolerable step voltage for human with 50 kg body weight (V)
E_{step70} = tolerable step voltage for human with 70 kg body weight (V)
$E_{touch50}$ = tolerable touch voltage for human with 50 kg body weight (V)
$E_{touch70}$ = tolerable touch voltage for human with 70 kg body weight (V)
C_s = surface layer derating factor
ρ_s = surface layer resistivity $(\Omega \cdot \mathrm{m})$
t_s = duration of shock current frequency (s)

Maximum of Mesh and Step Voltage

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

$$E_m = \frac{\rho \cdot K_m \cdot K_i \cdot I_G}{L_m} \tag{9}$$

where E_m = mesh voltage (V)
ρ = average soil resistivity (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)
L_C = total length of grid conductor (m)
L_R = total length of ground rods (m)

The step voltage is determined from

$$E_s = \frac{\rho \cdot K_s \cdot K_i \cdot I_G}{L_s} \tag{10}$$

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

$$L_s = 0.75 \cdot L_C + 0.85 \cdot L_R \tag{11}$$

where E_s = step voltage (V)
K_s = mesh factor defined for n parallel conductors
L_s = effective length of $L_C + L_R$ for step voltage (m)

4. SOIL CHARACTERISTIC

Resistivity Measurements

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 [1], [5], [6].

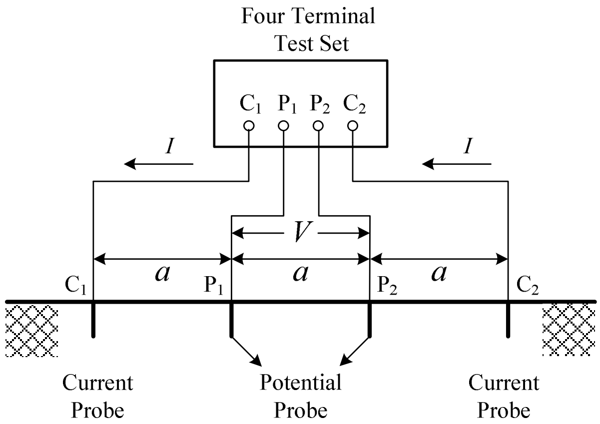

Fig.2. Wenner arrangement.

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

$$\rho_a = \frac{4\pi a R}{1 + \dfrac{2a}{\sqrt{a^2 + 4b^2}} - \dfrac{a}{\sqrt{a^2 + b^2}}} \tag{12}$$

where ρ_a = apparent resistivity of the soil in $(\Omega \cdot \mathrm{m})$
R = measured resistance (Ω)
a = Distance between adjacent electrodes (m)
b = depth of the electrodes (m)

When b is small compared to a, Eq. (13) becomes

$$\rho_a = 2\pi a R \tag{13}$$

Two-Layer Soil Apparent Resistivity

A resistivity of soil characterized with two layers shown in Figure 3 can be determined from the Wenner method. In this method, the apparent resistivity is calculated using Eq. (13) [6], [7]:

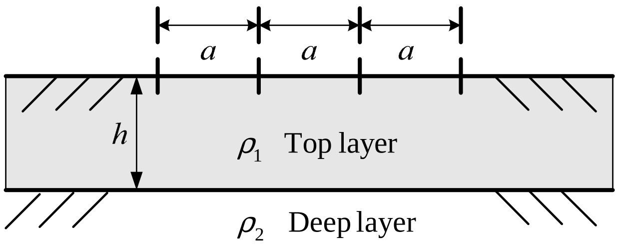

Fig.3. Two layer earth model.

$$\rho_a = \rho_1 \left(1 + 4 \sum_{i=1}^{\infty} \frac{K^n}{\sqrt{1 + \left(2n\frac{h}{a}\right)^2}} - \frac{K^n}{\sqrt{4 + \left(2n\frac{h}{a}\right)^2}} \right) \quad (14)$$

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \quad (15)$$

where h = first layer height (m)

ρ_1 = first layer resistivity ($\Omega \cdot \mathrm{m}$)

ρ_2 = deep layer resistivity ($\Omega \cdot \mathrm{m}$)

5. CASE STUDY

The Laksi grounding substation system shown in Figure 1 is analyzed in this case study. Three parameters of interest in the simulation are 1) cross section area of ground grid conductor, 2) length of ground rod, and 3) depth of ground grid. The cross section areas of ground grid conductor under investigation are 95, 120, 185, and 240 mm^2 (existing case). The lengths of ground rod are 2.4, 3.0 and 6.0 m and the depths of ground grid are 0.5, 0.6 and 1.0 m. A fault current of 31.5 kA is derived from the interrupting capacity of circuit breaker in the 115 kV circuit. The obtained simulation results demonstrate the voltage performance in terms of GRP, touch voltage and step voltage.

Ground Grid Model

The ground grid system for the Laksi substation was modelled using the CDEGS program as shown in Figure 4 [5].

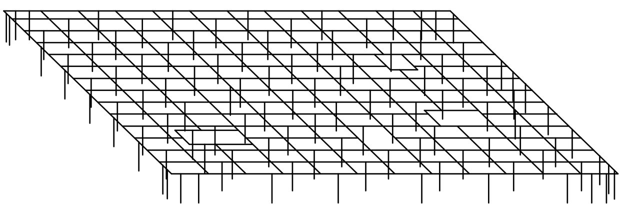

Fig.4. Ground grid model for Laksi substation.

Soil Resistivity Result

The soil layer characteristics of the Laksi 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 Laksi substation is shown in Table 1. The resistivity of the top and bottom layers is 14.1521 and 2.96357 $\Omega \cdot \mathrm{m}$ 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[8]. The three voltage performance indices are listed in Table 2. The data in Table 2 are graphically displayed in Figures 6-8.

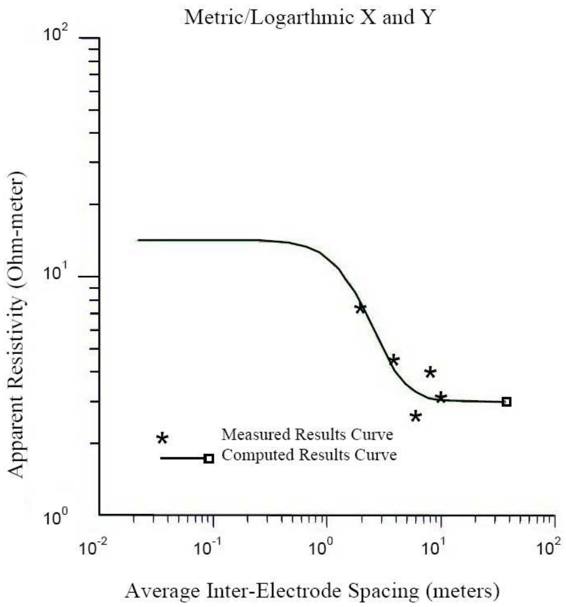

Fig.5. Soil resistivity model.

Table1. Summary of soil resistivity

Layer Characteristic				
Layer	**Resistivity ($\Omega \cdot \mathrm{m}$)**	**Thickness (m)**	**Reflection Coefficient (p.u.)**	**Resistivity Contrast Ratio**
Top	14.1521	1.21727	-1.0000	0.14152E-18
Bottom	2.96357	infinity	-0.6537	0.20941

Effect of Length of Ground Rod

As seen from Figures 6-8, lengthening ground rod reduces *GPR*, touch voltage and step voltage for ground grid conductors with the same cross-section area. In addition, the introduction of external ground grid lowers *GPR*, touch voltage and step voltage. For the 240 mm^2 ground grid, the external ground grid with 6-m ground rods gives the lowest *GPR* and touch voltage because this cross-section area has a more surface exposed to the soil for current dissipation. In this scenario, as much as

19.94% (1,170.20 volt to 936.86 volt) for maximum *GPR*, 38.88% (640.27 volt to 391.34 volt) for maximum touch voltage and 67% (177.98 volt to 58.65 volt) for maximum step voltage are decreased if the length of ground rod is changed from 2.4 m to 6 m.

Table 2. *GPR*, touch voltage and step voltage for different configurations

Rod Length (m)	Type of Voltage	Configuration	Voltage Level (V)			
			Cross-Section Area of Ground Grid (mm^2)			
			240	185	120	95
2.4	*GPR*	without grid	1,170.2	1,171.7	1,174.1	1,175.4
		with grid	1,117.5	1,119.5	1,122.8	1,124.5
	Touch	without grid	640.27	641.77	644.26	645.55
		with grid	563.48	565.88	569.71	571.71
	Step	without grid	177.98	176.31	174.8	173.78
		with grid	90.39	89.21	88.15	87.63
3	*GPR*	without grid	1,120.4	1,121.4	1,123	1,12.9
		with grid	1,080	1,080.4	1,082.8	1,084.1
	Touch	without grid	588.54	589.56	591.26	592.14
		with grid	526.24	527.39	530.34	531.87
	Step	without grid	159.4	157.73	156.44	155.49
		with grid	83.32	82.29	81.28	80.76
6	*GPR*	without grid	953.15	953.38	953.76	953.35
		with grid	936.86	937.33	938.1	938.5
	Touch	without grid	422.11	422.37	422.8	423.03
		with grid	391.34	392.06	393.25	393.86
	Step	without grid	104.61	103.21	102.52	101.87
		with grid	58.03	58.03	57.29	56.72

without grid: without external ground grid

with grid: with external ground grid

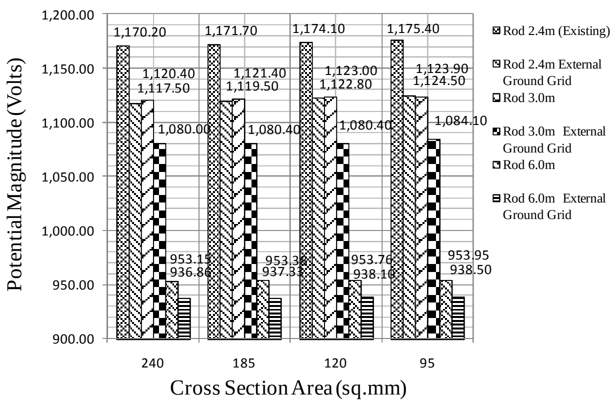

Fig.6. Ground potential rise for different configurations.

The safety criteria simulated from the CDEGS program are listed in Tables 3 and 4. For the existing case of ground grid design, 3-dimension *GPR* is shown in Figure 9, two-dimension spot touch voltage in Figure 10, and two-dimension spot step voltage in Figure 11. Because the maximum values for these three indices are 1,170.2 volt, 640.27 volt and 177.98 volt, only the touch voltage index for the existing case exceeds the safety values for 50 kg and 70 kg body weights. This constraint violation can be fixed, to some extent by, for instance, installing external ground conductors attached around the ground grid.

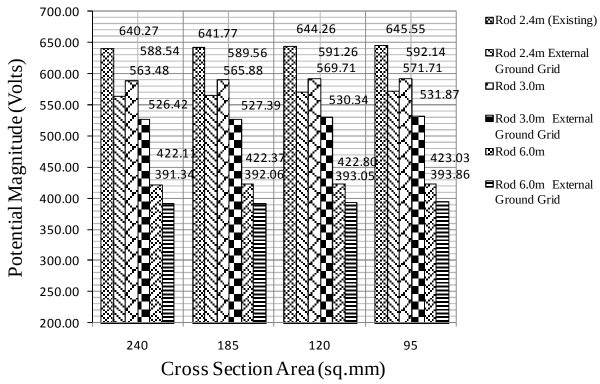

Fig.7. Touch voltage for different configurations.

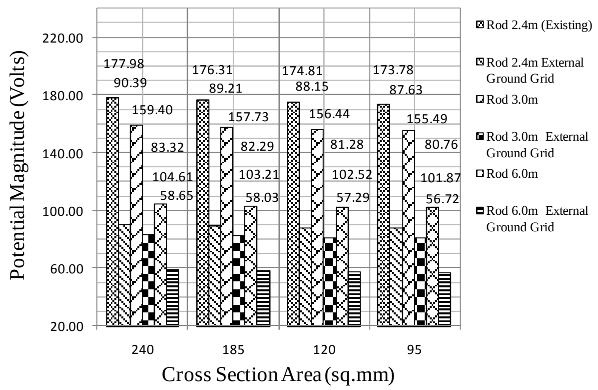

Fig.8. Step voltage for different configurations.

If one external ground conductor is added into Figure 1 (dash line), its effects are shown in Figure 12 for *GPR*, in Figure 13 for touch voltage, and in Figure 14 for step voltage. We can see that the peak spikes of *GPR* with external grounds (Figure 9) are not as high as those without external grounds (Figure 12). In this case, the maximum values of *GPR*, touch voltage, and step voltage for the 6 m ground rod with external ground grid are 936.86 volt, 391.34 volt, and 58.65 volt respectively. However, the touch voltage index still fails to meet the criteria given in Tables 3 and 4 and therefore more external ground wires are required.

Alternatively, this problem can be solved by topping the substation surface with gravel so that the soil resistivity is increased to 1,014.2 $\Omega \cdot \mathrm{m}$ (see Table 3) for 50 kg body weight and to 514.2 $\Omega \cdot \mathrm{m}$ (see Table 4) for 70 kg body weight. Note that inserting external ground grids offers a long term solution while topping the ground surface may provide a short or medium term one as the ground structure may be altered owing to digging, flooding etc.

Table 3. 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	367.9	603.9	44.2
514.2	587.3	1,481.7	1,562
1,014.2	806.7	2,359.2	3,079.2

Table 4. Safety criteria for 70 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	497.9	817.4	44.2
514.2	794.9	2,005.5	1,562
1,014.2	1,091.8	3,193.1	3,079.2

After installing the external ground grid, the areas with low touch voltage are expanded inside the ground grid. This reduces the risk of personnel working in the substation. We can see from Figures 10 and 13 that the maximum touch voltage of 640.27 volt at point T1 reduced to 391.34 volt at point T2. Also, the maximum step voltage is shifted from S1 (177.98 volt) in Figure 11 to point S2 (141.87 volt) in Figure 14.

Effect of Size of Ground Grid Conductor

It can be observed from Table 2 that *GPR*, touch voltage and step voltage are not much varied when the size of ground grid decreases from 240 mm^2 to 95 mm^2. Therefore, the 95 mm^2 is able to acceptably substitute the existing 240 mm^2. By means of this method, *GPR* and touch voltage see an increase of 0.44% (1,170.2 volt to 1,175.4 volt) and of 0.83% (640.27 volt to 645.55 volt) respectively whereas step voltage is decreased 2.36% (177.98 volt to 173.78 volt).

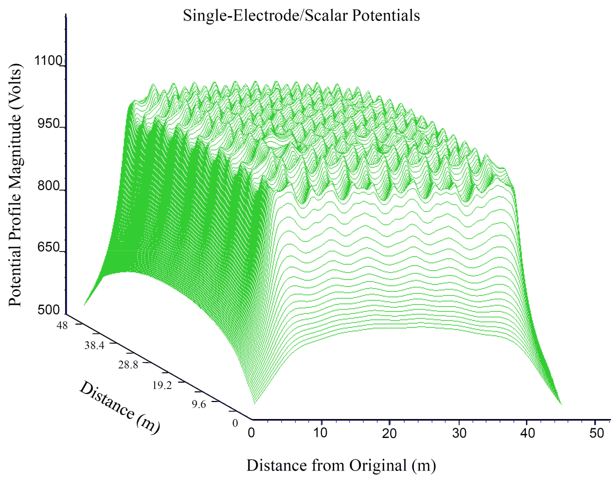

Fig.9. Ground potential rise for existing system.

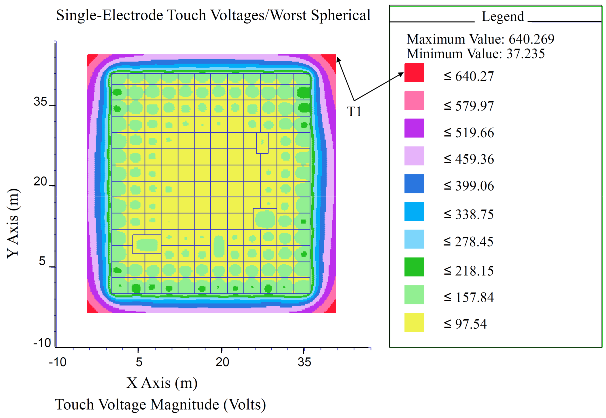

Fig.10. Touch voltage magnitude of existing system.

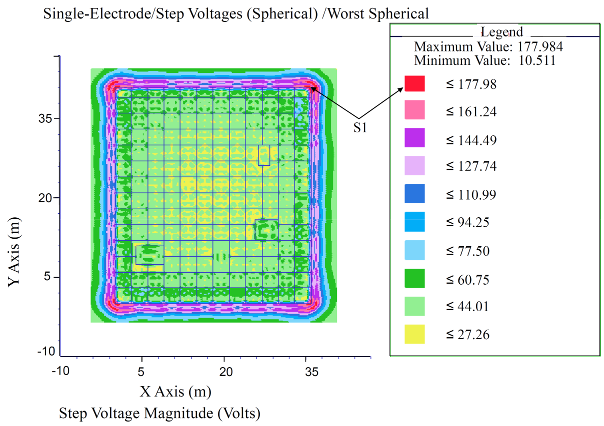

Fig.11. Step voltage magnitude of existing system.

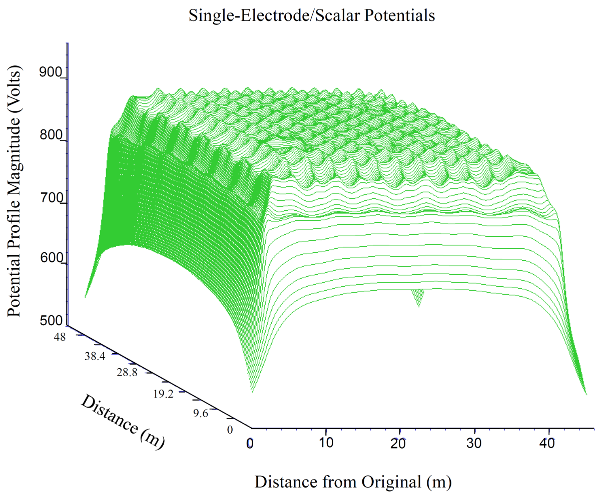

Fig.12. Ground potential rise of 240 mm^2 external ground grid with 6 m ground rod.

Effect of Depth of Ground Grid

The ground grid with an external ground conductor is analyzed to demonstrate the effect of its depth on the voltage performance. The tests results obtained from the depth of ground grid at 0.6, and 1.0 m are compared to those at the depth of 0.5 m. It is found that the value of *GPR* at the depth of 0.6 m is slightly different from that at the depth of 0.5 m. But *GPR*, touch voltage and step voltage at a depth of 1 m are approximately reduced by 9.64%(1,170.2 volt to 1,057.4 volt), 27.73%(640.27 volt to 501.14 volt), and 41.16%(177.98 volt to 104.72 volt) respectively. Therefore, placing ground grid at deep level is useful to improve the voltage performance indices.

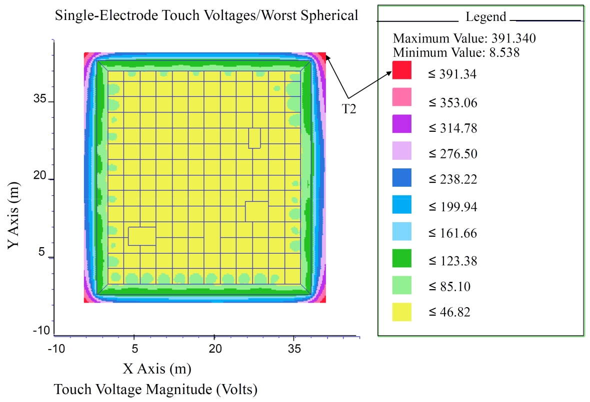

Fig.13. Touch Voltage Magnitude of 240 mm^2 external ground grid with 6 m ground rod.

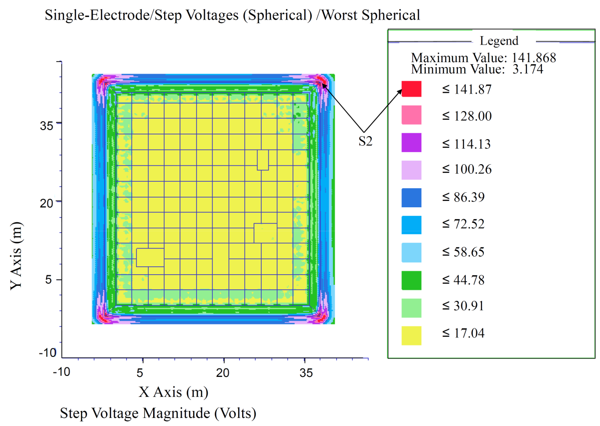

Fig.14. Step voltage magnitude of 240 mm^2 external ground grid with 6 m ground rod.

6. ECONOMIC ANALYSIS

For the practical design in substations of the MEA system, ground grid conductors with a cross sectional area of 240 mm^2 and ground rods with a length of 2.4 m have been in use. For the purpose of further investigation, we have analyzed the safety criteria using other sizes of ground grid and ground rods available in the market under the constraint that the step and tough voltages must abide by the safety criteria specified in Tables 3 and 4, based on a surface layer resistivity of 514.2 ohm-m. The results are listed in Table 5 and graphically shown in Figure 15. It is found that from safety point of view, the 6 m ground rod with 240 mm^2 external ground grid is the most suitable for this particular case study but is not cost-effective (1.32 million baht of investment cost). The 95 mm^2 ground grid and the 6 m ground rods are adequate to satisfy the safety criteria while the investment cost is only 0.61 million baht. This configuration would represent the optimal condition, making a significant saving of 0.71 million baht (53.79%). Note that although the saving obtained from the same size of ground grid but with a 2.4 m ground rod is 65.15%, it violates the safety constraint.

Table 5. Investment cost for different configurations

Rod Length (m)	Configura-tion	Investment Cost (Million Baht)			
		Cross-Section Area of Ground Grid (mm^2)			
		240	185	120	95
2.4	without grid	1.08	0.86	0.59	0.46
	with grid	1.23	0.98	0.67	0.52
3.0	without grid	1.10	0.88	0.61	0.48
	with grid	1.25	1.00	0.68	0.54
6.0	without grid	1.17	0.95	0.68	0.55
	with grid	1.32	1.07	0.76	0.61

without grid: without external ground grid

with grid: with external ground grid

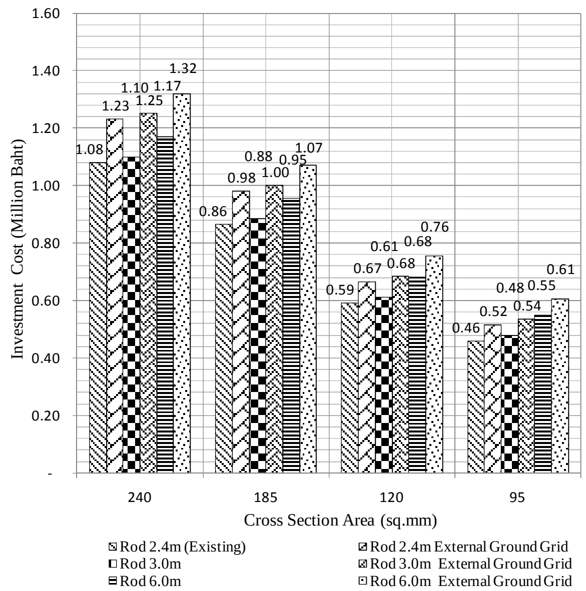

Fig.15. Investment cost for different configurations of grounding system.

7. 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 3 m or 6 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.

8. CONCLUSION

This paper presents a safety design of ground grid in distribution substation. The ground grid design for an MEA substation is analyzed 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 investigated to ensure that they satisfy the safety criteria defined in the IEEE Std 80-2000. The test results confirm that the length of ground rod and the number of conductors attached at the boundary of ground grid are a practical solution to reduce *GPR*, touch voltage, and step voltage. On the basis of the test results, a ground rod of 6 m and ground grid with a cross-section area of 95 mm^2 could be a suitable option for the grounding system. However, as far as installation costs and other necessary expenses in grounding system planning is concerned, the length of ground rods and the size of conductor should financially reflect incremental total cost and worth for various alternatives while respecting the established safety criteria.

ACKNOWLEDGMENT

The authors 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. Arwut Puttarach, Chiang Mai University, Thailand, Mr. Vaiwith Thammawutigul MEA, Bangkok, Thailand for his constructive comments.

REFERENCES

[1] Thasananutariya, T. and Spuntupong, K. and Chatratana, S. 2004. Design of grounding system for GIS substation. In *Proceedings of TENCON*, Chaingmai, Thailand, 21-24 November.

[2] Irwin, T. and Lopez-Roldan, L. 2000. Substation earthling: Special consideration for GIS substation, *IEE Seminar on Published:* , pp.5/1-5/5.

[3] Mcdonald, J.D, 2003. Electric Power Substations engineering. Florida: CRL Press LLC.

[4] IEEE std 80-2000. Guide for Safety in AC Substation Grounding.

[5] Puttarach, A., Chakpitak, N., Kasirawat, T. and Pongsriwat et al, C. 2007. Substation grounding grid analysis with the variation of soil layer depth method. In *Proceedings of Powertech*, Lausanne, Switzerland, 1-5 July.

[6] ANSI/IEEE Std 81-1983. IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System

[7] Dawalibi, F.P. and Blattner C.J. 1984. Earth resistivity measurement interpretation techniques. In *Proceedings* of *IEEE Transactions on Power Apparatus and systems,* Febuary

[8] BS std 7430:1998. Code of Practice for Earthing.