

Effects of Ground Grid Configuration of Two Neighbouring Distribution Substations on Ground Potential Rise in MEA's Power System

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Abstract

This paper presents construction planning procedures for a new small (temporary) or permanent distribution substation to replace an existing distribution substation that is served as a small or permanent substation to supply the load of the existing distribution 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 distribution 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. 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 distribution substation to a new distribution substation is suggested to comply with the IEEE standard 80-2000. The results in this paper could be served a guideline in grounding system design of distribution substation and modification of grounding standards in MEA's power distribution system.

Keywords: *Ground 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 32 % of the whole country power demand in 2013. MEA's networks consist of transmission, subtransmission and distribution systems.

The transmission line voltage is 230 kV, while the 69 and 115kV used in subtransmission systems and 12 and 24 kV in the distribution feeders.

This paper focus on construction procedures for new permanent distribution substation in order to renovate existing distribution substation to a new one. (while the other substation which can be the temporary or the existing old substation still has not yet been removed). During the time of two ground

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grids of two distribution substations are still isolated, when short circuit occur at main ground grid site; the effect of ‘auxiliary grounding system’ (de-energized electrical power site) to the main station which remains energized cannot be ignored. It will create high ground potential rise (GPR) to be steep between the ground grids of the two neighbouring distribution substations. For safety precaution, ground grid design for the safety of personal working around the vicinity of substation construction site should be ensured.

To achieve this, modeling and simulation are carried out on the Current Distribution Electromagnetic interference Grounding and Soil structure (CDEGS) software package. Safety step and touch voltage are analyzed with reference to safety criteria based on body weight defined in IEEE Std. 80-2000.

2 Effects of Nearby Auxiliary Grounding System of Substation

Several times, the new temporary (small) or permanent distribution substation is under construction while the existing substation is still in operation and not yet removed. There are two grounding systems for each substation that is not connected each other. The ground grid of the main substation is called main ground grid (energized electrical power site) whereas that of the other distribution substation (temporary or permanent distribution substation) is called auxiliary ground grid (de-energized electrical power site). During the time of disconnecting of ground grid, the small or permanent distribution substation is de-energized, its auxiliary grounding system however exposes to the risk of high GPR caused by the main distribution substation which is still in operation. The GPR’s steepness is located between the main and auxiliary ground grid.

3 Definition of Tolerable Voltage

According to [1], the following definitions for the voltage considered in this paper are given.

3.1 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.

$$GPR = I_G \times R_g \quad (1)$$

where

- GPR is ground potential rise (V)
- I_G is maximum grid current (A)
- R_g is resistance of grounding system (Ω)

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.

3.2 Touch Voltage

Touch voltage is 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 [1]

$$E_{touch} = I_B \times (R_B + 1.5C_s\rho_s) \quad (2)$$

where

- E_{touch} is tolerable touch voltage for human (A)
- R_B is resistance of the human body (Ω)
- C_s is surface layer derating factor
- ρ_s is surface layer resistivity (Ω -m)

$$I_B = \frac{k}{\sqrt{t_s}} \quad (3)$$

where

- I_B is current through the body (A)
- k is 0.116 for 50 kg body weight
0.157 for 70 kg body weight
- t_s is 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 listed in IEEE std 80-2000 [1].

3.3 Step Voltage

Step voltage is 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 [1]

$$E_{step} = I_B \times (R_B + 6C_s \rho_s) \quad (4)$$

where

E_{step} is tolerable step voltage for human (V)

3.4 Maximum of mesh and step voltage

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

$$E_m = \frac{\rho_a K_m \cdot K_i \cdot I_G}{L_m} \quad (5)$$

where

E_m is mesh voltage (V)

ρ_a is apparent resistivity of soil (Ω -m)

K_m is mesh factor defined for n parallel conductors

K_i is corrective factor for current irregularity

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

L_m is 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

$$L_s = 0.75 \cdot L_C + 0.85 \cdot L_R \quad (6)$$

where

L_s is effective length of $L_C + L_R$ for step voltage (m)

L_C is total length of grid conductor (m)

L_R is total length of ground rods (m)

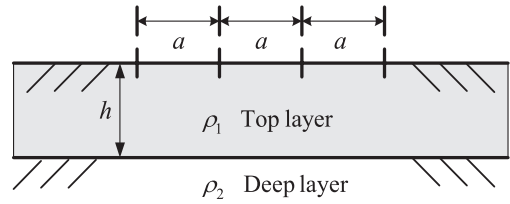


Figure 1: Two Layer earth model.

The step voltage is determined from

$$E_s = \frac{\rho_a \cdot K_s \cdot K_i \cdot I_G}{L_s} \quad (7)$$

where

E_s is step voltage (V)

K_s is 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.

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 (8) and (9) [1], [2-4]:

$$\rho_a = \rho_1 \left[1 + 4 \sum_{n=1}^{\infty} \frac{K^n}{\sqrt{1 + \left(2n \frac{h}{a}\right)^2}} - \frac{K^n}{\sqrt{4 + \left(2n \frac{h}{a}\right)^2}} \right] \quad (8)$$

$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \quad (9)$$

where

ρ_a is apparent resistivity of the soil in (Ω -m)

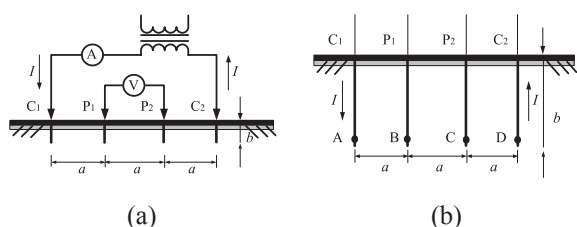
h is first layer height (m)

K is reflection factor

ρ_1 is first layer resistivity (Ω -m)

ρ_2 is deep layer resistivity (Ω -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 (8). 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.



(a) Principal diagram of an earth resistivity meter
 (b) Current injection into the soil

Figure 2: Wenner arrangement.

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 Figure 2, 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], [3-4].

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

$$\rho_a = \frac{4\pi aR}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \quad (10)$$

where

- R is measured resistance (Ω)
 - a is distance between adjacent electrodes (m)
 - b is depth of the electrodes (m)
- When b is small compared to a , (10) becomes

$$\rho_a = 2\pi aR \quad (11)$$

4 Case Study

For all scenarios, the cross section of the ground grid conductor is 95 mm^2 , the grid dimension is $3 \text{ m} \times 3 \text{ m}$, and the ground rod is 3.0 m long and 15.875 mm in diameter. All the ground grid conductors are 0.5 m deep buried in the top layer soil. The configuration of an installation of ground rod will be buried at 4 edges and the diagonal lines of the ground grid. The dimension of ground grid which presents the status of main ground grid and auxiliary grounding system of substation (return) will be categorized into 3 sizes :

small ($15 \text{ m} \times 15 \text{ m}$: S), medium ($30 \text{ m} \times 30 \text{ m}$: M), and large ($45 \text{ m} \times 45 \text{ m}$: L) shown configuration detail in Table 1. The main ones are of large, medium and small size.

Table 1: Two Neighbouring distribution substation is unconnected

Sec	Main Ground Grid Size	Configuration	Auxiliary Ground Grid Size
1	Large		Large
2	Large		Large
3	Large		Small
4	Medium		Large
5	Medium		Medium
6	Medium		Small
7	Small		Large
8	Small		Medium
9	Small		Small

Furthermore, the value of soil resistivity is chosen to be 10 Ω-m, 10/100 Ω-m and 100/10 Ω-m, this applies to both top and bottom layer soil. The above mentioned ground resistivities chosen because these ground resistivities represent the ones found by actually measured in MEA’s substation and calculated using equation (8)-(11). The soil resistivity of uniform layer is 10 Ω-m whereas 100/10 Ω-m for resistivity of top and bottom layer in two layer soil respectively. Moreover in scenario of lower resistivity of top layer soil at 10/100 Ω-m is studied also. The top layer has a more resistivity than the bottom layer (deep layer) or on the other hand 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 [4,5]. However this type of soil is rarely to find unless in the flood area. The thickness of the soil is determined at 2 m. Thus, the short circuit current of 25 kA is specified and the maximum fault clearing time is 100 ms. For this studied scenario (sce), ground grid of these substations is unconnected. The distance between ground grid are 25 m the configuration and position are as shown in Table 1.

Table 2: GPR, GPR ratio, maximum touch and step voltage unconnected at soil resistivity 10 Ω-m

Scenario	GPR (V)		A/Ma (%)	Touch (V)	Step (V)
	Ma	A			
1	2,268.0	601.10	26.50	1,245	479
2	2,275.6	663.31	29.14	1,353	459
3	2,282.5	729.92	31.97	1,562	460
4	3,312.1	662.97	20.01	2,249	753
5	3,325.7	752.00	22.61	2,332	750
6	3,336.5	852.59	25.55	2,545	748
7	6,181.9	728.98	11.79	5,184	1,636
8	6,201.1	852.40	13.74	5,192	1,633
9	6,217.9	1,011.80	16.27	5,292	1,630

Table 3: GPR, GPR ratio, maximum touch and step voltage unconnected at soil resistivity 100/10 Ω-m

Scenario	GPR (V)		A/Ma (%)	Touch (V)	Step (V)
	Ma	A			
1	2,874.1	601.32	20.92	1,831	997
2	2,873.4	663.79	23.10	1,942	924
3	2,877.9	730.65	25.38	2,155	925
4	4,308.3	662.98	15.38	3,231	1,432
5	4,317.7	752.22	17.42	3,316	1,430
6	4,324.7	852.86	19.72	3,531	1,429
7	8,640.7	729.61	8.44	7,634	3,222
8	8,654.1	853.02	9.86	7,640	3,218
9	8,665.1	1,012.3	11.68	7,737	3,216

Table 4: GPR, GPR ratio, maximum touch and step voltage unconnected at soil resistivity 10/100 Ω-m

Scenario	GPR (V)		A/Ma (%)	Touch (V)	Step (V)
	Ma	A			
1	13,587	5,626.9	41.41	5,159	1,316
2	13,748	6,135.7	44.62	5,797	1,310
3	13,884	6,664.1	47.99	7,305	1,303
4	17,732	6,134.4	34.59	8,896	1,972
5	17,949	6,855.0	38.19	9,433	1,944
6	18,150	7,639.3	42.08	10,991	1,924
7	26,737	6,656.7	24.90	18,193	3,535
8	27,028	7,636.6	28.25	18,318	3,509
9	27,320	8,847.0	32.38	19,130	3,480

Legend :

Ma: GPR of main ground grid system site,

A: GPR of auxiliary grounding system of substation site

From Tables 2-4, the results will separate into three categories. 4.1) The result of the voltages (GPR, maximum touch and step voltage) at the same configuration but only soil resistivity is different (it is varied among 10 Ω-m 100/10 Ω-m and 10/100 Ω-m. 4.2) The effects of the size of main and auxiliary grounding system. 4.3) Maximum touch voltage analysis with GPR ratio (% A/Ma)

4.1 The result of the voltages at the same configuration but only soil resistivity is different

As shown in Tables 2-4, at the same configuration but only soil resistivity is varied among 10 Ω-m, 100/10 Ω-m and 10/100 Ω-m, it shows that 10 is the resistivity that make the lowest value of GPR, maximum touch voltage and maximum step voltage. On the other hand, when the resistivity is 10/100 Ω-m Ground rods are penetrated into the bottom layer which is higher resistivity than top layer. The reflection coefficient shows as positive, it contributes the voltages to be higher. Thus, the values of three voltages in this case are highest. For example, scenario 1 in Table 2, the resistivity is 10 Ω-m. GPR, maximum touch and step voltage are 2,268 V 1,245 V and 479 V which shown in Figures 3, 4 and 5 respectively. Scenario 1 in Table 3, the resistivity is 100/10 Ω-m. GPR, maximum touch and step voltage are 2,874.1 V 1,831 V and 997 V respectively. Scenario 1 in Table 4, the resistivity is 10/100 Ω-m. GPR, maximum touch and step voltage are 13,587 V 5,159 V and 1,316 V respectively.

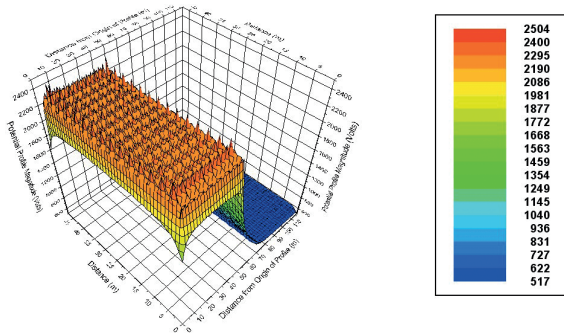


Figure 3: 3-D GPR for scenario 1 of 10 Ω-m.

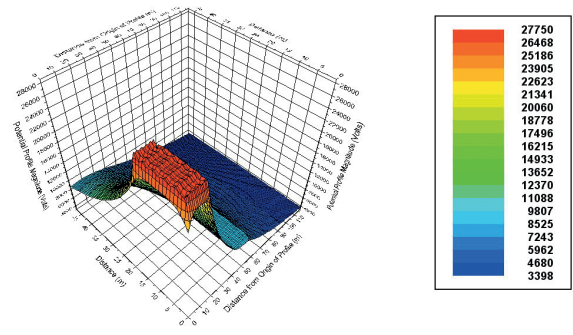


Figure 6: 3-D GPR for scenario 9 of 10/100 Ω-m.

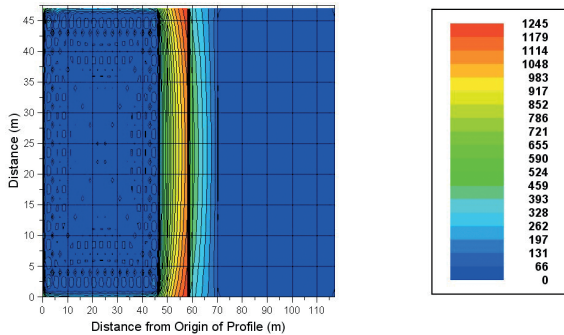


Figure 4: 2-D spot touch for scenario 1 of 10 Ω-m.

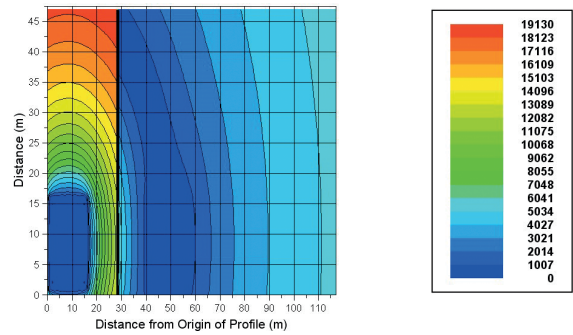


Figure 7: 2-D spot touch for scenario 9 of 10/100 Ω-m.

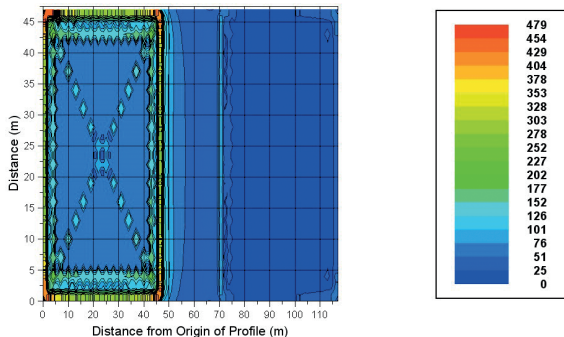


Figure 5: 2-D spot step for scenario 1 of 10 Ω-m.

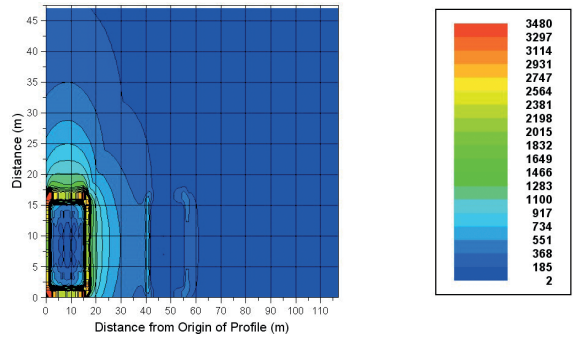


Figure 8: 2-D spot step for scenario 9 of 10/100 Ω-m.

4.2 The effects of the size of main and auxiliary grounding system

As shown in Tables 2-4, if vary the size of auxiliary grounding system whereas the size of main ground grid is fixed. GPR and maximum touch voltage are lowest when the size of auxiliary grounding system is large, but maximum step voltage is not the same;

it is highest. For instance, from scenario 4, 5 and 6, it shows that scenario 4 which is the size of auxiliary grounding system is large makes the value of GPR and maximum touch voltage lowest. In the same way, if the size of main ground grid is varied whereas the size of auxiliary grounding system is fixed. Large size still makes the value of GPR and maximum touch voltage lowest. Scenario 3, 6 and 9 represent

this condition which the size of main ground grid is varied among small, medium and large but the size of auxiliary grounding system is fixed as small. Scenario 3, it makes GPR and maximum touch voltage lowest but scenario 9, it makes these voltages highest. The reason is large size has more electrode connected in parallel than small size which make the total electrode resistance lower.

Figures 6-8 show GPR, maximum touch and step voltage from scenario 9 which are 27,300 V, 19,130 V and 3,480 V respectively. Figure 6 shows that the steepest of GPR is quite high at the middle of distance between two substations. The GPR is high. It does not mean unsafe though. It is safe in case ground potential different (GPD) or maximum touch voltage not over safety criteria.

4.3 Maximum touch voltage analysis with GPR ratio (% A/Ma)

GPR ratio is the ratio between GPR of auxiliary grounding system (A) and GPR of main ground grid (Ma). It can use for maximum touch voltage analysis but only in case of the soil is uniform or the bottom layer resistivity has lower than top layer. In other words, it can only use in case the soil is 10 Ω -m and 100/10 Ω -m. It found that the more ratios, the more we safe. The more ratios mean the closer of two GPR also. Since the maximum touch voltage is GPD or the different between GPR, therefore; it makes maximum touch voltage decrease. For instance, from scenario 1, maximum touch voltage and GPR ratio in Table 2 are 1,245 V and 26.5 % but the voltage and ratio in Table 3 are 1,831 V and 20.92 % respectively. It shows that Table 2 has lower maximum touch voltage than Table 3 but GPR ratio is higher. As mentioned above, it ensures that GPR ratio can use for maximum touch voltage analysis by the higher ratio, the better safety. However, if the two neighbouring ground grids are connected, it is safe for the people if working around [6-7].

5 Conclusions

The study of the sizes of the ground grid (main and auxiliary grounding of substation) have an effect on GPR, maximum touch and step voltage of ground grid system which can be concluded as follows:

1. Among 10 Ω -m, 100/10 Ω -m and 10/100 Ω -m,

focus on the same others configuration; GPR, maximum touch and step voltage are lowest when the soil is uniform layer which the resistivity is 10 Ω -m. It doesn't mean the uniform layer is always better than two layers soil though. For example, if the resistivity of uniform layer is 500 Ω -m, the voltages will higher than the two layers soil which the resistivity is 100/10 Ω -m.

2. Comparison with the others size, if the size of main ground grid and auxiliary grounding system are both large size. It leads to the lowest of GPR and maximum touch.
3. GPR ratio can be used to compare the level of maximum touch voltage for ground grid of the same configuration, e.g. scenario 1, 5 and 9 with one condition: the resistivity of the bottom layer is less than that of the top layer for two layer soil, including uniform soil.
4. The investment budget is the first priority to consider. It has to cover the appropriate design in order to support short circuit current from the electricity demand growth in the future. It also has to bring the safety to power system apparatus and human nearby the substation. So, the investment budget depends on the size of substation and the materials such as diameter of the conductor, length of ground grid and ground rod etc.
5. The inter-distant between neighboring substations is only one of the safety parameter, the incurred touch and step voltage depend on other parameters, such as: soil resistivity, grid configuration, short circuit current, total resistant of ground, etc. So the appropriate inter-distant between the neighboring substations cannot be simply specified.

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