Case Study of Ground Potential Rise on Two Neighboring Substations

W. Pobporn, D. Rerkpreedapong, and A. Phayomhom

Abstract— *This paper presents the effects of constructions of a new permanent substation while the existing substation has not yet been removed. the Isolation of ground grids of the two substations creates ground potential rise (GPR) to be steep between the ground grids of two neighboring substations. Modeling and simulation are performed on the Current Distribution Electromagnetic interference Grounding and Soil structure (CDEGS) program. It is found that the percentage of GPR ratio between the auxiliary grounding system and the main ground grid in uniform or homogenous soil is constant while the percentages of GPR ratio are different in the two layer soils. If the top layer soil resistivity is higher than the fixed bottom layer soil resistivity, the percentage of GPR ratio will decrease. However if the bottom layer soil resistivity is higher than the fixed top layer soil resistivity, the percentage of GPR ratio will increase. This implies that only a risky case can be considered in substation design, although the condition of soil is varied by season. Moreover, the case studies are analyzed by varying the thickness of top layer and distance between the main ground grid system and auxiliary grounding system, which affect the percentage of GPR ratio. The more distance between main ground grid system and auxiliary grounding system is, the less the percentage of GPR ratio is, as GPR return of the auxiliary grounding system is lower. This will make the touch voltage higher due to the steepness of GPR, which increases the risk of hazard.*

Keywords— **Ground potential rise, Safety criteria, Step voltage, Touch voltage.**

1. INTRODUCTION

This paper presents a construction procedure for a new permanent substation while the existing substation has not yet been removed. While the ground grids of the two distribution substations are isolated, the effect of the auxiliary grounding system of the de-energized electrical power site will exist. This creates ground potential rise (GPR) to be steep between the ground grids of two neighboring substations. It is a concern for safety issues because a short circuit can generate a large current that flows through the aboveground structures and grounding system and dissipates in the soil, which the high potential may cause a hazard to personnel working nearby or in the area of distribution substations.

The ground grid design for distribution substations of the Provincial Electricity Authority of Thailand (PEA) is examined with the main objective to assess grounding grid system conditions in terms of ground potential rise, maximum touch voltage and step voltage. These three values are analyzed to ensure that they comply with the safety criteria defined in the IEEE Std. 80- 2000. Modeling and simulation are carried out on the Current Distribution Electromagnetic interference Grounding and Soil structure (CDEGS) program. The results are found that ground grid isolation should not be allowed during the time of construction because the auxiliary grounding system of the de-energized substation can create steep ground potential rise and therefore the large voltage difference can harm personnel working nearby and cause a damage to equipment in the vicinity of faults, particularly when the ground grid of the two neighboring substations are not connected.

2. DIFFINITION OF TOLERABLE VOLTAGE

In the process of designing the ground grid system, safety criteria is firstly calculated to specify a tolerable 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 voltages.

Touch Voltage Criteria

The potential difference between the ground potential rise (*GPR*) and the surface potential at the point where a person is standing while having a hand in contact with a grounded structure.

The tolerable touch voltage in volts is defined in (1).

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

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

The current through the body is determined by (2)

$$I_B = \frac{k}{\sqrt{t_s}} \tag{2}$$

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 is de-energized. 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 of 50kg and 70kg can be found in [1],[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 in (3) [1]

$$E_{step} = I_B \times \left(R_B + 6\rho_S\right) \tag{3}$$

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 [1] is calculated by (4)

$$E_m = \frac{\rho_a K_m \cdot K_i \cdot I_G}{L_m} \tag{4}$$

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, can be determined by (5)

$$L_s = 0.75 \cdot L_C + 0.85 \cdot L_R \tag{5}$$

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)

Then, the step voltage is determined from (6)

$$E_s = \frac{\rho_a \cdot K_s \cdot K_i \cdot I_G}{L_s} \tag{6}$$

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

4. NEARBY DISTRIBUTION SUBSTATION

For, a new distribution substation grounding grid close to the existing substation whose ground grid is depicted as a mesh of rebar conductor, safety considerations require that the new and existing distribution substation grids are interconnected and thus the de-energized electrical power site of ground grid acts as an auxiliary grounding system of the substation. However, if the effect of the existing is taken into account for a grounding design so as to reduce the performance requirements of the substation grounding system, the copper conductors must be connected in a reliable manner to the substation grid [3].

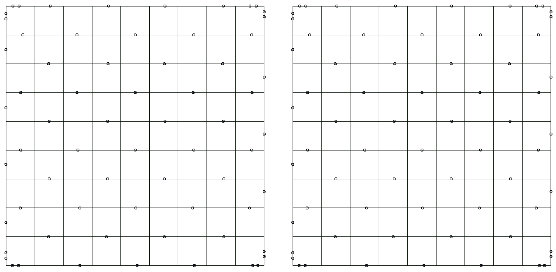
5. CASE STUDY

In this paper, case studies use the cross section of the ground grid conductor with size of 95 mm^2, and the ground rod is 3.0 m long with 15.875 mm in diameter. All the grid conductors are buried 0.5 m deep in the top layer soil. The figure of an installation of ground rod will be spread out. The dimension of ground grid which presents the status of return will be categorized into 45 m x 45 m. The main one is of medium size 45 m x45 m. Furthermore, the value of soil resistivity is chosen to be 1, 50, 100 and 1,000 $\Omega \cdot \text{m}$ for both top and bottom layers of soil. In case studies, the top and bottom layers has difference resistivity 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]. Thus, the short circuit current of 25 kA is specified. This study is separated into 3 cases as follows:

Case 1 The distance between main ground grid and auxiliary grounding system is 5 m as shown in Fig. 1. The thickness of the top layer soil is 1 m.

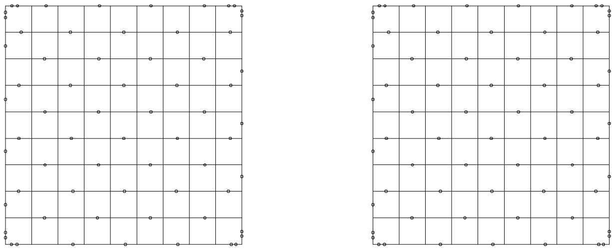
Case 2 Configuration is shown in Fig. 1. The thickness of the top layer soil is 4 m. Distance between 2 ground grids is the same as case 1.

Case 3 The distance between main ground grid and auxiliary grounding system is 25 m as shown in Fig. 2. The thickness of the top layer soil is 1 m.



Main 45mx45m **Auxiliary 45mx45m**

Fig. 1. Ground Grid Configuration for Cases 1 and 2.



Main 45mx45m **Auxiliary 45mx45m**

Fig. 2. Ground Grid Configuration for Case 3.

The cases are of interest as follows:

Case 1: GPR, touch voltage and step voltage from the study of grounding system installation in various soil resistivity, the results are shown in Table 1. % GPR ratio between auxiliary grounding system and main ground grid is determined as percentage displayed in Table 2. For detailed consideration, it can be divided into 2 cases.

5.1.1 *Top layer resistivity (ρ_1) is higher than the bottom layer resistivity (ρ_2)*

GPR of main ground grid, maximum touch voltage and step voltage will be increased when ρ_1 or ρ_2 increases. % GPR ratio between auxiliary grounding system and main ground grid is found lower than the uniform soil case. Therefore, the safety is also worse than the uniform soil.

5.1.2 *Top layer resistivity (($\rho 1$) is lower than the bottom layer resistivity ($\rho 2$)*

GPR of main ground grid, maximum touch voltage and step voltage will be increased when ρ_1 or ρ_2 increases. % GPR ratio between auxiliary grounding system and main ground grid is found higher than uniform soil case. Therefore the safety is also higher than uniform soil.

For example, 3-dimension *GPR* of ground grid design in case 1 is shown in Fig. 3. Fig. 4 and 5 are the graphs of touch and step voltages, which illustrate the 2-dimension view to help determine the safe and unsafe contour areas. Between 2 substations, the touch voltage in Fig. 4 around the junction or the edge is very high. The step voltage in Fig. 5 is also high at the edge but lower than the touch voltage.

Table 1. GPR, Touch Voltage and Step Voltage for Case 1

Type of voltage		ρ_1 $(\Omega \cdot m)$	Voltage level (V)			
			$\rho_2\,(\Omega \cdot m)$			
			1	50	100	1,000
GPR	M	1	229.07	4,262.9	6,049.6	12,628
		50	326.93	11,454	20,185	123,330
		100	332.64	12,919	22,907	152,950
		1,000	338.37	15,645	29,664.0	229,070
	Au	1	92.567	3,281.2	4,981.6	11,494
		50	91.913	4,628.4	8,887	83,528
		100	92.015	4,851.3	9,256.7	91,264
		1,000	92.134	4,583.8	9,164.6	92,567
Touch		1	85.55	552.4	588.3	2,395
		50	168.12	4,277.5	6,899.4	22,262
		100	172.93	5,059.6	8,555	34,830
		1,000	177.72	7,820.4	14,180	85,550
Step		1	28.19	178.5	264.9	3,379
		50	56.60	1,409.4	2,230.5	7,529
		100	58.34	1,628.3	2,818.7	11,470
		1,000	60.02	2,619.8	4,710.5	28,190

ρ_1	resistivity of top layer soil
ρ_2	resistivity of bottom layer soil
M	main ground grid system
Au	auxiliary grounding system

Table 2. GPR Ratio between Auxiliary and Main Ground Grid Configuration for Case 1

Type of voltage	ρ_1 $(\Omega \cdot m)$	GPR (%)			
		$\rho_2\,(\Omega \cdot m)$			
		1	50	100	1,000
GPR	1	40.41	76.97	82.35	91.02
	50	28.11	40.41	44.03	67.73
	100	27.66	37.55	40.41	59.67
	1,000	27.23	29.30	30.89	40.41

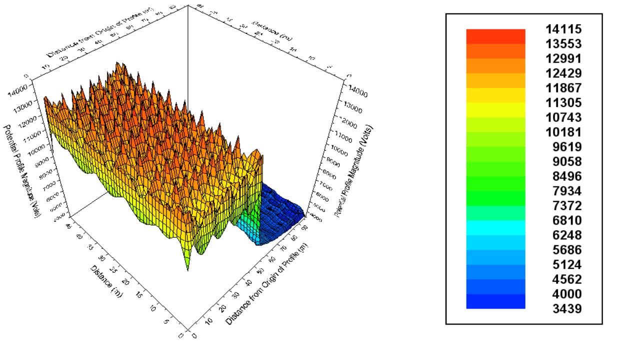


Fig. 3. Ground Potential Rise on 1000/50 $\Omega \cdot m$ for Case 1.

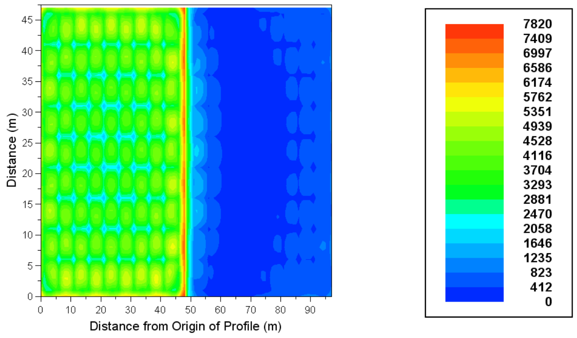


Fig. 4. Touch Voltage on 1000/50 $\Omega \cdot \mathrm{m}$ for Case 1.

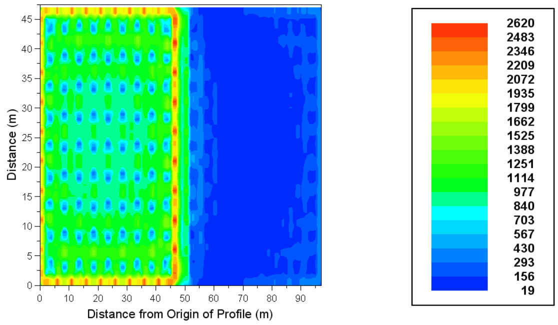


Fig. 5. Step Voltage on 1000/50 $\Omega \cdot \mathrm{m}$ for Case 1.

Case 2: The results are shown in Table 3 and Table 4. For detailed consideration, it can be divided into 2 cases.

5.2.1 *Top layer resistivity (ρ_1) is higher than the bottom layer resistivity (ρ_2)*

The GPR of the main ground grid, maximum touch voltage and step voltage have the same trend as in case1, but these 3 voltages in case 2 are higher than those in case 1. This is because the ground rods of case 2 are still in the top layer soil with higher soil resistivity. Consideration of % GPR ratio between auxiliary grounding system and main ground grid at the same soil resistivity found that % GPR ratio in case 2 is lower than in that in case 1. This means that safety of case 2 is worse than case 1 because the maximum touch voltage is higher.

5.2.2 *Top layer resistivity ($\rho1$) is lower than the bottom layer resistivity ($\rho2$)*

The GPR of the main ground grid, maximum touch voltage and step voltage have the same trend as in case 1 but these 3 voltages in case 2 are lower than in the case 1. This is because the ground rods of case2 are still in the top layer soil with lower soil resistivity. Consideration of % GPR ratio between the auxiliary grounding system and main ground grid at the same soil resistivity found that % GPR ratio of case 2 is higher than that in case 1. This means that safety of case 2 is lower than in case 1 from the reason that the tolerable touch voltage is lower.

For example, 3-dimension *GPR* of ground grid design in case 2 is shown in Fig. 6. Fig. 7 and 8 are the graphs of the touch and step voltages, which illustrate the 2-dimension view to help determine the safe and unsafe contour areas.

Table 3. GPR, Touch Voltage and Step Voltage for Case 2

Type of voltage		ρ_1 $(\Omega \cdot \mathrm{m})$	Voltage level (V)			
			$\rho_2\,(\Omega \cdot \mathrm{m})$			
			1	50	100	1,000
GPR	M	1	229.07	2,111.2	2,695.3	4,465.4
		50	2,531	11,454	17,814	71,074
		100	4,837	15,213	22,907	98,655
		1000	46,333	57,292	68,331	229,000
	Au	1	92.57	1,756.2	2,334.9	4,120.9
		50	111.79	4,628.4	8,642.4	54,487
		100	132.62	5,070.4	9,256.7	69,647
		1000	509.62	4,988.3	9,833.8	92,576
Touch		1	85.55	200.3	204.0	948.6
		50	1,921	4,277	5,519	9,378
		100	3,771	6,683	8,555	17,200
		1000	37,055	40,520	43,830	85,550
Step		1	28.19	69.6	74.4	1,279.9
		50	646	1,409	1,822	3,155
		100	1,271	2,199	2,819	5,703
		1000	12,526	13,520	14,490	28,190

Table 4. GPR Ratio between Auxiliary and Main Ground Grid Configuration for Case 2

Type of voltage	ρ_1 $(\Omega \cdot \mathrm{m})$	GPR (%)			
		$\rho_2\,(\Omega \cdot \mathrm{m})$			
		1	50	100	1,000
GPR	1	40.41	83.18	86.63	92.29
	50	4.42	40.41	48.51	76.66
	100	2.74	33.33	40.41	70.60
	1,000	1.10	8.71	14.39	40.43

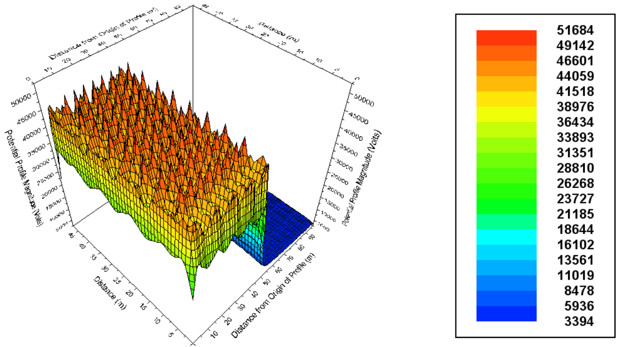


Fig. 6 Ground Potential Rise on 1000/50 $\Omega \cdot \mathrm{m}$ for Case 2.

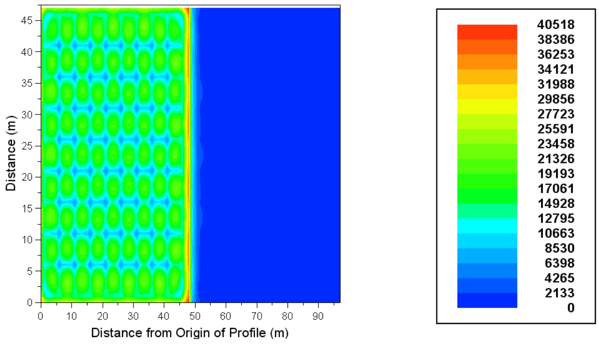


Fig. 7. Touch Voltage on 1000/50 $\Omega \cdot \mathrm{m}$ for Case 2.

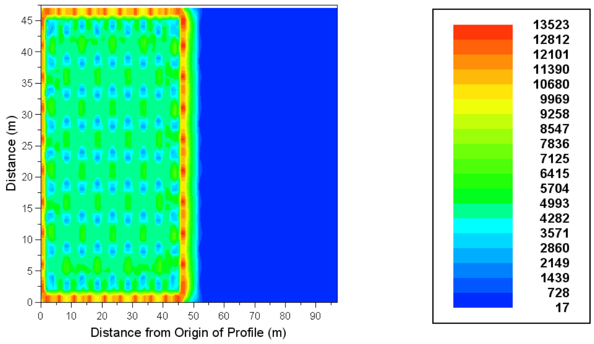


Fig. 8. Step Voltage on 1000/50 $\Omega \cdot \mathrm{m}$ for Case 2.

Case 3: The results are shown in Table 3 and 4. For detailed consideration, it can be divided into 2 cases.

5.3.1 Top layer resistivity (ρ_1) is higher than the bottom layer resistivity (ρ_2)

The GPR of main ground grid, maximum touch voltage and step voltage have the same trend as in case1 but these 3 voltages in case 3 are higher than those in case 1. This is because the difference between GPR of the main ground grid and auxiliary grounding system is significantly higher than that in case1. % GPR ratio between the auxiliary grounding system and main ground grid for the same soil resistivity in case 3 is found lower than that in case1. This means that safety of case 3 is lower than case 1 because the maximum touch voltage is higher than that in case1.

5.3.2 Top layer resistivity (ρ_1) is lower than the upper ayer resistivity (ρ_2)

The GPR of the main ground grid, maximum touch voltage, step voltage and % GPR ratio between the auxiliary grounding system and main ground grid at different soil resistivity have the same trend as in 3.1.

Table 5. GPR, Touch Voltage and Step Voltage for Case 3

Type of voltage		ρ_1 ($\Omega \cdot \mathrm{m}$)	Voltage level (V)			
			ρ_2 ($\Omega \cdot \mathrm{m}$)			
			1	50	100	1,000
GPR	M	1	237.44	4,644.6	6,508.7	13,151
		50	331.49	11,872	21,130	134,670
		100	337.12	13,299	23,744	165,860
		1,000	342.78	15,885	30,182	237,440
	Au	1	237.44	4,644.6	6,508.7	101,470
		50	331.49	11,872	21,130	134,670
		100	337.12	13,299	23,744	165,860
		1,000	342.78	15,885	30,182	237,440
Touch		1	134.81	1,374.13	1,582	1,844.66
		50	226.7	6,740.1	11,453	50,100
		100	232.26	7,747.2	13,480	71,380
		1,000	237.81	10,660	19,720	134,810
Step		1	24.59	175.02	237.14	1,105.97
		50	54.11	1,229.62	1,898.98	6,398.23
		100	56.12	1,430.79	2,459.24	9,602.98
		1,000	58.10	2,475.33	4,380.68	24,592

Table 6. GPR Ratio between Auxiliary and Main Ground Grid Configuration for Case 3

Type of voltage	ρ_1 ($\Omega \cdot \mathrm{m}$)	GPR (%)			
		ρ_2 ($\Omega \cdot \mathrm{m}$)			
		1	50	100	1000
GPR	1	25.29	52.09	59.70	77.16
	50	18.16	25.29	27.05	42.25
	100	17.86	23.83	25.29	35.83
	1000	17.58	18.93	19.92	25.29

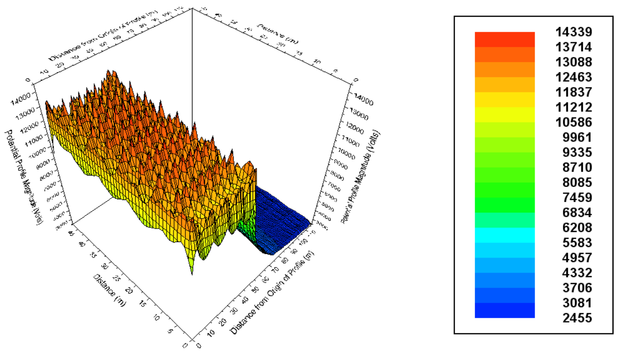


Fig.9. Ground Potential Rise on 1000/50 $\Omega \cdot \mathrm{m}$ for Case 3.

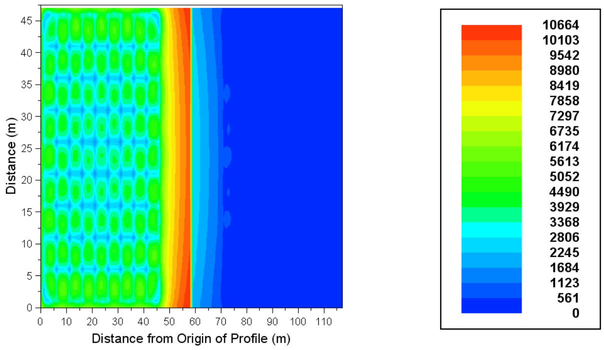


Fig. 10. Touch Voltage on 1000/50 $\Omega \cdot \mathrm{m}$ for Case 3.

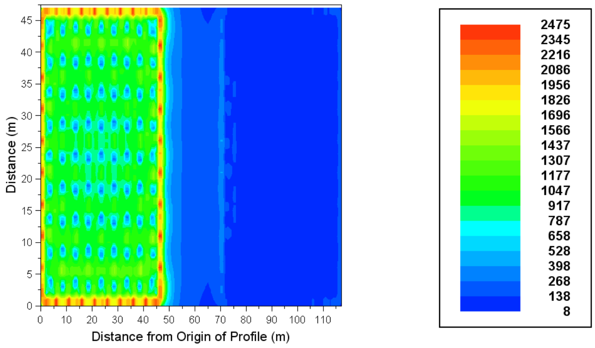


Fig. 11. Step Voltage on 1000/50 $\Omega \cdot \mathrm{m}$ for Case 3.

For example, 3-dimension *GPR* of the ground grid design in case 3 is shown in Fig. 9. Fig. 10 and 11 are the graph of touch and step voltages, which illustrate the 2-dimension view to help determine the safe and unsafe contour areas.

Table 7. Safety Criteria for 50 kg Body Weight, 1000/50 $\Omega \cdot \mathrm{m}$

Surface Layer Resistivity ($\Omega \cdot \mathrm{m}$)	Fault Clearing Time 0.1 sec		Foot Resistance: 1 Foot (Ω)
	Touch Voltage (V)	Step Voltage (V)	
None	741	2,096	3,125
1,500	936.2	2,877.3	4,475
3,000	1,508.3	5,165.8	8,431.9
4,000	1,863	6,588	10,891
8,000	3,335	12,472	21,066
1,2000	4,802	18,342	31,215
1,6000	6,268	24,208	41,356
20,000	7,734	30,072	51,495
24,000	9,200	35,935	61,633

Table 7 is the safety criteria of 1000/50 $\Omega \cdot \mathrm{m}$ soil structure by material surface covering with 20 cm thick. For the base case, it is found that at the same soil resistivity, the maximum touch voltage is equal to 7,802.4 V and step voltage is 2,619.8 V. To comply with the safety criteria, it must be covered by 20,000 $\Omega \cdot \mathrm{m}$ resistivity material. The touch voltage also meets the safety criteria. The step voltage does not violate the safety criteria and it can be easily solved. . Generally, PEA will spread the ground with crushed rock No.2 (Resistivity of crushed rock No.2 is about 3,000 $\Omega \cdot \mathrm{m}$). The step voltage can be solved. From Table 7, spreading with 3,000 $\Omega \cdot \mathrm{m}$ material, the step voltage criteria is 5,165.8 $\Omega \cdot \mathrm{m}$, which can be met.

The study found that the danger may occur at the edge of ground grid, so the study concentrates at ground grid connections between the 2 substations. It is found that GPR, maximum touch voltage and step voltage are equal to 10,112 V, 3,846.36 V and 1,408 V respectively. The decrease is obtained by the reduction of resistance of electrode system.

6. CONCLUSION

The ground grid design for the distribution substation is examined with the main objective to assess its grounding system condition in terms of ground potential rise, touch voltage, step voltage and % GPR ratio between the auxiliary grounding system and main ground grid. These values are analyzed to ensure that they comply with the safety criteria defined in the IEEE Std. 80-2000 with three cases classified by 25 kA Power's Distribution in PEA. It is found that when the ground grid is separated or two neighboring substations are disconnected, the safety issue must be taken into account.

In case of ground grids of two neighboring distribution substations, connecting ground grids between two distribution substations can reduce the voltages to meet the safety criteria.

In the procedure of renovation of the existing distribution substation that requires a small distribution substation in order to supply temporary electricity, a large ground potential difference between two separate ground grids of the distribution substations can occur when the ground grids of two neighboring distribution substations are not connected together. This high GPR can damage intelligent electronic devices (IED), which will be used in distribution substations in the future or electronic controllers which are currently used. This incident can occur after a fault or lightning in a distribution system. Moreover, this high GPR is also dangerous to personnel operating in the distribution substation or nearby. The connection between 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 that can lead to power supply outage in industrial zones or densely populated areas. Therefore, this method has more advantages compared with other methods e.g. installing more protection devices which needs more investment cost but it cannot completely solve the problem.

As far as installation costs and other necessary expenses in grounding system planning are concerned, the length of ground rods, the size of conductors, the short circuit current should financially reflect incremental cost and worth for various alternatives while respecting the established safety criteria [5].

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