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GROUNDING SYSTEM DESIGN FOR A LARGE POWER PLANT

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ABSTRACT
The grounding system design of a large power plant is described and discussed. Major procedures necessary for the design of an extensive grounding system are demonstrated. These procedures include constructing adequate soil structures based on short and long traverse soil resistivity measurements, conducting fault current distribution calculations, designing the grounding system, and performing the safety evaluations of the grounding system. The procedures presented in this paper can be used as a guide when designing extensive grounding systems in large power plants.

KEY WORDS
Grounding, safety, soil resistivity, fault current, touch voltage, power plant

1. Introduction

A complete grounding design generally consists of four major steps: soil resistivity measurements, fault current distribution calculations, grounding system design and performance analysis. However, compared to grounding design for electric substations, power plant grounding design presents a few additional challenges. These include the following. (1) A power plant usually covers a substantial area of land and therefore the associated grounding system is often very extensive. As a result, large electrode spacing soil resistivity measurements must be carried out in order to reveal deep layer soil resistivities which affect the performance of large grounding systems. (2) Due to the existence of step-up transformers in the power plant, there is a substantial local fault current contribution in the event of a fault. This current contribution will be circulating between the fault location and the transformer neutrals and can generate significant ground potential difference (GPD) between different parts of the grounding system. (3) Power plant grounding systems may not cover all the areas inside the plant perimeter fence. As a result, special attention has to be paid to the areas which are not covered by the grounding system. (4) Because the perimeter fence may not be close to the grounding system at all locations, safety concern with respect to the fence must be addressed adequately. (5) Due to the extensiveness of the grounding system, equal-potential assumption may not be valid in the performance evaluation. Therefore, more sophisticated computation tools have to be used in the analysis and different fault locations have to be studied in order to determine adequately the grounding system performance. This paper presents a grounding design of an extensive electric power plant and demonstrates the necessary design procedures. These procedures can be used as a guide when designing extensive grounding systems in large power plants.

2. Description of the Power Plant Site

Figure 1 shows the plan view of the power plant site. The dimension of the plant site is about 200 m by 450 m. A 230 kV switchyard is inside the power plant site on the north side, as indicated in the figure. A large part of the boundary of the power plant grounding grid does not overlap with the perimeter fence. Therefore, in the gaps between the perimeter fence and the grounding grid boundary, there are no ground conductors. Actually, the areas in the gaps are not even flat. They are parts of the hills surrounding the grounding grid. The power plant has three step-up transformers.

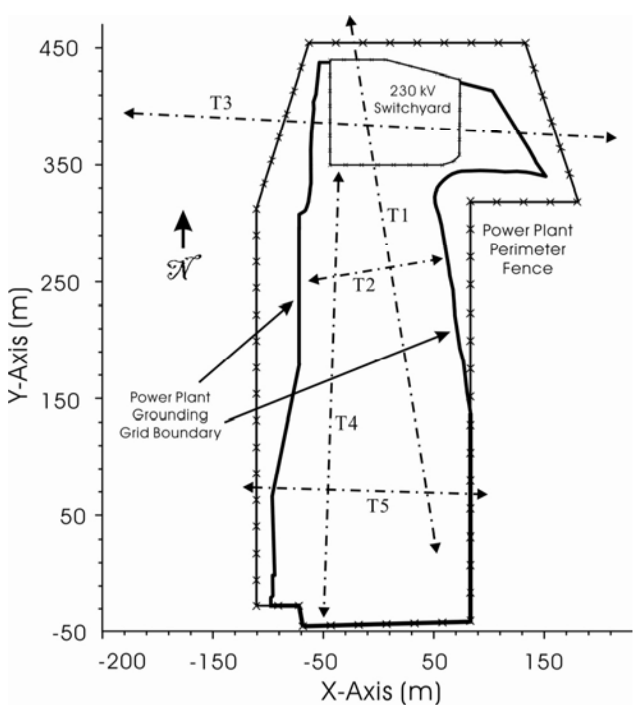

Figure 1. Plan view of the power plant site

3. Soil Resistivity Measurements and Interpretation

Soil resistivity measurements were made using the Schlumberger-Palmer 4-pin method, along two North-South long traverses, one East-West long traverse, and two East-West short traverses within the power plant site. These traverses are shown in Figure 1. The short measurement traverses were selected to sample shallow depth soil resistivities and the long ones were selected to provide a representative sample of average soil resistivities at greater depths. The maximum current electrode spacings of the five traverses are 163.4 m, 227.4 m, 315.9 m, 439 m, and 439 m, respectively.

Soil resistivity measurements constitute the basis of any grounding study and are therefore of capital importance. Soil resistivity measurements are made by injecting current into the earth between two outer electrodes and measuring the resulting voltage between two potential probes placed along a straight line between the current-injection electrodes. When the adjacent current and potential electrodes are close together, the measured soil resistivity is indicative of local surface soil characteristics. When the electrodes are far apart, the measured soil resistivity is indicative of average deep soil characteristics throughout a much larger area. In principle, soil resistivity measurements should be made up to a spacing (between adjacent current and potential electrodes) that is at least on the same order as the maximum extent of the grounding system (or systems) under study, although it is preferable to extend the measurement traverses to several times the maximum grounding system dimension, where possible [1]. Often, the maximum electrode spacing is governed (i.e., limited) by other considerations, such as the maximum extent of the available land that is clear of interfering bare buried conductors.

The interpreted soil models corresponding to the five traverses are listed in Table I. The computation software used for the interpretation and for subsequent earth current calculation and grounding analysis is described in [2]. Figures 2 and 3 show the measured and computed resistivity curves generated during the interpretation process for Traverses 1 and 3, respectively. The results in Table I show that the soil can be best described as a three layer soil. The top layer resistivity is about 160 ohm-m. The bottom later resistivity is about 1000 ohm-m. The middle layer resistivity is about 500 ohm-m. For a large grounding system, the ground potential rise (GPR) is influenced greatly by the deep soil layers. Therefore, the soil model based on Traverse 1 will result in the largest GPR because it has the highest bottom layer resistivity. The top layer resistivity has a great influence on touch and step voltages as a percentage of the GPR. For this plant site, the top 4.6 m soil at the plant site will be excavated, crushed, and then compacted back to the site. Based on box tests at laboratory, the resistivity of the top 4.62 m soil will have three possible values: 85 ohm-m being the low limit, 160 ohm-m being the average, and 270 ohm-m being the upper limit. As a result, the final soil models used in this study are the three shown in Table II.

Table 1
Equivalent soil models based on soil resistivity measurements

Traverse	Layer	Resistivity (Ω-m)	Thickness (m)
1	Top	182	1.9
	Middle	512	39.8
	Bottom	1350	Infinite
2	Top	203	1.3
	Bottom	494	Infinite
3	Top	97	3.8
	Middle	199	11.8
	Bottom	776	Infinite
4	Top	145	4.3
	Bottom	1029	Infinite
5	Top	160	5.4
	Bottom	998	Infinite

Table 2
Final soil models used in the study

Soil Model	Layer	Resistivity (Ω -m)	Thickness (m)
1	Top	85	4.62
	Middle	512	37.1
	Bottom	1350	Infinite
2	Top	160	4.62
	Middle	512	37.1
	Bottom	1350	Infinite
3	Top	270	4.62
	Middle	512	37.1
	Bottom	1350	Infinite

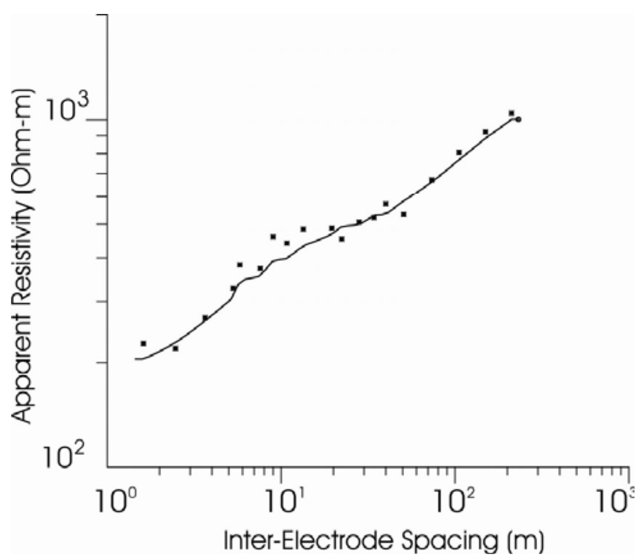

Figure 2. Measured and computed apparent resistivity for Traverse 1

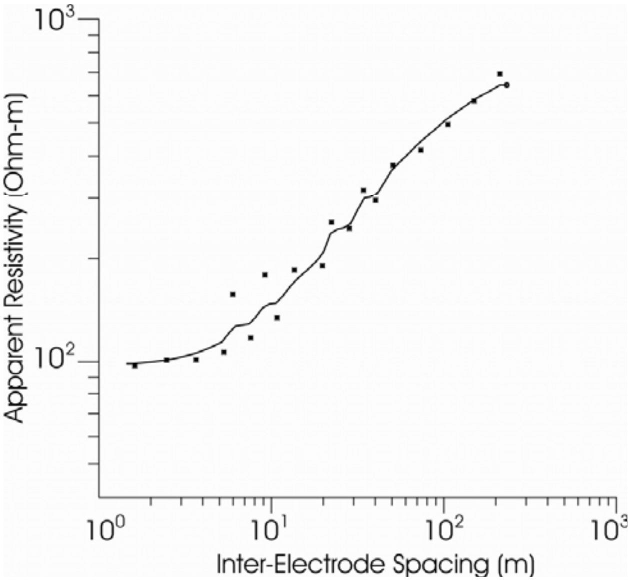

Figure 3. Measured and computed apparent resistivity for Traverse 3

4. Fault and Current Distribution Calculation

The touch and step voltages associated with the grounding network are directly related to the magnitude of the fault current discharged into the soil by the grounding network. It is therefore important to determine how much of the fault current returns to remote sources by means of the overhead ground wires of the transmission lines connected to the power plant.

For a single-line-to-ground fault at the switchyard, the total fault current contribution from all sources is 28,110 A, of which 16,550 A is provided by the three local step-up transformers and 11,560 A is the contribution from outside sources. The following is a detailed list of the current sources:

- 6,500 A from Substation A which is 1 km away from the power plant.
- 1100 A from Substation B which is 41 km away from the power plant.
- 3960 A from two future lines which will be 45 km away from the power plant.
- 4,921 A from Step-Up Transformer #1.
- 4,921 A from Step-Up Transformer #2.
- 6,708 A from Step-Up Transformer #3.

For the purpose of computing the current discharged by the power plant grounding system (earth current), the local fault current contribution from the step-up transformers can be ignored first because it represent a circulating current from the fault location to the step-up transformers via the ground conductors. A circuit model for computing the earth current is shown in Figure 4. The three current sources are Substation A, Substation B, and Substation Future, which contribute a fault current of 6,500 A, 1,100 A, and 3,960 A, respectively. Substation A is very close to the power plant (a total of two spans with a span length of 490 m). The OHGW at Substation A is not connected to the grounding system. The tower resistance is 8 ohms. There are 111 spans between the power plant and Substation B and 121 spans between the power plant and Substation Future, with a span length of 370 m. the tower resistance is 17 ohms. The ground resistance for Substations B and Future are assumed to be a low value of 0.1 ohm to be conservative. All the transmission line cross sections are the same. The height of the faulted phase conductor is 17.1 m and that of the OHGW is 39.6 m. The type of the OHGW is 19#10 Alumoweld conductor. The ground impedance for the power plant is needed for the computation of the earth current. An initial grounding grid with a mesh size of 10 m by 10 m is used for the ground impedance calculation. The computed ground impedance for the three soil models are listed in Table III. Table III also lists the calculated total earth current for the three soil models. Note that the earth current is NOT inversely proportional to the ground impedance. The earth current for each soil model, together with the circulating currents from local step-up transformers at the power plant, will be injected into the grounding system at proper locations, in order to calculate touch and step voltages.

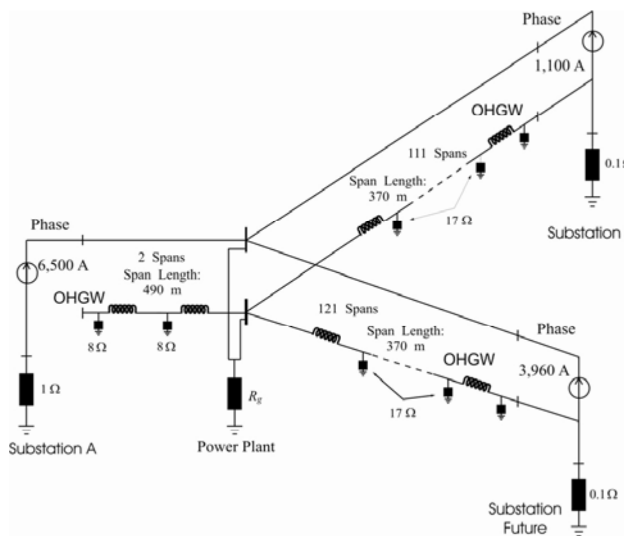

Figure 4. Circuit model representing the transmission system

Table 3
Ground impedance and Earth current

Soil Model	Ground Impedance (Ω)	Earth Current (A)	Grid GPR (V)
1	1.086	5456	5925
2	1.204	5180	6237
3	1.283	5010	6428

5. Grounding Performance Evaluations

For the evaluation of the safety performance of the grounding system design, all the three soil models shown in Table II have to be considered. However, it is expected that an analysis based on Soil Model 3 (top layer resistivity: 270 ohm-m) will be sufficient. The reason is that this soil model results in the largest grid GPR and the largest touch and step voltages as a percentage of the grid GPR due to its higher top layer resistivity. Therefore, grounding design satisfying the safety criteria based on Soil Model 3 will still be satisfactory for Soil Models 1 and 2 even though the safety thresholds will be somewhat lower for the two other soil models. The final grounding system design is shown in Figure 5.

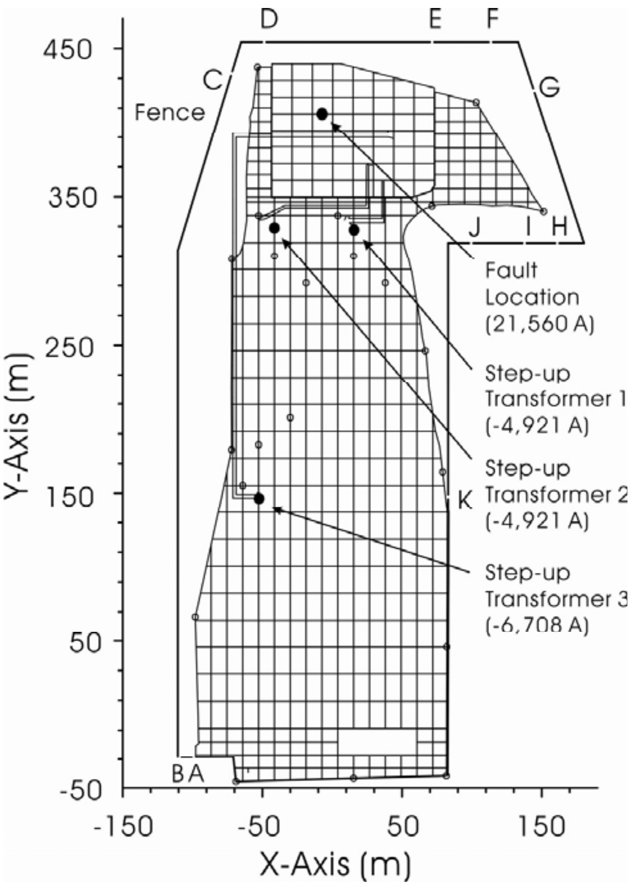

Figure 5. Power plant grounding system

In order to compute the grid GPR, touch and step voltages, a total current of 21,560 A is injected into the grounding system at a fault location in the switchyard as shown in Figure 5. At the three step-up transformer locations, a total of 16,550 A is taken out, which is the sum of the fault current contributions from the three transformers (4921 A + 4921 A + 6708 A). The net current discharged into the earth by the grounding grid is 5010 A which is calculated based on Soil Model 3. In the computer model, the cable sheaths between the switchyard and the step-up transformer locations are modeled as shown in the figure. The fence is modeled as a group of fence posts connected by an insulated conductor representing the above-ground portion of the fence. The required gaps in the fence shown in Figure 1 (indicated by the letters A through K) are the locations of the isolating sections. Determining these locations requires a rather sophisticated process that is described in full detail in [3].

Table IV shows the safe touch and step voltages based on the IEEE Standard 80 [4] for all the three soil models. It can be seen that there is no significant difference in the safe touch and step voltages for the three soil models. When the top layer resistivity is larger, the safe touch and step voltages are higher because of a larger foot resistance. The safe touch and step voltages are obtained using the following data.

- Fault duration: 0.25 second
- System X/R ratio: 20
- 50 kg body weight
- Crushed rock layer resistivity: 3000 ohm-m
- Crushed rock layer thickness: 10 cm

Table 4
Safe touch and step voltages

Soil Model	Top Layer Resistivity (Ω -m)	Safe Touch Voltage (V)	Safe Step Voltage (V)
1	85	897	2954
2	160	907	2997
3	270	922	3057

Figure 6 shows the computed touch voltages. The shaded areas in Figure 6 represent the locations where the touch voltage is between 200 V and 733 V, with 733 V being the maximum touch voltage in the whole area 1 m beyond the grid perimeter conductor. The touch voltages in the non-shaded area are below 200 V. The maximum touch voltage is below the safe touch voltage of 922 V. Step voltages for an area extending 10 m outside the plant perimeter fence are also computed. It is found that the maximum step voltage is only 299 V, far below the safe step voltage of 3057 V.

Touch and step voltage calculations are also carried out based on Soil Models 1 and 2 using the corresponding earth currents shown in Table III, to ensure safety criteria are satisfied for these two soil models. The computation results for all three soil models are summarized in Table V. It can be seen that in all the cases the maximum touch voltage and the maximum step voltage are below their respective safe threshold values. When the top layer resistivity is lower while the middle and bottom layer remain the same, both the touch and the step voltages are lower, as expected

It should be pointed out that safety regarding the power plant perimeter fence must be addressed. Because the fence is close to the grounding system in some locations and far from it in other locations, the fence needed to be grounded (connected to the grounding system) at locations where the fence is close to the grounding system and isolated in other locations to satisfy the safety criteria. Interested readers may refer to [3] in which detailed analysis of the safety regarding the perimeter fence has been carried out.

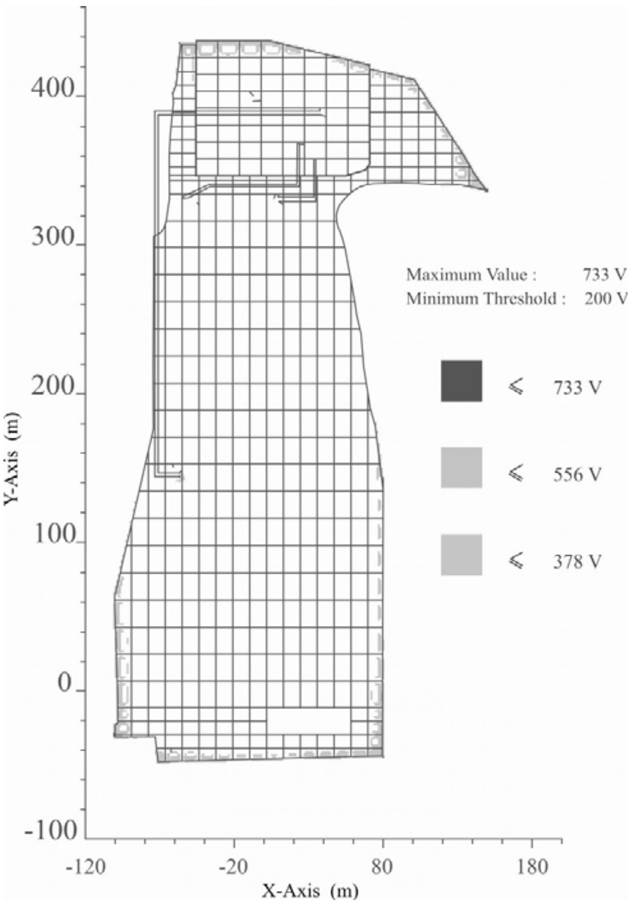

Figure 6. Computed touch voltages

Table 5
Ground impedance and Earth current

Soil Model	Maximum Touch Voltage (V)	Maximum Step Voltage (V)	Maximum Potential Difference in Grid (V)
1	399	157	404
2	566	227	442
3	733	299	468

Other fault locations have also been examined and it is found that the results are similar to the case presented here. Due to the nature of the soil (low resistivity over high resistivity), the potential difference between different parts of the grid is not very large. Table V lists the maximum potential difference for the three soil models. For Soil Model 3, the maximum potential difference is 468 V between the fault location and the Step-up transformer #3.

6. Conclusion

A complete grounding study of an extensive grounding system of a large electric power plant is presented. The necessary procedures required for an accurate grounding analysis for large grounding systems have been demonstrated. These procedures include constructing adequate soil structures based on short and long traverse soil resistivity measurements, conducting fault current distribution calculations, designing the grounding system, and performing the safety evaluations of the grounding system. The procedures presented in this paper can be used as a guide when dealing with extensive grounding systems in large electric power plants.

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