CORRELATION BETWEEN WORST CASE SAFETY CONDITIONS AND SOIL RESISTIVITY UNDER POWER SYSTEM FAULT CONDITIONS

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Abstract

This paper examines the correlation between worst case safety conditions and soil resistivity under power system fault conditions. For a simplified power system network, analytical expressions have been derived which clearly show the relation between safety and soil resistivity. It is interesting to see that neither the very low resistivity (close to zero Ω-m) nor the very high resistivity (> 10000 Ω-m) represents the worst case for human safety under power system fault conditions. Depending on system parameters, the worst case soil resistivity is generally on the order of a few hundred Ω-m. For complicated realistic power system networks, computer modeling is carried out for the analysis and similar conclusions are reached. The findings described in this paper have not been published in the open literature.

Keywords

Transmission and Distribution, Power Plant, Safety, Grounding, Body Current, Touch Voltage

1. Introduction

A typical safety assessment for a fault in a power plant or a substation consists of soil resistivity measurement and interpretation, fault current distribution computations, and grounding system analysis. Typical results from the safety assessment includes GPR (Ground Potential Rise) and ground resistance of the substation grounding grid, touch and step voltages in the substation area, and body currents when a person is subjected to a touch or step voltage under fault conditions. From these results, conclusions can be reached regarding the safety in the substation area during a fault. It is known that grounding system performance and safety are closely related to soil characteristics. A widespread conventional thinking is that the highest soil resistivity results in the worst condition concerning safety. This seems logical because the GPR of the grounding grid is the highest in this case. However, a closer look at this logic reveals that it is merely a misconception. The objective of this paper is to correct this misconception and to present the right conclusion regarding the correlation between worst case safety and soil resistivity, from both analytical and practical points of view. Previous publications such as [1-4] studied soil effects on grounding system performance. In [5], soil effects on ground fault current are studied. However, direct relation between soil resistivity and safety has not been studied, which is the main objective of this paper.

2. Analytical Derivations

Let us first consider a simplified power system network under fault conditions as shown in Figure 1 in which the following notations are used.

V: system voltage (phase-to-ground);

Z_s: system impedance including the equivalent source impedance and line impedance;

Z_g: shield wire impedance;

R_g: ground resistance of grounding grid at faulted substation;

R_s: ground resistance of grounding grid at power plant;

I_f: current flowing in the faulted phase conductor;

I_g: current flowing in the shield wire;

I_e: current flowing into the grounding grid at faulted substation;

I_b: body current;

V_g: GPR of the grounding grid at faulted substation;

V_{touch}: touch voltage.

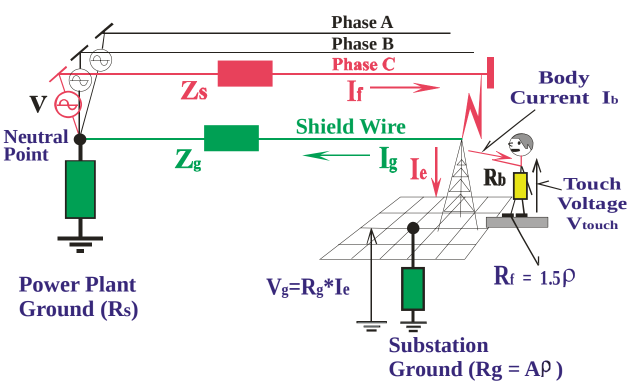

Figure 1. Simplified Power System Network under Fault Conditions.

Note that in Figure 1 we have ignored the mutual impedance between the phase conductor and the shield wire and also the towers along the shield wire, for simplicity.

We now try to derive the analytical expression of the body current as a function of the soil resistivity for a fault at the substation shown in Figure 1.

$$\begin{aligned} V &= Z_s I_f + Z_g I_g \\ Z_g I_g &= (R_g + R_s) I_e \\ I_f &= I_g + I_e \end{aligned} \tag{1}$$

Solving (1) for I_e we obtain

$$I_e = \frac{Z_g V}{Z_s(Z_g + R_g + R_s) + Z_g(R_g + R_s)} \tag{2}$$

$$V_g = R_g I_e = \frac{R_g Z_g V}{Z_s(Z_g + R_g + R_s) + Z_g(R_g + R_s)} \tag{3}$$

$$V_{touch} = aV_g = \frac{aR_g Z_g V}{Z_s(Z_g + R_g + R_s) + Z_g(R_g + R_s)} \tag{4}$$

where a is the touch voltage as a percentage of the GPR of the grounding grid. The body current can be calculated using

$$I_b = \frac{V_{touch}}{R_b + R_f} \tag{5}$$

The foot resistance (two feet in parallel) for body current calculation due to touch voltages is [6]

$$R_f = 1.5\rho \tag{6}$$

For a uniform soil, R_g and R_s are proportional to soil resistivity ρ. Therefore, they can be expressed as

$$R_g = A_g\rho \quad \text{and} \quad R_s = A_s\rho \tag{7}$$

where A_g and A_s are factors determined by the configuration of the grounding systems at the power plant and at the faulted substation.

Using (4)-(7), we obtain

$$I_b = \frac{aV\rho}{\frac{A_g + A_s}{A_g}\frac{1.5(Z_s + Z_g)}{Z_g}\rho^2 + \left[\frac{1.5Z_s}{A_g} + \frac{A_g + A_s}{A_g}\frac{R_b(Z_s + Z_g)}{Z_g}\right]\rho + \frac{R_b Z_s}{A_g}} \tag{8}$$

Equation (8) clearly shows the expression of the body current as a function of the soil resistivity. Let us first examine two limiting cases: $\rho = 0$ and $\rho = \infty$. From (8), it can be seen that when $\rho = 0$, $I_b = 0$. This means that there is no current going through the body when the earth consists of a perfect conducting material. This is understandable because in this case the touch voltage a person is subjected to during a fault is 0 V. When $\rho = \infty$, we see from (8) again that $I_b = 0$, even though in this case the touch voltage is the largest because the GPR of the grid is the largest. The reason is that the person is standing on a perfect insulating material and therefore no current could pass through his body. The above phenomenon implies that there must be at least one resistivity value between 0 and ∞ that results in a maximum body current (see Figure 2 for a conceptual illustration of this common sense proof). This is rather surprising because of the conventional thinking that highest soil resistivity always results in worst conditions concerning safety.

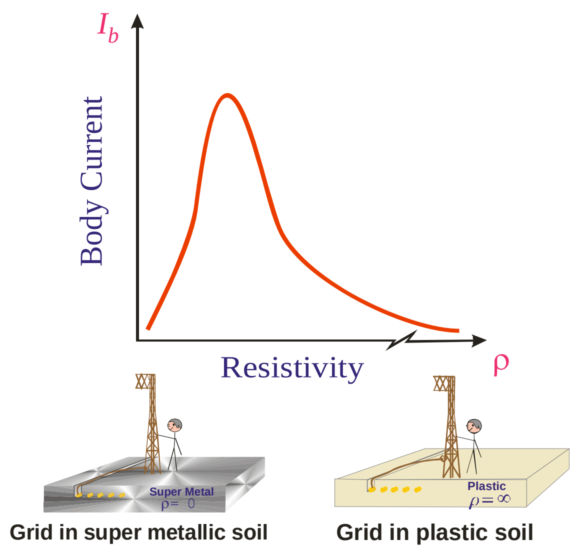

Figure 2. Conceptual Worst Case Resistivity Scenario.

We can actually prove analytically that such a maximum does exist. Let us rewrite (8) as

$$I_b = \frac{aV\rho}{\alpha\rho^2 + \beta\rho + \delta} \tag{9}$$

where

$$\begin{aligned} \alpha &= \frac{A_g + A_s}{A_g}\frac{1.5(Z_s + Z_g)}{Z_g} \\ \beta &= \frac{1.5Z_s}{A_g} + \frac{A_g + A_s}{A_g}\frac{R_b(Z_s + Z_g)}{Z_g} \\ \delta &= \frac{R_b Z_s}{A_g} \end{aligned} \tag{10}$$

Now let $dI_b/d\rho = 0$, we have

$$\frac{dI_b}{d\rho} = aV\frac{-\alpha\rho^2 + \delta}{\left(\alpha\rho^2 + \beta\rho + \delta\right)^2} = 0 \tag{11}$$

Solving (11) we obtain

$$\rho_m = \sqrt{\delta / \alpha} \tag{12}$$

It is easy to see from (11) and (12) that when $\rho < \rho_m$, $dI_b/d\rho > 0$, implying that I_b as a function of ρ is increasing with ρ in this region. Conversely, when $\rho > \rho_m$, $dI_b/d\rho < 0$, implying that I_b is decreasing with ρ in this region. Therefore, I_b reaches a maximum at

$\rho = \rho_m = \sqrt{\delta / \alpha}$, which is

$$I_{b\max}\big|_{\rho=\rho_m} = \frac{aV}{2\sqrt{\alpha\delta} + \beta} \tag{13}$$

Let us now examine three cases for different system parameters: (1) $Z_s = Z_g = 5\ \Omega$, (2) $Z_s = Z_g = 20\ \Omega$, (3) $Z_s = Z_g = 50\ \Omega$. For all the three cases let us assume that (a) the system voltage (phase-to-ground) is 19 kV; (b) both grounding systems at the power plant and the faulted substation are a 50m by 50m 64-mesh grid buried at a depth of 0.5 m. We then have the following parameters: V=19 kV, $A_g = A_s = 0.009$, and $a = 0.19$. Note that the values of A_g, A_s, and a are calculated using the grounding software package described in [7]. The theory behind the grounding software package can be found in [1,3]. A body resistance value, R_b=1000 Ω, is used based on [6]. Figure 3 plots the body current as a function of soil resistivity for the three cases described above. It can be seen that, indeed, when ρ = 0, I_b = 0 and when $\rho \to \infty$, $I_b \to 0$. The maximum body current for the three cases is between 300 Ω-m and 1000 Ω-m. Using (12) and (13), we can obtain $\rho_m = 304\,\Omega$ and $I_{b\max}\big|_{\rho=\rho_m} = 0.428$ A for Case (1). This is consistent with the peak value shown in Figure 3, as expected.

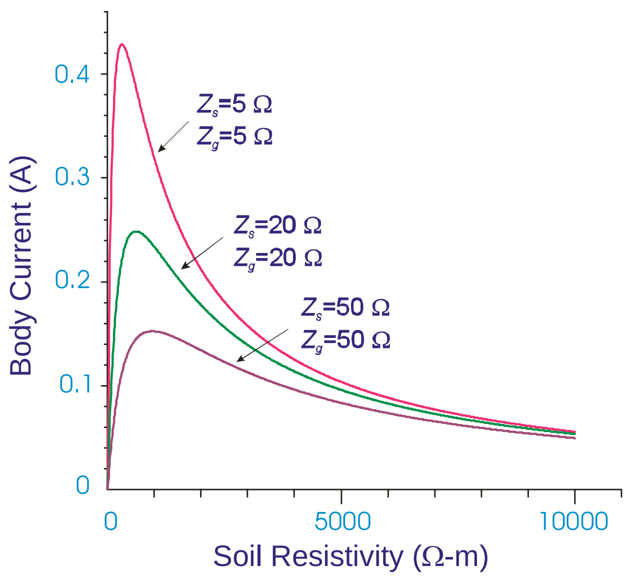

Figure 3. Body Current as a Function of Soil Resistivity.

If there is no shield wire or neutral wire in a power system, then Z_g in Figure 1 is ∞ and consequently (8) becomes

$$I_b = \frac{aV\rho}{\frac{1.5(A_g + A_s)}{A_g}\rho^2 + \left[\frac{1.5Z_s}{A_g} + \frac{(A_g + A_s)R_b}{A_g}\right]\rho + \frac{R_b Z_s}{A_g}} \tag{14}$$

Figure 4 shows the body current as a function of soil resistivity for three different source impedance values: Z_s=1 Ω, Z_s=10 Ω, and Z_s=50 Ω, with $Z_g = \infty$ and all other parameters kept the same as those used in the previous three cases. It can be seen that the body current curves have a similar trend as those in the previous cases.

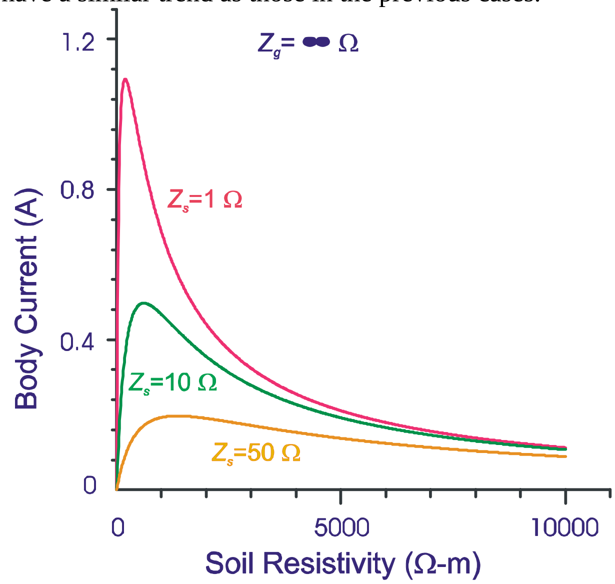

Figure 4. Body Current as a Function of Soil Resistivity for the No Shield Wire Case.

3. Practical System Network

In the previous section, we have demonstrated theoretically that there is a worst case soil resistivity from a safety point of view. We have derived the expression of body current as a function of soil resistivity and showed numerical results for a simplified system network. In this section, we will examine practical system configurations to see if a similar behavior exists.

Figure 5 shows a network with four terminals and a faulted Central Substation and Figure 6 shows the cross section of the transmission line in the network. Due to the complex nature of the system, simple analytical expressions such as (8) can no longer be derived. We will use computer modeling to solve the network and obtain the desired numerical results. The line parameters shown in Figure 5 including self impedances of the phase conductors and shield wires and mutual impedances between them were first computed using the software package described in [7]. The circuit shown in Figure 5 was then solved using the double elimination method described in [8-9]. The tower ground resistance shown in Figure 5 is 20 Ω for a 100 Ω-m soil resistivity. The ground resistances of the feeding terminals and the Central Substation are assumed to be the same: 0.907 Ω for a 100 Ω-m soil resistivity (corresponding to a 50m by 50m 64 mesh grid buried at a depth of 0.5 m). In the computer analysis of the network, the terminal ground resistance, R_s, the Central Substation ground resistance, R_g, and the tower ground resistance, R_t, were treated as variables and were proportional to the soil resistivity.

Three cases were analyzed: (1) the shield wire is

19#8 alumoweld; (2) the shield wire is 3#8 steel; (3) there is no shield wire. Figure 7 shows the GPR of the Central Substation grounding system as a function of soil resistivity for the three cases.

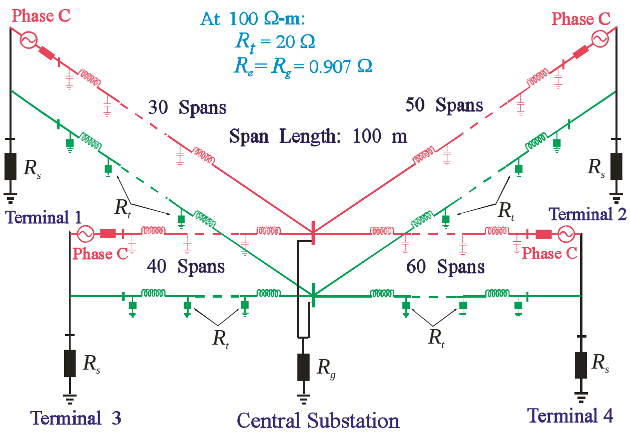

Figure 5. Circuit Model Representing the Four-Terminal 69 kV Transmission Line System under Fault Conditions.

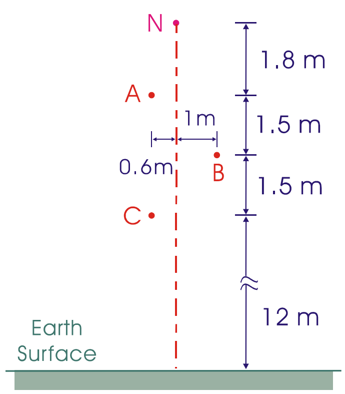

Figure 6. Cross Section of the 69 kV Transmission Line System.

It can be seen from Figure 7 that the GPR is always increasing when the soil resistivity increases for all three cases. The increase is fast at low values of soil resistivity and quickly levels off. The case without shield wire produces the highest GPR and the case with an alumoweld shield wire the lowest. This is logical because when shield wires are present, they provide a good return path to the sources for fault currents, thereby reducing the current going into the Central Substation ground.

Figure 8 shows the body current as a function of soil resistivity for the three cases. Indeed, we can see that the computed body current for the three cases exhibit a similar behavior as that shown for the simple cases presented in the previous section. For each case, there exists a worst case soil resistivity that corresponds to the maximum body current. The case without shield wire produces the highest body current and the case with an alumoweld shield wire the lowest. Again, this is because the touch voltage, which is proportional to the grid GPR, is largest when there is no shield wire and it is the lowest when the alumoweld shield wire is present. For the case of a steel shield wire, the body current is always between those applicable for the other two cases.

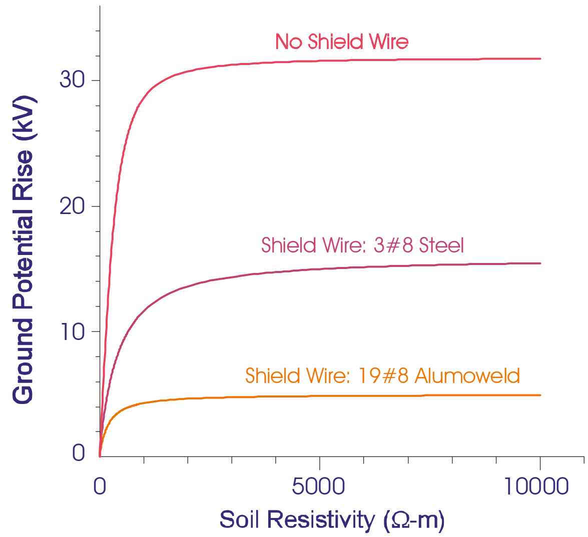

Figure 7. GPR of Central Substation Ground as a Function of Soil Resistivity.

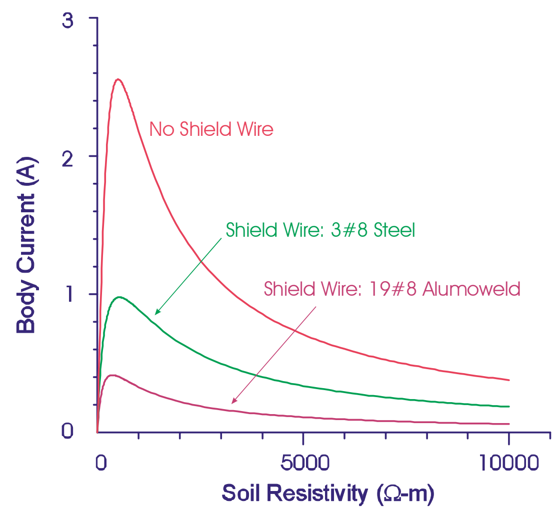

Figure 8. Body Current as a Function of Soil Resistivity Due to a Fault at the Central Substation of the 69 kV Transmission Line System.

4. Conclusions

Correlation between safety and soil resistivity under power system fault conditions has been studied from both theoretical and practical points of view. For a simplified power system, analytical expressions have been derived which clearly show the relation between safety and soil resistivity. It is interesting to see that neither the very low resistivity (close to zero Ω-m) nor the very high resistivity (> 10000 Ω-m) represents the worst case for human safety under power system fault conditions. The findings are published here for the first time. Depending on system parameters, the worst case soil resistivity is generally on the order of a few hundred Ω-m. For more complicated realistic power system networks, computer modeling has been carried out and similar conclusions have been reached. This study explains why, often, the grounding design of some electrical substations is considerably more difficult than other substations that are quite similar except for their soil structures. Future research work on this subject will focus on the effects of seasonal resistivity variations of the surface layers on safety.

5. References

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6. Biographies

Dr. Jinxi Ma was born in Shandong, P. R. China in December 1956. He received the B.Sc. degree from Shandong University, Jinan, Shandong, China, and the M.Sc. degree from Beijing University of Aeronautics and Astronautics, both in electrical engineering, in 1982 and 1984, respectively. He received the Ph.D. degree in electrical and computer engineering from the University of Manitoba, Winnipeg, Manitoba, Canada in 1991.

From 1984 to 1986, he was a faculty member with the Department of Electrical Engineering, Beijing University of Aeronautics and Astronautics. He worked on projects involving design and analysis of reflector antennas and calculations of radar cross sections of aircraft. Since September 1990, he has been with the R & D Dept. of Safe Engineering Services & technologies in Montreal, where he is presently serving as manager of the Analytical R & D Department. His research interests are in transient electromagnetic scattering, EMI and EMC, and analysis of grounding systems in various soil structures.

Dr. Ma is the author of more than ninety papers on transient electromagnetic scattering, analysis and design of reflector antennas, power system grounding, lightning, and electromagnetic interference. He is a senior member of the IEEE Power Engineering Society, a member of the IEEE Standards Association, and a corresponding member of the IEEE Substations Committee and is active on Working Groups D7 and D9.

Dr. Farid Paul Dawalibi was born in Lebanon in November 1947. He received a Bachelor of Engineering degree from St. Joseph's University, affiliated with the University of Lyon, and the M.Sc. and Ph.D. degrees from Ecole Polytechnique of the University of Montreal.

From 1971 to 1976, he worked as a consulting engineer with the Shawinigan Engineering Company, in Montreal. He worked on numerous projects involving power system analysis and design, railway electrification studies and specialized computer software code development. In 1976, he joined Montel-Sprecher & Schuh, a manufacturer of high voltage equipment in Montreal, as Manager of Technical Services and was involved in power system design, equipment selection and testing for systems ranging from a few to several hundred kV. In 1979, he founded Safe Engineering Services & technologies, a company specializing in soil effects on power networks. Since then he has been responsible for the engineering activities of the company including the development of computer software related to power system applications.

He is the author of more than one hundred and fifty papers on power system grounding, lightning, inductive interference and electromagnetic field analysis. He has written several research reports for CEA and EPRI.

Dr. Dawalibi is a corresponding member of various IEEE Committee Working Groups, and a senior member of the IEEE Power Engineering Society and the Canadian Society for Electrical Engineering. He is a registered Engineer in the Province of Quebec.