Analysis of a Steel Grounding System: A Practical Case Study

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Abstract: This paper presents a thorough analysis of the performance of a large grounding system made of steel instead of copper conductors. The grounding system is located in a relatively low resistivity soil and is interconnected to an extensive network of overhead transmission lines, in low soil resistivity. The extent of the grounding combined with its steel conductors and the low resistivity soil invalidates the equipotential assumption that is usually made when analyzing grounding systems. The presence of a large circulating fault current in the grounding system aggravates this problem further. Obviously, classical grounding analysis methods are no longer applicable and more advanced techniques must be used. This paper presents a detailed study of such problems. The measured soil resistivities and the grounding system impedance are compared to the computed values. Fault current distribution between the grounding system and the other metallic paths are computed to determine the portion of fault current discharged in the grounding system. The performance of the grounding system, including its GPR (ground potential rise), GPDs (grounding potential differences) between the ground conductors and the touch and step voltages have been evaluated accurately, taking into account the impedance of the steel ground conductors and their mutual inductive components. Numerical results are presented and compared to those obtained based on a conventional approach. The paper also examines briefly the electromagnetic coupling between the control cables and the ground conductors to illustrate a typical analysis of the integrity of the electronic equipment connected to the control cables.

Keywords: Ground potential rise, ground potential difference, touch voltage, step voltage, steel conductors.

1. Introduction

Appropriate power system grounding is important for maintaining reliable operation of electric power systems, protecting equipment, and insuring the safety of public and personnel. A grounding system must be properly designed and its performance needs to be evaluated. Improper or inaccurate analysis can lead to millions of dollars in excess expenses due directly to overdesign or resulting from the consequences of underdesign. Most power engineers have a complete understanding of the situation whereby a power substation or a power plant introduces current into the grounding system and soil when a single-phase-to-ground fault occurs inside the station or a power line structure outside the station. Unfortunately, when a professional faces a real problem and must estimate the performance of a grounding system, it is very difficult to do it correctly and accurately. Many factors have to be considered and adequate software must be used.

As it may be known, many grounding systems in China and several other countries are made of steel that have higher permeability and lower conductivity than that of copper [1]. This raises some unique issues particularly if the substation size is large and the soil resistivity is low. In a conventional grounding analysis approach, a grounding system is generally assumed as an equipotential structure. This would be inaccurate for such a case. In fact, the ground impedance of the grounding system has a significant inductive component, which is not taken into account by classical grounding analysis methods. Furthermore, under such conditions, it is likely that there are significant potential differences between parts of the grounding system which could endanger the normal operation of the secondary electronic equipment inside a substation.

This paper presents a typical thourough analysis of a large grounding system consisting of steel conductors buried in a low soil resistivity using advanced techniques, taking into account the impedance of steel ground conductors. In other words, the grounding system is not assumed to be an equioptential structure in the study. First, the measured soil resistivity data is studied to obtain equivalent multi-layer soils for the grounding analysis. Then the performance of the grounding grid, i.e. ground potential rises and ground potential differences (GPRs and GPDs), touch voltages and step voltages, is evaluated accurately during a phase-to-ground fault condition. In addition, the paper examines briefly the electromagnetic coupling between the control cables and the ground conductors to illustrate a typical analysis of the integrity of the electronic equipment connected to the control cables. Numerical results are presented and compared to those obtained a conventional approach. Results are also compared with the field measurements.

The analysis and the discussions presented in this paper can be used as a guide to study large grounding systems and other systems consisting of other high impedance conductors such as steel conductors.

2. Description of the System

Figure 1 is the plan view of the substation grounding system and the electrical network connected to it. The substation is connected to eight substations through fourteen 220 kV transmission line circuits and to two substations through four 500 kV transmission line circuits. Figure 2 represents the multiphase circuit for a single-line-to-ground fault in the 220 kV substation yard. It shows the equivalent circuit of the computer model used. The fault current contribution from each source, span lengths and overall lengths of the transmission lines to the remote substations are shown in the figure. The overhead ground wire is made of GJ-50 (steel) for the 220 kV lines and LHBGJF2-95/55 (OPGW) for the 500 kV lines. The total 220 kV fault current level is 46.88 kA. The fault current contributions from the 220 kV transmission lines are discharged in the soil by the ground system while the 500 kV transformers contribute to the 220 kV fault in the form of a current circulating almost entirely in the grounding system conductors (referred as circulating current). Figure 3 shows a typical cross section of all the transmission line towers modeled. A value of 5 ohms was used for all tower structure grounds.

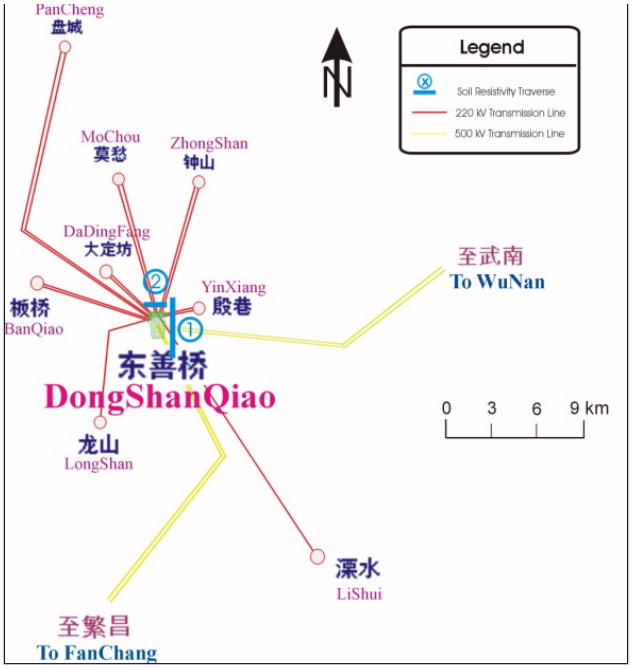

Figure 1. Plan view of the grounding system and the associated interconnected network (Soil resisitivity traverses 3-6 are inside the substation. The substation and soil traverses are not to scale. The substation dimensions are 290 m by 390 m. Soil traverses 1 is about 900 m and traverse 2 is 225 m).

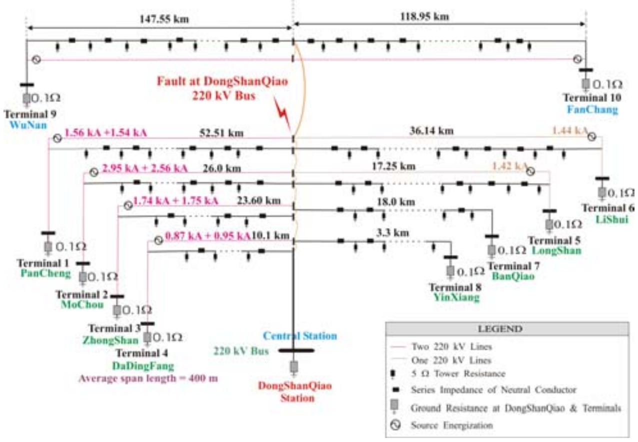

Figure 2. Circuit model of the 220 kV network used to determine the fault current distribution.

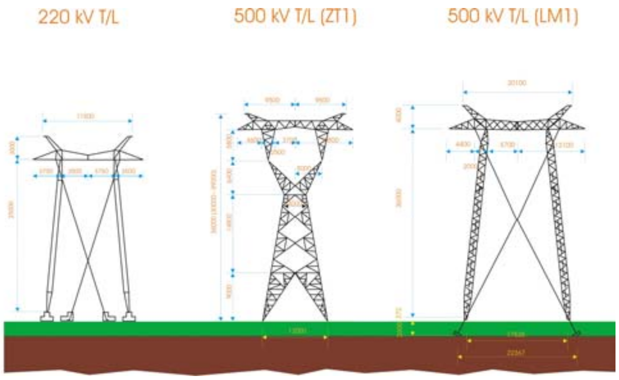

Figure 3. Typical cross-section of the transmission lines.

Figure 4 shows a detailed plan view of the substation grounding system. The ground conductors are buried at a depth of 0.6 m and are made of L50*6 mm steel (represented as a cylindrical conductor with an equivalent radius of 1.01 cm in the model). A number of ground rods are installed at various locations of the grid. They are 2 m long and are made of L50*50*5 mm steel (represented as a cylindrical conductor with an equivalent radius of 0.56 cm in the model). A representative sample of the control cables inside the substation have also been shown in Figure 4. Two types of cables were modeled. The first type, KVVP2-22, has a radius of 0.437 cm and the second type, VV22 has a radius of 0.1382 cm. Figures 1 and 4 also provide the soil resistivity measurement locations.

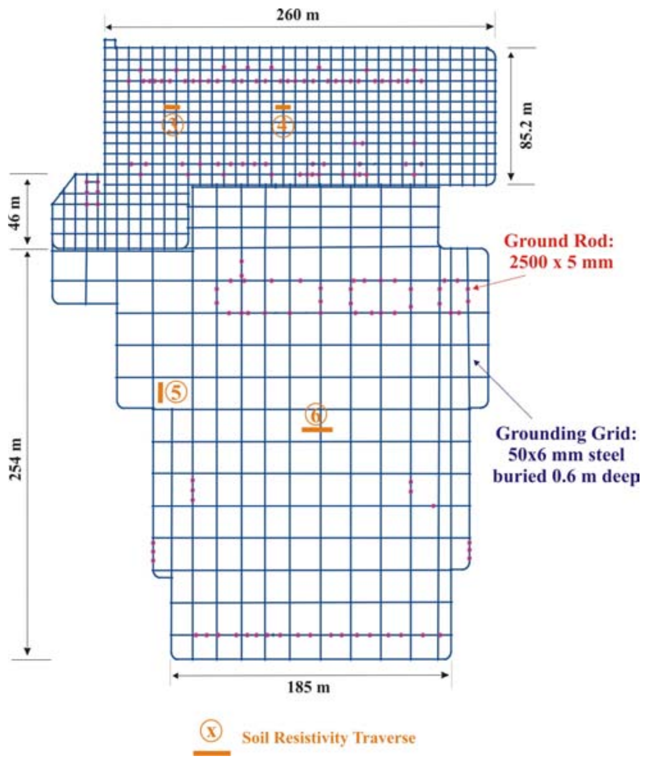

Figure 4. The detailed substation grounding system and soil resistivity measurement within the substation.

3. Methodology of the Analysis

The main objective of this analysis is to evaluate the adequacy of the substation grounding system and to provide necessary mitigation measures, if necessary, accounting for the inductive components of the grounding system which are not taken into account by conventional grounding analysis methods. Therefore, an electromagnetic field analysis method [2] is used: First, soil resistivity measurements and interpretation are an essential task for an accurate grounding analysis. Realistic soil model instead of a uniform one has to be developed and to be applied throughout the grounding system analysis [3]. Second, the grounding system impedance needs to be measured and validated with computer predictions while assessing the accuracy of the measured values [4-6]. Third, the fault current distribution between the grounding system and the rest of the network must be computed. When a single–phase-to-ground occurs, the available total fault current splits into two components (excluding the circulating current through local transformers): part flows into the earth from the substation grounding grid, while part of it flows back out of the station on overhead ground wires, neutral conductors or cable sheaths which are connected to other grounding systems. The current injected into soil, instead of the total fault current, should be used to evaluate the grounding system. Fourth, the safety of the grounding grid, including the ground potential rises and ground potential differences (GPRs and GPDs), touch voltages and step voltages, is evaluated accurately during a phase-to-ground fault condition using modern computational methods [7]. Finally, the integrity of the electronic equipment connected to the control cables due to electromagnetic coupling between the control cables and the ground conductors is analyzed.

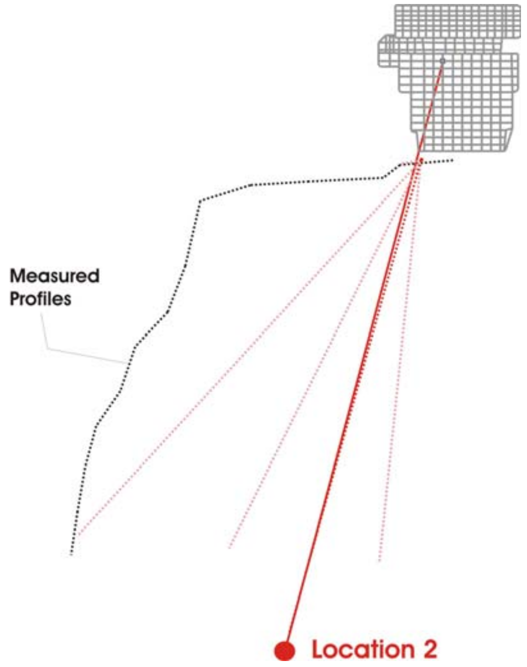

Figure 5a. Locations of return electrode and FOP profiles.

4. Computation Results And Discussions

4.1 Soil Resistivity

Soil resistivity measurements constitute the basis of any grounding study and are therefore of capital importance. Furthermore, accurate soil resistivity interpretation must be performed [8-9]. In this study, soil resistivity measurements were made in (6 traverses) and around (2 traverses) the substation. The shortest measurement traverses, within the grounding system, were selected in order to sample shallow depth soil resistivities, therefore, the measurements are indicative of local surface soil characteristics. The longer measurement traverses, located outside the substation, were selected in order to provide a representative sample of soil resistivities at greater depths, which would have been impossible to detect within the substations due to interference from the grounding system conductors. The measurement is indicative of average deep soil characteristics. 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 systems under study, although it is preferable to extend the measurement traverses to several times the maximum grounding system dimension, where possible.

In order to estimate touch and step voltages within the substation it is important to determine accurately local (shallow depth) soil characteristics as well as the GPR of the grounding system. The GPR also depends, to a large extent, on the characteristics of the deeper soil layers. Consequently, a final soil model is obtained based on the measurements as follow:

Soil Structure		
Layer	**Resistivity (Ω-m)**	**Thickness (m)**
Top layer	12.0	1.0
Middle layer	3.3	14.5
Bottom layer	200.0	Infinite

4.2 Grounding Impedance Measurement and Interpretation

To evaluate the performance of a substation grounding system, the ground impedance of the grounding system must be obtained either by measurement or by computation with appropriate soil resistivity measurements. Incorrect ground impedance will lead to incorrect fault current computation, therefore affecting the results of the analysis. Ideally, the impedance should be computed and then validated by measurement.

Figure 5 shows the measured and computed curves based on various scenarios. Because of the uncertainty of the exact locations of the current and voltage electrodes, several profiles instead of a single one are set. Figures 5b and 5c present the computed curves along with the measured one using two different approaches, respectively. Each computed curve represents a Fall-of-Potential (FOP) profile along a direction corresponding to a scenario shown in Figure 5a.

As shown in Figures 5b and 5c, the measured and computed values agree reasonably well for all profile directions, scenarios, or computation methods used [9]. The difference between the measured values and the computed ones are due to measurement inaccuracies, coupling between the current lead and grid conductors or potential lead, differences between the real soil structure and the one that has been modeled, effects of the external metallic paths (overhead ground wires, distribution neutrals, etc.) that are interconnected to additional grounds that are not accounted for in the computer model and, most probably, uncertainties regarding the exact locations (with respect to the grounding system boundaries) of the return current electrode and the observation points along the measured FOP traverse. The computed curves were obtained using the MALZ and HIFREQ engineering software modules described in [8]. The MALZ module takes into account the voltage drops along a grounding system and is therefore capable of modeling large grounding systems with steel conductors (Figure 5b). The HIFREQ module is based on the full electromagnetic field theory and, therefore, takes into account inductive as well as capacitive coupling between conductors (buried and above ground) (Figure 5c).

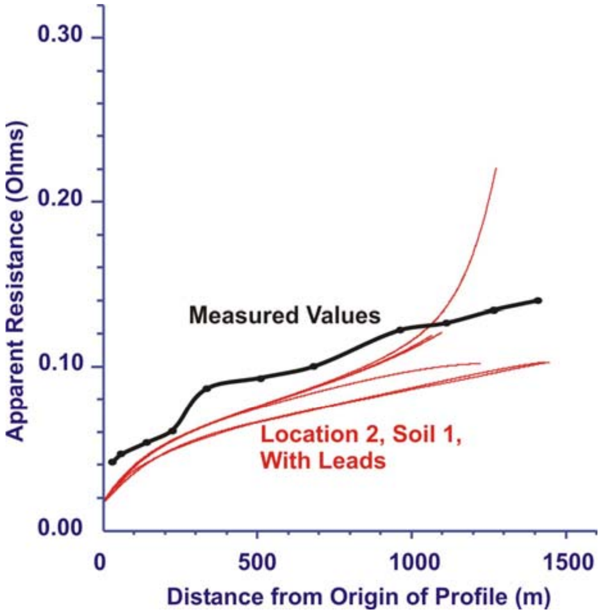

Figure 5b. Measured and computed apparent impedances accounting voltage drop along the conductor.

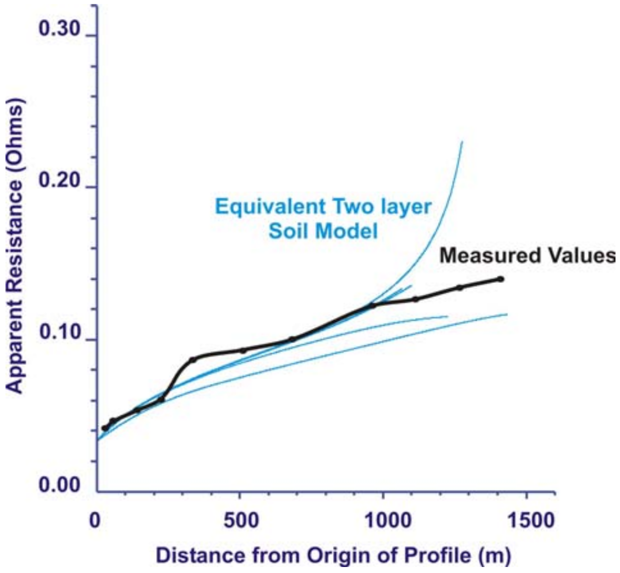

Figure 5c. Measured and computed apparent impedances using field theory.

4.3 Fault Current Distribution Analysis

Under most of the conditions, the total fault current doesn't discharge entirely in the substation grounding system. Part of the fault current, which does not contribute to the GPR of the grid, will return to the remote source terminals and to the transformer neutrals through shield wires, neutral wires or conductors of the grid. It is well known that the GPR, the touch and step voltages associated with the grounding network are directly proportional to the magnitude of the fault current component discharged directly into the soil by the grounding network. It is therefore important to determine how much of the fault current returns to remote sources via the overhead ground wires and neutral wires of the transmission lines and distribution lines connected to the substation.

Computer simulations have been performed using the Right-Of-Way software described in [8] based on the final circuit model shown in Figure 2 with the computed ground impedances of the substation. Table 1 shows the currents injected into the substation grounding system (earth currents) as well as the ground potential rise (GPR) of the grid without considering the circulating current in the ground conductors, while Figure 6 shows the distribution of the fault current along the transmission line overhead ground wires.

Table 1 and Figure 6 show quite clearly that a lot of the fault current returns to the sources through the overhead ground wires (close to 50%). This is due to the mutual coupling between the faulted phase and overhead ground wires on one hand and because of the low transmission line ground resistances (about 5 ohms) on the other hand as shown in Figure 6. Indeed, the horizontal portions of the curves correspond to the inductive coupling that maintains the current flowing in the ground wire although the current that is dissipating in the tower grounds are already depleted.

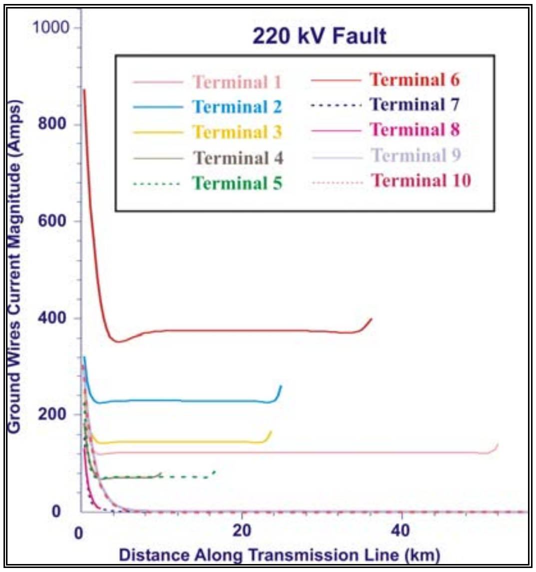

Figure 6. Computed fault current in the transmission line overhead ground wires (only one line for each terminal is represented. The currents in the other line, are about the same).

Table 1: Fault current and ground potential rise at the substation

Total Fault Current	Ground Wires Current	Substation Ground Current	Ground Potential Rise
16810.7<84.2	8658.0<-93.7	8388.6<-74.6	884.99<-74.6

Analyzing fault current distribution accurately is a complicated subject. It is influenced by many factors, such as the number of source terminals, the impedance of the grounding grid, the type of overhead ground wires, the tower resistance, the soil resistivity etc. Fault current distribution becomes even more complicated when transformers, non-source terminals etc. are taken into account. This will be the subject of a subsequent paper.

4.4 Safety Analysis

The GPR, GPD, touch and step voltages are important results when a substation is assessed. The calculation of GPR, GPD, touch and step voltages was carried out using the MALZ grounding software [8], which takes into account voltage drops along conductors in a grounding system, therefore eliminating the assumption that a grounding grid is an equipotential. The current shown in Table 1 was injected into the grounding system at a fault location for the 220 kV voltage levels. Figure 7 shows that the ground potential rise (GPR) along the grid conductors in the 220 kV yard. The maximum GPR is 838 V. The maximum touch voltage is 116 V.

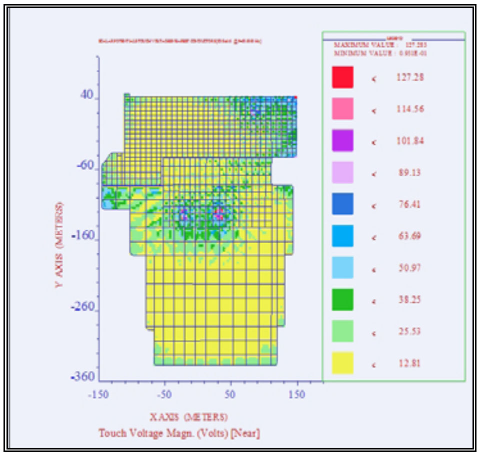

Figure 8. Touch voltages at the substation with the final mitigation design.

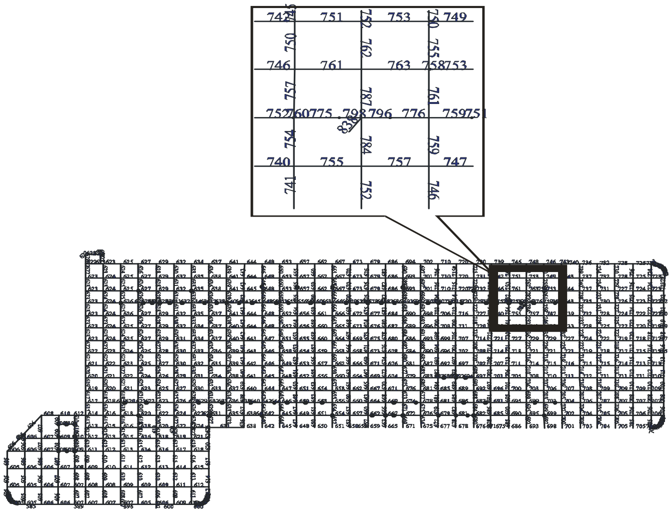

Figure 7. Ground potential rise of the grid conductors in the 220kV yard, no circulating current is considered.

However, when the effect of the fault currents circulating in the grounding system due to local sources (i.e., 220/500kV transformers #1 and #2, 14.69 kA and 15.56 kA are the transformer fault current contributions, respectively.) was considered, the result is completely different. During a fault on the secondary side of a transformer located in a substation, considerable currents can flow through the grounding system from the fault location to the transformer feeding the fault, resulting in large potential differences between different locations of the grid. Under such condition, the current injected at the fault location is the sum of the total earth current and the circulating currents. The circulating currents are then drained to earth via the neutral bonding wires of the transformer that are connected to the grounding system at locations. When the circulating current is taken into account, the maximum GPR of the grid and the maximum GPD between two points inside the substation are 1850 V and 1723 V (accounting for the phase angle), respectively. Figure 8 shows the touch voltages inside the substation.

4.5 Electromagnetic Compatibility Analysis

As shown in the previous section, the circulating currents within the grounding system cause ground potential differences (GPD) between various grounded points of the substation metallic structures. This phenomenon is particularly severe when sparse interconnections are used between different sections of the grounding system and if steel ground conductors are used instead of copper. Non-grounded conductors, such as control and communication cables, connected to equipment at two such parts of the grid, may be subjected to large voltages resulting in possible damage to the equipment. As already mentioned, this is an important aspect of the electromagnetic compatibility assessment of the grounding system that is often ignored in most conventional grounding analysis.

Figure 9 shows the grounding system of the substation along with a representative sample of the control cables that have been modeled during a 220 kV fault. HIFREQ module of CDEGS [8] has been used to carry out the study since it accounts for the inductive and capacitive interactions between conductors. The maximum stress voltage between a control cable core and its sheath occurs for Control Cable 1 and is more than 500 Volts as shown in Figure 10. Note that the maximum stress voltage between the control cable core and its sheath can be reduced due to special cable routings, i.e., there are preferred paths for the control cable routing, in a substation. Detailed study on this subject will be presented in a future research work.

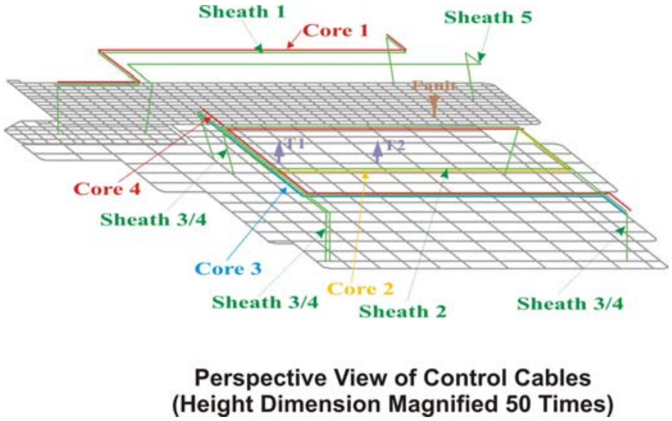

Figure 9. Perspective view of the control cables and grounding system at the substation (height magnified 50 times).

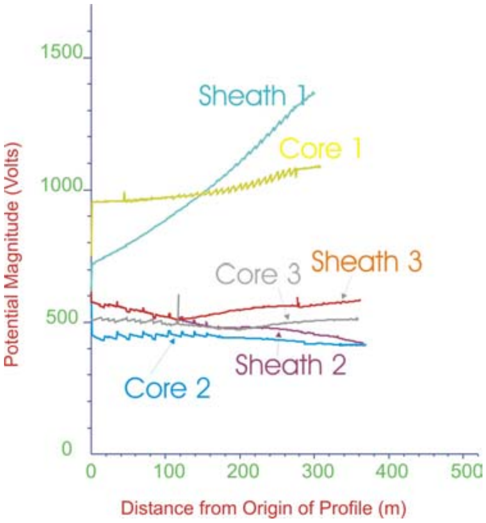

Figure 10. GPR of the control cable, core and sheaths: 220 kV fault case, no mitigation.

5. Conclusions

The performance of a large substation grounding system has been evaluated using modern techniques. A non-uniform soil model has been derived based on soil resistivity measurements, and it has been applied throughout the study. Grounding impedance measurements using the Fall-of-Potential method are compared and validated with computer modeling of an extensive network including aboveground shield wires. A complete circuit model of the overhead transmission line network has been built in order to determine the current distribution during a single-phase-to-ground fault. Current injected into the soil through the grid which contributes to the GPR, touch and step voltages, therefore, is obtained. Because of the large grounding system size, the relative low soil resistivity as well as the grid made of steel ground conductors, the conventional approach used in grounding analysis (assumption of equipotentiality of grounding system) leads to wrong results. Therefore, adequate modern techniques, taking into account voltage drops along the grid conductors, inductive and capacitive couplings between conductors, circulating currents within the substation, has been used to compute the grid GPR, GPD, touch and step voltages. Finally, the electromagnetic coupling between control cables and the ground conductors has been examined in order to illustrate that large potential differences (stress voltages) between equipment connections to the grounding grid can be obtained, situation that could endanger the normal operation of the electronic equipment inside a substation.

6. References

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8. Biographies

Ms. Yexu Li received the B.Sc. degree in Geophysics from Beijing University and the M.Sc. degree in Seismology from the Chinese Academy of Sciences in 1986 and 1989, respectively. She received the M.Sc. degree in Applied Geophysics from Ecole Polytechnique of the University of Montreal in 1996 and the Graduate Diploma in Computer Sciences from Concordia University in 1998.

From 1995 to 1998, she worked as a Geophysicist with the SIAL Geosicences Inc. in Montreal, and was involved in geophysical EM survey design, data acquisition and processing as well as interpretation.

She joined Safe Engineering Services & technologies ltd. in Montreal in March 1998 as a scientific researcher and software developer. She is presently working on AC interference studies, grounding system analysis and software development.

Ms. Li has authored (or coauthored) more than ten papers and twenty research reports on geophysics, electromagnetic interference analysis and system grounding.

Dr. Farid P. Dawalibi (M'72, SM'82) 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 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.

Dr. Jinxi Ma was born in Shandong, P. R. China in December 1956. He received the B.Sc. degree in radioelectronics from Shandong University, and the M.Sc. degree in electrical engineering from Beijing University of Aeronautics and Astronautics, in 1982 and 1984, respectively. He received the Ph.D. degree in electrical and computer engineering from the University of Manitoba, Winnipeg, Canada in 1991. From 1984 to 1986, he was a faculty member with the Dept. 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 seventy 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, the IEEE Standards Association, and a corresponding member of the IEEE Substations Committee and is active on Working Groups D7 and D9.

Dr. Yixin Yang received the B.Sc., M.Eng. and Ph.D. degrees in 1982, 1985 and 1992 respectively. From 1989 to 1997, he was a senior Electronic Engineer. From 1997 to 1998, he was a visiting fellow at Griffith University, Australia. Since September 1998, he has been with the R & D Dept. of SES in Montreal. His research interests are in transient electromagnetic scattering, EMI and EMC, and analysis of grounding systems in various soil structures.

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