ANALYSIS AND VALIDATION OF THE PERFORMANCE OF GROUNDING SYSTEMS BURIED IN SOIL STRUCTURES CONTAINING HETEROGENEOUS VOLUMES

F. P. Dawalibi, N. Mitskevitch
Safe Engineering Services & technologies ltd.
1544 Viel, Montreal, Quebec, Canada, H3M 1G4
Email: info@sestech.com

Abstract

The study of grounding systems in various types of layered soils has been the subject of considerable attention in the past decades. However, there is a class of grounding problems that has not been studied as much but that is crucial for the investigation of a range of practical problems that cannot be approximated by a layered soil structure. This type of problems involves grounding systems that are either close to, partially immersed in or totally immersed in one or several finite volumes of soil materials that have resistivity values quite different from that of the bulk volume of surrounding soil (native soil). This paper focuses on this class of problems by describing and discussing the computed results that pertain to a number of typical grounding scenarios and by comparing them to some known limiting case solutions.

Keywords

Grounding; Earthing; Heterogeneous Soil Volumes

1. Introduction

The study of grounding systems in various types of layered soils has been the subject of considerable attention by several researchers in the past decades [1-6]. Analysis of grounding systems buried in soils containing a number of finite volumes of soil with arbitrary resistivity values has also been carried out quite recently [7-9]. The analytical model is described in [7], while typical examples and validation are provided in [8-9]. However, the examples given in these papers are limited in scope and are restricted to a few practical cases that concentrate mainly on validating the theoretical model. Consequently, there is a lack of suitable publications that discuss in detail the performance of grounding systems that are partially or totally embedded in finite volumes of soil with arbitrary resistivities different from that of the native surrounding soil. This paper and future ones that are under preparation intend to fill this gap.

A successful grounding analysis should be based on a soil structure model that is as close as possible to the real soil at the site of interest. In many cases, a horizontally layered soil provides a very good approximation. However, there is a class of grounding problems that is crucial for the investigation of a range of practical problems that cannot be approximated by a layered soil structure. This type of problems involve grounding systems that are either close to, partially immersed in or totally immersed in one or several finite volumes of soil materials that have resistivity values that are quite different from that of the bulk volume of surrounding soil (native soil). Most practical problems that involve soils with heterogeneous volumes can be classified in the following four categories:

1. The grid is totally immersed in the heterogeneous volume (for example, the grounding system of a hydroelectric dam or a grounding system that is embedded in a conductive backfill material).
2. The grid is partially immersed in the heterogeneous volume (for example, the grounding grid portion that has been replaced by backfill material for drainage purposes or the part of the grid that is embedded in a concrete slab or an area of the grid that is wet, dry or simply totally exposed, etc.).
3. The grid is totally outside, but close to and under the influence of nearby heterogeneities (for example, proximity to a lake or proximity of a void in the soil, such as a deep valley or an excavation, etc.).
4. Multiple volumes and multiple grounding systems are involved in various patterns. Typical cases involve the study of extensive grounding networks that are buried in different soil structures as one moves from one location to another (for example, inductive and conductive interference problems along large transmission line right-of-way distances).

In this paper we will focus on the first two categories. The analysis of the other two categories will be the subject of future investigations.

2. Analyses

2.1 Summary of the Theoretical Model

The analysis of grounding systems located near or within finite soil volume heterogeneities can be carried out only using numerical methods when the shape of the volume is arbitrary. There are only a few special types of heterogeneous soils that allow exact analytical closed form solutions. Typical cases include hemispherical [5] and cylindrical [6] soil types. The hemispherical soil type is used in this study to validate computation results pertaining to rectangular-shaped finite soil volumes.

The electric field generated by a grounding system located in a soil with finite heterogeneities is caused by charges located on the finite volume interface with the soil and on the surface of the ground conductors. The method employed in the analysis is the so-called boundary element method. The surface of each rectangular volume is subdivided into small elements (patches). Each of the patches is assumed to have a uniform charge distribution. Each ground conductor is subdivided into small conductor segments. Each conductor segment is assumed to have a uniform surface charge distribution. The method of images is applied for all interface patches and all conductor segments, taking into account the presence of the earth surface. The charge distribution in the system is determined by numerically solving integral equations expressing the boundary conditions on each surface element of the finite volume interfaces and on the conductor segments. Finally, the earth potentials anywhere can be computed by considering the contributions from all the charges on the conductor segments and on the finite volumes soil interfaces. See Reference [7] for detailed analytical derivations on this topic.

2.2 Totally Immersed Grid (Rectangular versus Hemispherical Volumes)

Let us first examine the case of a 49-mesh, 100m x 100m grid buried at a depth of 0.5m below grade. The grid is immersed in a rectangular finite soil volume with a resistivity ρ_{Volume}, as shown in Fig.1a. The surrounding soil resistivity is ρ_{Native}. The top face of the rectangular volume coincides with the earth surface.

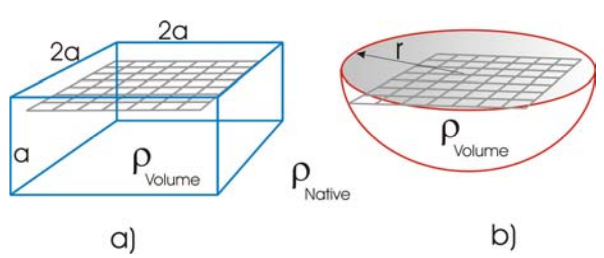

Figure 1. Rectangular (a) and Hemispherical (b) Soil Models.

Table 1. Resistivities of Finite Volume and Native Soil

ρ_{Volume} (Ω·m)	ρ_{Native} (Ω·m)	ρ_{Volume} / ρ_{Native}
10	1000	0.01
100	1000	0.1
100	200	0.5
200	100	2
1000	100	10
1000	10	100

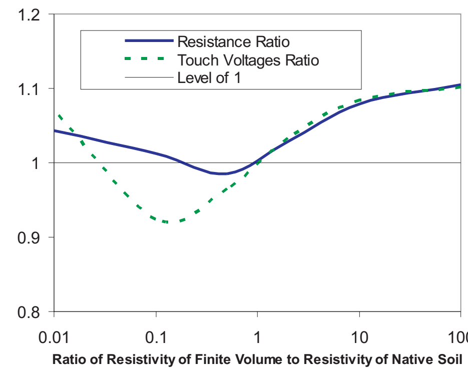

Figure 2. Resistance Ratio and Maximum Touch Voltage Ratio as a Function of Resistivity Ratio.

In all our examples, we assume that a current of 1000 Amps is injected into the grounding system modeled. The results obtained with the rectangular soil model are compared and validated using the equivalent hemispherical soil model shown in Fig.1b. The volume of this hemispherical soil is about the same as that of the rectangular soil. The radius of the hemispherical soil *r* is 75m and *a* represents a parameter related to the dimensions of a rectangular volume of soil (2*a* x 2*a* x *a* where *a* is 60m). The series of analyses is conducted for various values of ρ_{Volume} and ρ_{Native}, which are shown in Table 1. The ground resistance ratio $R_{Hemispherical}/R_{Rectangular}$ and the maximum touch voltage (over the grid area) ratio $V_{Hemispherical}/V_{Rectangular}$ are shown in Fig. 2 as a function of the resistivity ratio $\rho_{Volume}/\rho_{Native}$. As expected, the resistance ratio (solid curve) and the maximum touch voltage ratio (dashed curve) are close to 1 along a wide range of resistivity ratios.

As mentioned in Section 2.1, a numerical method is used to carry out the analysis of the rectangular volume soil heterogeneity. In this numerical approach, every surface of the rectangular volume is subdivided into hundreds of small surface elements or patches having a uniform charge distribution. The charge distribution over the soil volume surfaces helps us better understand the influence of local soil heterogeneities on the performance of grounding systems. These charge distributions are illustrated in the following figures by unfolding the rectangular volume surfaces as one would unfold a hollow cube, in order to see all faces at once. The top of the rectangle is centered with respect to the rectangle sides. The bottom of the rectangle is to the right of the right side of the rectangle.
Figs. 3 and 4 show the charge density distribution over the rectangular volume interface for two extreme cases: $\rho_{Volume} \ll \rho_{Native}$ and $\rho_{Volume} \gg \rho_{Native}$, respectively. Note that we show no charges on the top volume surface, because it coincides with the earth surface. In Fig. 3 (ρ_{Volume}=10 Ω·m and ρ_{Native}=1000 Ω·m), charges are mostly concentrated over the volume edges and corners.

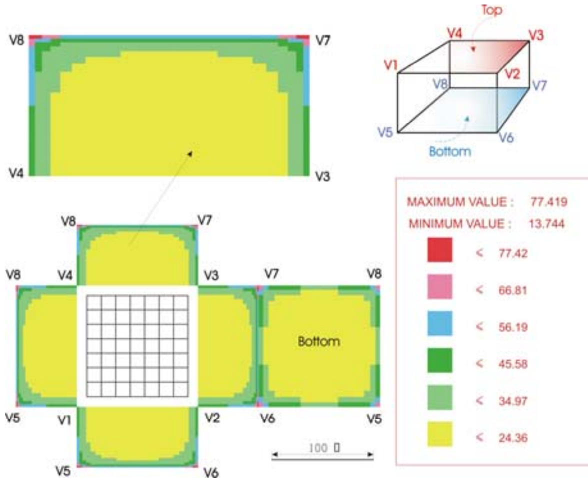

Figure 3. Charge Density Distribution over Rectangular Volume Surfaces: $\rho_{Volume} << \rho_{Native}$ (ρ_{Volume}=10 Ω·m and ρ_{Native}=1000 Ω·m).

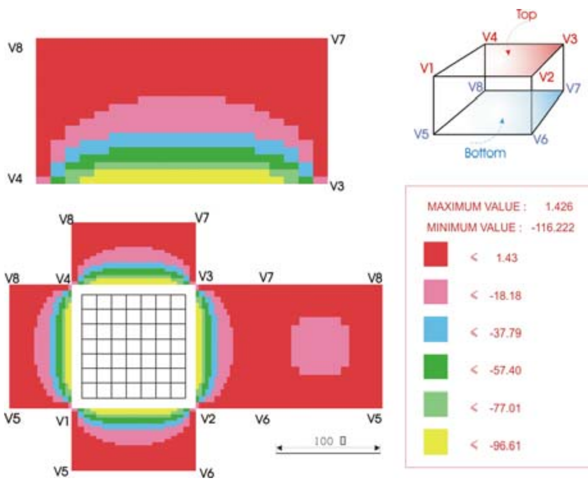

Figure 4. Charge Density Distribution over Rectangular Volume Surfaces: $\rho_{Volume} >> \rho_{Native}$ (ρ_{Volume}=1000 Ω·m and ρ_{Native}=10 Ω·m).

In this case, the whole volume acts as a conductive media. The situation is reversed when ρ_{Volume}=1000 Ω·m and ρ_{Native}=10 Ω·m (Fig. 4). In this case, the rectangular volume is not an attractive medium for earth currents. The current leaking from the grid tries to find the shortest path to leave the volume. The largest electric charges occur on the surface areas that are the closest to the grid conductors.

2.3 Totally Immersed Grid (Rectangular Volumes versus Layered Soils)

In some cases when, for example, the grounding grid is immersed in a concrete slab or in a backfill material, the soil heterogeneity can be modeled as a flat rectangular volume. When the volume increases in size and when its top surface coincides with the earth surface, then the limiting case solution for this kind of soil is a horizontal two-layer soil model.

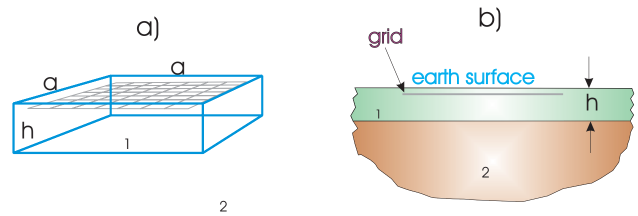

Figure 5. Rectangular (a) and Horizontal Two-Layer (b) Soil Models.

In this section we will compare the behavior of a rectangular volume (a x a x h), resistivity ρ_1 surrounded by a uniform soil, resistivity ρ_2 (Fig. 5a), with its corresponding two-layer soil limiting case (Fig. 5b). We use the same 100m x 100m grid used in Section 2.2. The grid is buried at a depth of 0.5m.

In this series of analyses, we will determine the approximate minimum size of the rectangular volume that can be approximated by a two-layer soil model. We will vary the parameter a, while h=20m is kept constant. The computer simulations are conducted for cases where $\rho_1 < \rho_2$ and $\rho_1 > \rho_2$. Let us first analyze the scenario corresponding to ρ_1=200 Ω·m and ρ_2=1000 Ω·m. The resistance of the grounding system when immersed in the two-layer soil model is 2.14 Ω and the maximum touch voltage magnitude over the grid area is 252 V. Let us compare the same quantities for the case when the grid is immersed in rectangular soil volumes of different sizes as shown in Table 2. The smallest volume size of 120m x 120m x 20m results in the largest resistance value, which is about 68% larger than for two-layer soil model resistance. The resistance and touch voltages of such soil volumes become comparable with those of a two-layer soil only when the volume size reaches about four times the grid size.

Table 2. Ground Resistance of the Grid and Maximum Touch Voltage over the Grid Area

Rectangular Volume Size, a (m)	Resistance (Ω)	Maximum Touch Voltage (V)
120	3.15	235
160	2.75	238
200	2.53	240
400	2.1	242

The charge density distribution over the volume surfaces is shown in Fig. 6 and Fig. 7 for a 120m x 120m x 20m volume and a 200m x 200m x 20m volume, respectively. It is easy to see that in this case of low resistivity volume, the grid current has a tendency to distribute evenly over the entire volume surfaces that are in contact with the high resistivity native soil. The situation is reversed when $\rho_1 > \rho_2$. Let's consider the case where ρ_1=1000 Ω·m and ρ_2=200 Ω·m.

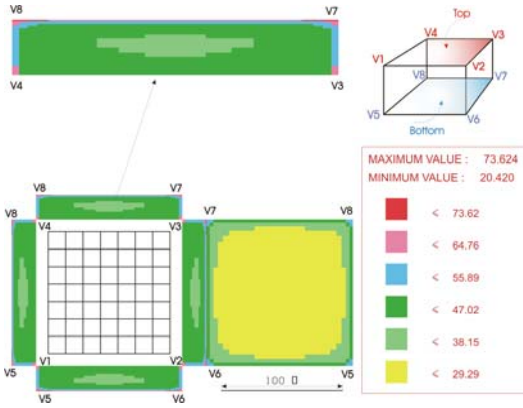

Figure 6. Charge Density Distribution over the Rectangular Volume Surfaces: ρ_1=200sΩ·m and ρ_2=1000sΩ·m. Volume Dimensions Are 120msxs120msxs20m.

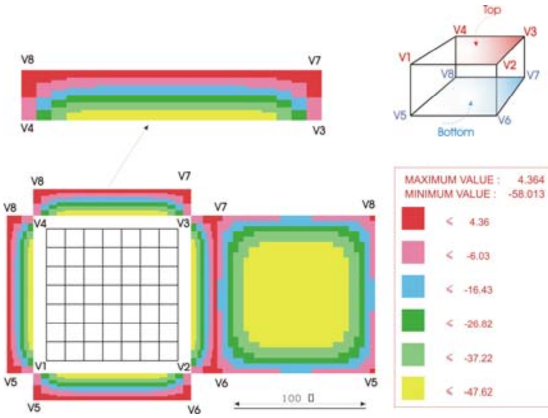

Figure 8. Charge Density Distribution over the Rectangular Volume Surfaces: ρ1=1000sΩ·m and ρ2=200sΩ·m. Volume Dimensions Are 120msxs120msxs20m.

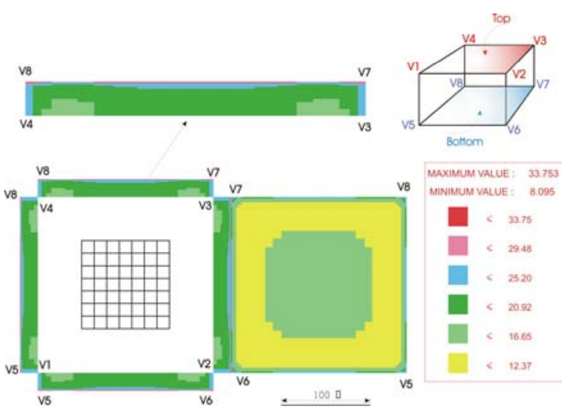

Figure 7. Charge Density Distribution over the Rectangular Volume Surfaces: ρ1=200sΩ·m and ρ2=1000sΩ·m. Volume Dimensions Are 200msxs200msxs20m.

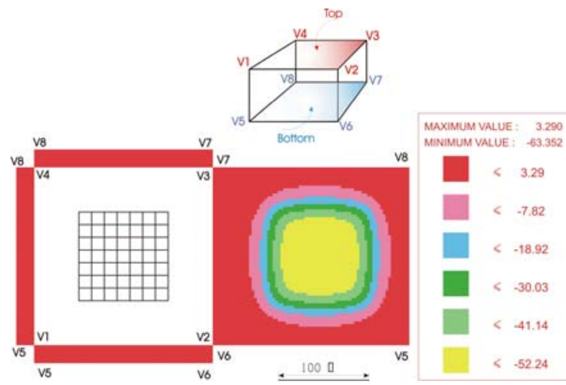

Figure 9. Charge Density Distribution over the Rectangular Volume Surfaces: ρ1=1000sΩ·m and ρ2=200sΩ·m. Volume Dimensions Are 200msxs200msxs20m.

The resistance of the grounding system immersed in the two-layer soil model is 2.55 Ω and the maximum touch voltage magnitude over the grid area is 924 V. Table 3 shows the same quantities for the case when the grid is immersed in rectangular soil volumes of different sizes.

Table 3. Ground Resistance of the Grid and Maximum Touch Voltage over the Grid Area

Rectangular Volume Size, *a*, (m)	Resistance (Ω)	Maximum Touch Voltage (V)
120	2.35	917
160	2.4	896
180	2.4	896

The results in Table 3 show that even for the smallest rectangular volume size of 120m x 120m x 20m the resistance differs from that of the two-layer soil model by 8% only. That is because the current leaking from the grid is trying to escape the high resistivity rectangular volume by the shortest possible path.

The largest amount of current leaves from the central part of the grid along the shortest path, which is the bottom surface of the volume, as shown in Fig. 8 and Fig. 9. This is why any increase of the extent of the rectangular volume does not practically change the performance of the grounding system any more.

2.4 Partially Immersed Grid

This category of partially immersed grids is illustrated using the following two examples. First let's consider the cases depicted in Fig. 10, where the grounding system is partially immersed in the low resistivity material. The grounding system consists of a 150m x 150m, 49-mesh grid buried at a depth of 0.5m and partially immersed, on one hand, in an 80m x 80m x 5m rectangular volume of soil (slab) and on the other hand, in a 60m radius hemispherical volume. The resistivity of the surrounding native soil is 1000 Ω·m and that of the heterogeneous volume is 100 Ω·m. The touch voltages over the immersed region of the grid for both the rectangular and hemispherical soil volumes are shown in Figs. 11 and 12, respectively. Table 4 summarizes the resistance computation results that apply for both cases.

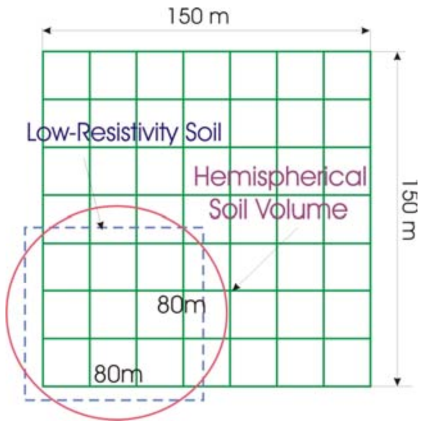

Figure 10. Grid Partially Immersed in Low Resistivity Soil Volume.

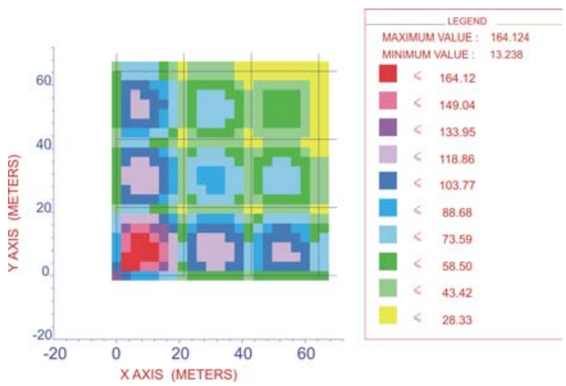

Figure 11. Touch Voltages over the Immersed Region of the Grid: Rectangular Soil Volume.

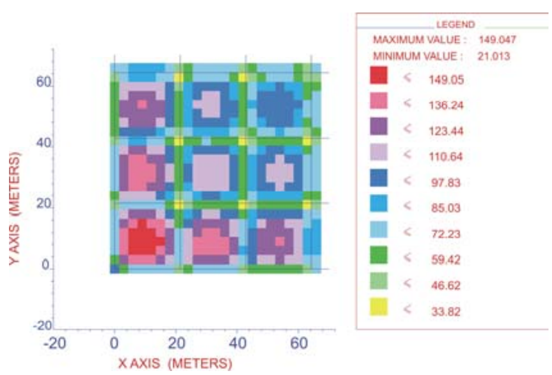

Figure 12. Touch Voltages over the Immersed Region of the Grid: Hemispherical Soil Volume.

Table 4. Ground Resistance of the Grid

Soil Type	Resistance (Ω)
Rectangular Volume	2.98
Hemispherical Volume	2.76
Uniform 1000 Ω·m soil	3.26

The thickness of the rectangular soil volume is rather small compare to its horizontal dimensions. Therefore it is impossible to match it to a hemispherical soil volume. In this example, however, it is more important that the hemispherical soil volume contains about the same portion of the grid as in the case of the rectangular soil. It is quite clear that the results for both types of finite soil volume are quite similar despite the difference in volume size between the two types of heterogeneities. The difference between the ground resistances and the maximum touch voltages are less then 8% and 9.2%, respectively. Note that the maximum touch voltage occurs at the bottom left corner mesh in both cases.

Fig. 13 shows another example of an actual grounding system that is partially in contact with a thin rectangular volume of high resistivity material.

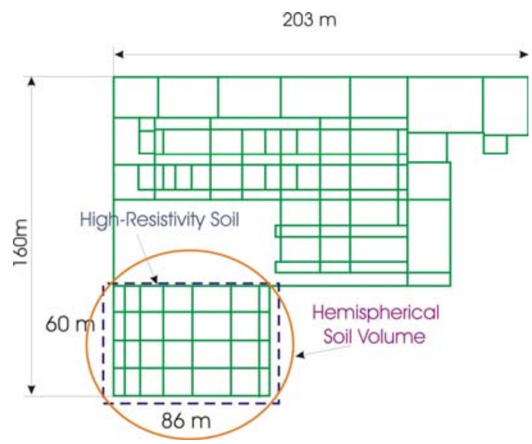

Figure 13. Grid Partially Immersed in High Resistivity Soil Volume.

A portion of the grounding grid is immersed in the 60m x 86m x 3.75m rectangular volume, which is made of a 1000 Ω·m backfill material. The surrounding soil has a resistivity of 100 Ω·m. This case is also compared to a 54m radius hemispherical backfill volume. The results are comparable, as shown in Table 5.

This confirms that the effect of the size of the immersed portion of the grid is the prevalent factor both for this case and for the previous case.

Table 5. Ground Resistance of the Grid and Maximum Touch Voltage over the Grid Area

Soil Type	Resistance (Ω)	Maximum Touch Voltage Magnitude (V)
Rectangular Volume	0.35	194.7
Hemispherical Volume	0.37	194.8

3. Conclusions

Grounding systems that are either close, partially immersed or totally immersed in one or several finite volumes of soil materials that have resistivity values quite different from that of the bulk volume of soil surrounding (native soil) constitute an important class of practical grounding problems.

This paper focuses on this class of problems by describing and discussing the computed results that pertain to a number of typical grounding scenarios and by comparing them to some known limiting case solutions. Most results that are presented have not been published before.

It is shown that the finite soil volume model approaches two known limiting cases, namely hemispherical soil volumes and horizontally layered soils, when the finite soil volume becomes a square volume or when it becomes a flat rectangular soil volume of suitable dimensions.

More complex soil volumes will be examined in future research work.

4. Acknowledgments

The authors wish to thank Safe Engineering Services & technologies ltd. for the financial support and facilities provided during this research effort. They also thank Dr. Jinxi Ma and Mr. Robert D. Southey for their help and constructive comments on the paper manuscript.

References

[1] F.P. Dawalibi and D. Mukhedkar, "Optimum Design of Substation Grounding in Two-Layer Earth Structure - Part I, Analytical Study," *IEEE Trans. on PAS*, Vol. 94, No. 2, March-April 1975, pp. 252-261.

[2]A.P. Meliopoulos, R.P. Webb, and E.B. Joy, "Analysis of Grounding Systems," IEEE Trans. on PAS, Vol. 100, No. 3, March 1981, pp. 1039-1048.

[3]F.P. Dawalibi and N. Barbeito, "Measurements and Computations of the Performance of Grounding Systems Buried in Multilayer Soils," *IEEE Trans. on PWRD*, Vol. 6, No. 4, October 1991, pp. 1483-1490.

[4] T. Takahashi and T. Kawase, "Calculation of Earth Resistance for a Deep-Driven Rod in a Multi-Layer Earth Structure," *IEEE Trans. on PWRD*, Vol. 6, No. 2. April 1991, pp. 608-614.

[5]J. Ma, F.P. Dawalibi, and W.K. Daily, "Analysis of Grounding Systems in Soils with Hemispherical Layering," *IEEE Trans. on PWRD*, Vol. 8, No. 4, October 1993, pp. 1773-1781.

[6] J. Ma and F.P. Dawalibi, "Analysis of Grounding Systems in Soils with Cylindrical Soil Volumes," IEEE/PES Transactions on PWRD, Vol. 15, No. 3, July 2000, pp. 913-918.

[7] J. Ma and F.P. Dawalibi, "Analysis of Grounding Systems in Soils with Finite Volumes of Different Resistivities," IEEE/PES Transactions on PWRD, Vol. 17, No. 2, April 2002, pp. 596-602.

[8] J. Ma, N. Mitskevitch, and F.P. Dawalibi, "Performance Evaluation of Grounding Systems in Soils with Finite Volumes of Different Resistivities," Proceedings of the 62nd Annual Meeting of the American Power Conference, Chicago, April 10-12, 2000, pp. 338-342.

[9] N. Mitskevitch, J. Ma, and F.P. Dawalibi, "Study of Grounding System Safety Aspects in the Presence of Finite Heterogeneities", Proceedings of the 2000 IEEE IAS Workshop on Electrical Safety in Industry, New Delhi, April 14-15, 2000, pp. 9-14.

Biographies

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. Nina Mitskevitch was born in Russia, September 1961. She received the M.Sc. degree in Engineering Physics and the Ph.D. degree in Physics from the Moscow University of Technology in 1984 and 1989, respectively. From 1989 to 1995 she worked as a research scientist on projects involving the study of nonlinear effects of electromagnetic wave propagation in wave-guide structures in the Research and Development Institute of Physics in Moscow. In 1997, she joined Safe Engineering Services & technologies ltd. in Montreal, where she is a research scientist in the Analytical R&D Department. Her research interests include analysis of grounding systems in various soil structures. Dr. Mitskevitch is the author of more than 15 papers.