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COMPARISON BETWEEN SIMULATION AND MEASUREMENT OF FREQUENCY DEPENDENT AND TRANSIENT CHARACTERISTICS OF POWER TRANSMISSION LINE GROUNDING

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Abstract – This paper describes application of three different theoretical models for high frequency and transient analysis of grounding systems depending on their complexity. The first two are based on transmission line and the third one on rigorous electromagnetic field theory. The first one is suitable for the simplest single horizontal and vertical ground electrodes, the second one is suitable for more complex arrangements of grounding electrodes, typical for transmission line grounding, and the third one is suitable for arbitrary complex grounding systems. Paper then presents comparison between rigorous and simplified theoretical and experimental results by EDF. Soil ionization was not considered since only low currents were used in the considered experiments.

1 INTRODUCTION

The operational safety and proper functioning of electric power systems is influenced by the proper design of their earth terminations. The design of grounding circuits becomes particularly important in case of power system abnormal operation or lightning. In such cases the grounding systems must be able to discharge impulse currents into the earth without causing any danger to people or damage to installations [1].

In contrast to the grounding systems behavior at low frequencies [2], the high frequency and transient behavior is considerably more complex. This problem has been approached from both theoretical [3]–[17] and experimental [19]–[26] points of view.

Regarding the experimental work, it can be seen that the most systematic measurements have been performed by the Électricité de France (EDF), [21], [23]–[26]. However, only smaller and simpler grounding structures, typical for power line transmission line grounding, were investigated.

Most of the previous theoretical work is based on simplified quasi-static approximation and circuit theory [3]–[12]. More recently, rigorous formulations based on antenna theory, which are derived from the full set of the Maxwell's equations, has been used [13]–[17]. The exact and quasi-static methods, applied to vertical rod electrodes, have been compared in [28], analyzing the limitations of the validity of quasi-static methods.

The dynamical behavior of grounding systems depends on two different physical processes:

- non-linear behavior of soil due to soil ionization in the immediate proximity of the grounding electrodes, and
- propagation of electromagnetic waves along grounding electrodes and in soil.

Soil ionization occurs for large enough currents when the electric fields at the ground electrode surface may become greater than the ionization threshold of approximately 300 kV/m [30]. As a result of this phenomenon, when smaller electrodes are subjected to high current impulses, their ground impedance may be reduced for a factor of 2 or 3 from their low current value, after a short period of time (approximately 5 μs).

The propagation effects are effectively analyzed in frequency domain. Such effects become more dominant in electrically larger and more complicated structures. Buried structures are electrically larger at higher frequencies and in better conducting soil. Therefore, these effects are more important when steep impulses, with higher frequency content, are considered.

This paper firstly describes three different models for high frequency and transient analysis of grounding systems depending on their complexity. The first one is suitable for the simplest: single horizontal and vertical ground electrodes. The second one is suitable for more complex arrangements of grounding electrodes, typical for transmission line grounding. The third one is suitable for arbitrary complex grounding systems. Paper then presents comparison between rigorous and simplified theoretical and experimental results by EDF Soil ionization was not considered since only low currents were used in the considered experiments.

2 SIMULATION OF SINGLE HORIZONTAL AND VERTICAL GROUND ELECTRODES

The complex valued, frequency dependent longitudinal impedance and transversal admittance per unit length are solved in the well-known reference book by Sunde [3]:

$$\underline{Z}'(\omega) \approx \frac{j\omega\mu_0}{2\pi}\ln\frac{1.85}{a\sqrt{\underline{\gamma}^2+\underline{\Gamma}^2}} \tag{1}$$

$$\underline{Y}'(\omega) \approx \frac{\pi(1+j\omega\rho\varepsilon)}{\rho\ln\frac{1.12}{\underline{\gamma}\sqrt{2ah}}} \tag{2}$$

where ℓ and a are length and radius of the electrode, and h is depth of the electrode. Here, the internal impedance of the electrode is neglected. Also here $\underline{\Gamma}(\omega)=\sqrt{j\omega\mu_0(1/\rho+j\omega\varepsilon)}$ describes the propagation of a TEM-wave in homogeneous earth with resistivity ρ, permittivity ε and permeability μ_0.

The characteristic impedance $\underline{Z}_C$ and the propagation coefficient $\underline{\gamma}$ are given by:

$$\underline{Z}_C(\omega)=\sqrt{\underline{Z}'(\omega)/\underline{Y}'(\omega)} \tag{3}$$

$$\underline{\gamma}(\omega)=\sqrt{\underline{Z}'(\omega)\cdot\underline{Y}'(\omega)} \tag{4}$$

The solution of the nonlinear equation (4) for the propagation coefficient leads to the solution of the characteristic impedance (3).

Simple formulas for the characteristic impedance $\underline{Z}_C$ and the propagation coefficient $\underline{\gamma}$ of vertical rod electrodes are [26]:

$$\underline{Z}_C=\frac{\rho}{2\pi}\left(\ln\frac{4\ell}{a}-1\right)\sqrt{\frac{j\omega\mu_0}{\rho(1+j\omega\varepsilon\rho)}}$$

$$\underline{\gamma}=\sqrt{j\omega\mu_0(1/\rho+j\omega\varepsilon)} \tag{5}$$

Corresponding simple formulas for linear horizontal electrodes are:

$$\underline{Z}_C=\frac{\rho}{\pi}\left(\ln\frac{2\ell}{\sqrt{2ah}}-1\right)\sqrt{\frac{j\omega\mu_0}{2\rho(1+j\omega\varepsilon\rho)}}$$

$$\underline{\gamma}=\sqrt{j\omega\mu_0(1/\rho+j\omega\varepsilon)/2} \tag{6}$$

Then, the grounding impedance of the electrode $\underline{Z}$ with length ℓ is obtained by:

$$\underline{Z}=\underline{Z}_C\coth\underline{\gamma}\ell \tag{7}$$

The time domain response is then obtained by application of inverse Fourier transform:

$$v(t)=F^{-1}\{Z(j\omega)\cdot F[i(t)]\} \tag{8}$$

Here $v(t)$ is the response to arbitrary excitation $i(t)$, $Z(j\omega)$ is the impedance to ground (7), and F and F^{-1} are Fourier and inverse Fourier transform, respectively.

3 SIMULATION OF TRANSMISSION LINE GROUNDING SYSTEMS WITHIN EMTP

Once the characteristic impedance and the transfer function of linear earth conductors are known, more complex arrangements of grounding electrodes can be modeled by a network of transmission line segments, provided that coupling between the different grounding electrodes segments can be neglected. At first sight, it is not evident that this assumption is permissible, but it has been shown [12] that the resulting error is within acceptable limits. This approach has great advantage in simultaneous modeling of the grounding system together with live parts of the power electric system components. It is also capable of modeling soil ionization effects. Interested reader may find all details on the model, its implementation within widely used ATP version of *Electromagnetic Transients Program* (EMTP), its validation by comparison with experimental data and its application in practical lightning protection studies in [12]. However, application of this method for more extended and complex substation meshed grounding systems, may lead to erroneous results [18].

4 SIMULATION OF ARBITRARY COMPLEX GROUNDING SYSTEMS

The computational methodology is based on the general method of moments [33]. This methodology is first developed for antennas near to and penetrating the earth, and later it is applied to grounding systems [13]–[15]. More details on modifications of antenna solutions for grounding systems can be found in [32].

The grounding system is assumed to be a network of connected straight cylindrical metallic conductors with arbitrary orientation [15]. The first step is to compute the current distribution, as a response to injected current at arbitrary points on the conductor network. First, the conductor network is divided into a number of fictitious smaller segments. Then axial current distribution in the conductor network $I(\ell)$ is approximated by a linear combination of M expansions functions $F_k(\ell)$ [15]:

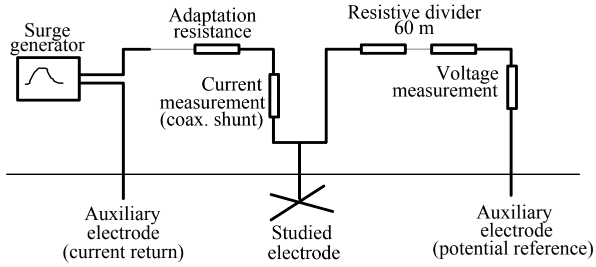

Figure 1: Measuring set-up (adapted from [21]).

$$I(\ell)=\sum_{k=0}^{M} I_k F_k(\ell) \tag{9}$$

where I_k are unknown current samples. Longitudinal current distribution (A1) may be evaluated from the system of equations:

$$[Z]\cdot[I]=[V] \tag{10}$$

where the elements of the column matrix $[I]$ are unknown current samples, elements of $[Z]$ express all mutual electromagnetic interactions between parts of the conductor network, and elements of $[V]$ are related to the excitation. Ref. [15] provides all details on evaluation of the elements of [Z], and [12] give complete derivation of the formulas for the electric field.

When current distribution in the conductor network is known, it is a simple task to evaluate: electric field [12], voltage [15] and impedance [14]. Integration of this method with the EMTP is described in [17].

The advantage of this method in the analysis of larger and more complex substation grounding systems has been demonstrated in [18].

5 FIELD MEASUREMENTS BY EDF

Recordings from extensive field measurements of transient voltages to remote ground performed by the Electricite de France (EDF) are used to verify above described models. Impulse currents have been fed into single- and multi-conductor grounding arrangements and resulting transient voltage to remote ground has been measured by means of a 60 m long ohmic divider with measuring bandwidth of 3 MHz [21].

Figure 1 provides only a simple illustration of the measuring set-up. Surge generator with a peak value of 20 kV was connected to the investigated electrode with a conductor, which was insulated from ground and adapted to the surge generator's characteristic impedance ($Z_c \cong 500\ \Omega$). The resulting current impulses had peak values about 30 A and rise times adjustable from 0.2 to 3 μs. To

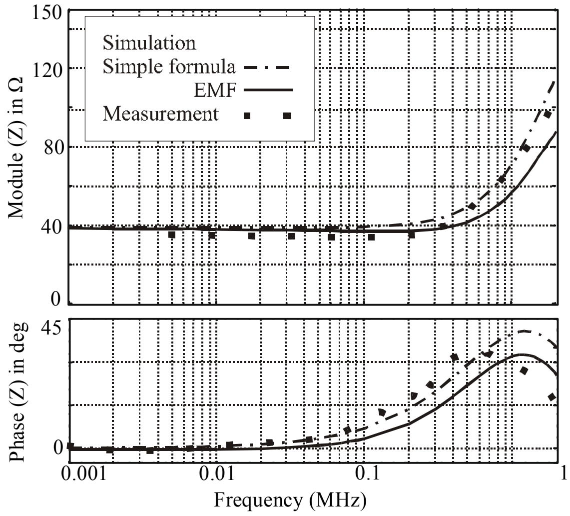

Figure 2: Measurement and simulation of frequency dependent impedance of 16 meters vertical rod electrode.

avoid stationary waves generated on high frequencies, the investigated electrode was connected to the potential reference auxiliary electrode by a voltage divider with high voltage (HV) arm of sufficient length (60 m). The HV arm was composed of a series of ceramic resistances connected to very short connectors. By employing this measuring arrangement a constant transfer function in the measuring bandwidth could be realized. Interested reader is referred to numerous publications by the EDF (for example [21], [23]–[26]) for more details on the measurements.

6 COMPARISON OF SIMULATION AND MEASUREMENT RESULTS

Figure 2 illustrate computed and measured frequency dependent impedance of a vertical rod electrode with length 16 m. The studied earth electrode was constructed of a 50 mm^2 copper cable inserted in holes 62 mm in diameter filled with a mixture of bentonite and water. The semi-liquid mixture coating of the earth electrodes had a resistivity about 1 Ω·m, while the resistivity of the surrounding soil was 1300 Ω·m. However, an average resistivity of equivalent homogeneous medium is set for the simulations to 450 Ω·m to match low current low frequency rod resistance to earth. Also, the soil relative permittivity has not been measured and is set to 10.

The simulations were made using the rigorous electromagnetic field approach (denoted by EMF in Fig. 2) and using the formulas (5). The results show good agreement with the measurements performed by EDF in the whole observed frequency range.

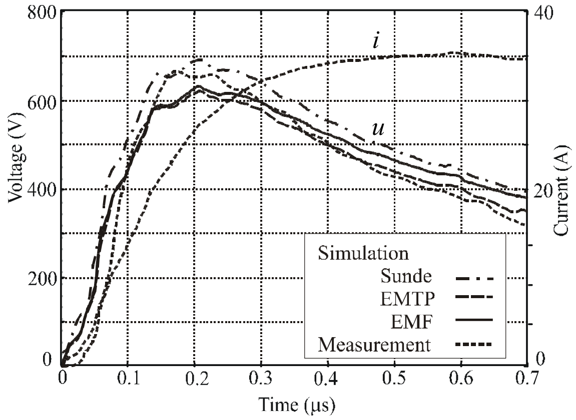

Figure 3: Measurement and simulation of transient voltages to remote ground at the beginning point of 15m long horizontal wire.

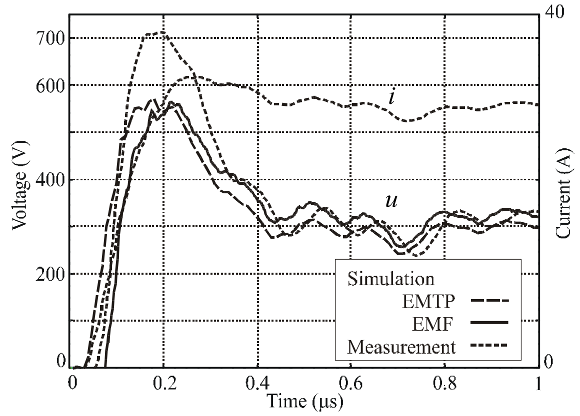

Figure 4: Measurement and simulation of transient voltages to remote ground at the beginning point of 8m long horizontal wire.

Figure 3 shows the oscillograms of recorded current impulse injected in the beginning point of 15 meters long horizontal ground wire and transient voltage to remote ground at the same point on the wire. The electrode was constructed of a 116 mm^2 copper wire buried at 0.6 m depth. The characteristics of the soil were not separately measured at the time of the recording of the oscillograms. Therefore, the soil resistivity was set to 70 Ω·m and the relative permittivity to 15 in [27] and [24], to match low frequency ground resistance. The simulations were made using the rigorous electromagnetic field approach, and using the Sunde's approach (eqs. (1)–(4) and (8)). The results are compared with the EMTP simulation results [12] and with the measurements performed by EDF [27] and [24]. The simulation results show good consistency with the measurements.

Figure 4 shows similar comparison between simulations and measurement for shorter horizontal grounding electrode. The electrode was constructed of a 116 mm^2 copper wire, with 8 m length buried at 0.6 m depth. The characteristics of the soil were not separately measured. The soil resistivity was set to 65 Ω·m and the relative permittivity to 15, to match the low frequency resistance to ground of the electrode. Transient voltages to remote ground were computed using the rigorous electromagnetic field approach, and the results are compared with the EMTP simulation results and with the measurements performed by EDF. Figure 4 shows that there is an agreement between the simulation results except during the current rise when the measured voltage is higher than the corresponding values of the computation.

Figures 5 illustrate comparison between meas-

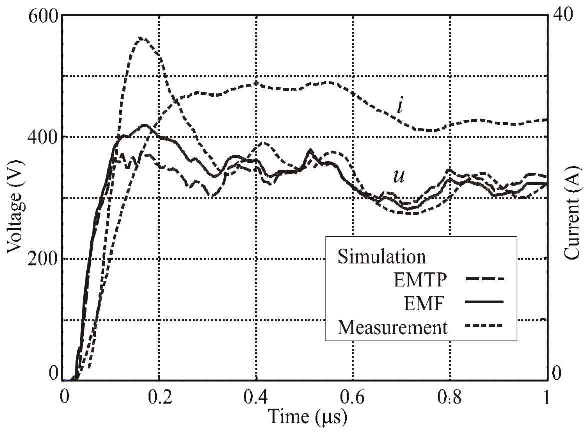

Figure 5: Measurement and simulation of transient voltages to remote ground of double-loop power transmission line tower grounding.

urements and simulation of transient voltages to remote ground of a double-loop grounding. The loops were of 116 mm^2 copper wire with dimensions 1 × 1.5 m^2. The upper loop was buried at 1 m and the lower loop at 2 m depth. Loops were connected with vertical ground conductor at the middle point of the larger loop side. The characteristics of the soil were not separately measured. The soil resistivity was set to 68 Ω·m and the relative permittivity to 15, to match the low frequency resistance to ground. Again, there is an agreement between the simulation results except during the current rise when the measured voltage is higher than the corresponding values of the computation.

The higher measured than computed voltages during the current rise were also observed during validation of the simulation and measurement results at EDF at Paris, France [27] and [24]. It was concluded in [24] that the measured voltages are likely to be amplified by some remaining inductive voltage drop during the wave front along the divider that is added to the actual potential rise at the clamp of the ground conductors. It should be noted that the presented results of the computations are only voltages to neutral ground of points at the surface of the buried conductor. The connecting conductors and the measurement circuit with the 60 m long voltage divider were not included in the simulation.

7 CONCLUSIONS

The comparison between different theoretical methods show that the most adequate for simulation of high frequency and transient performance of power transmission line grounding is method based on transmission line theory. That is especially true for the method that is integrated within EMTP [12], since it is also capable for simulation of the soil ionization effects.

The rigorous method based on the electromagnetic field theory does not have any advantage over more simplified methods for analysis of grounding electrode arrangements typical for power transmission line grounding. This method has clear advantage in the analysis of larger and more complex substation grounding systems [18].

Knowledge of the soil characteristics is critical for successful simulation of the high frequency and transient behavior of grounding systems. However, the necessary soil characteristics are not always measured and have to be estimated, which introduce uncertainty in the comparison.

In some of the analyzed cases, simulated results tend to underestimate the peak values of transient voltages. Further research is necessary to investigate the influence of simplified modeling of the equivalent homogeneous soil at higher frequencies and the influence of the measuring circuit on the measured and simulated results.

In spite of uncertainties in the estimation of the soil parameters, simulations lead to results generally consistent with measured ones.

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REFERENCES

[1] A. P. Meliopoulos, *Power System Grounding and Transients*, New York and Basel: Marsel Dekker, Inc., 1988.

[2] *IEEE Guide for Safety in AC Substation Grounding*, New York: IEEE, 1986, (ANSI/IEEE Std. 80-1986).

[3] E. D. Sunde, *Earth Conduction Effects in Transmission Systems*, New York: Dover Publications, Inc., 1968.

[4] A. C. Liew, M. Darveniza, "Dynamic Model of Impulse Characteristics of Concentrated Earths," *Proceedings on IEE*, Vol. 121, No. 2, February 1974, pp. 123-135.

[5] C. Mazzetti, G. M. Veca, "Impulse Behavior of Grounded Electrodes," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-102, September 1983, pp. 3148-3156.

[6] B. R. Gupta and B. Thapar, "Impulse Impedance of Grounding Grids," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-99, Nov./Dec. 1980, pp. 2357-2362.

[7] R. Verma and D. Mukhedkar, "Fundamental Considerations and Impulse Impedance of Grounding Grids," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-100, March 1981, pp. 1023-1030.

[8] M. Ramamoorty, M. M. B. Narayanan, S. Parameswaran, and D. Mukhedkar, "Transient Performance of Grounding Grids," *IEEE Transactions on Power Delivery*, Vol. PWRD-4, Oct. 1989, pp. 2053-2059.

[9] A. Geri, "Behavior of Grounding Systems Excited by High Impulse Currents: the Model and Its Validation", *Proceedings of the 14th IEEE/PES Transmission and Distribution Conference*, Los Angeles, 1996.

[10] A. P. Meliopoulos and M. G. Moharam, "Transient Analysis of Grounding Systems," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-102, Feb. 1983, pp. 389-399.

[11] A. D. Papalexopoulos and A. P. Meliopoulos, "Frequency Dependent Characteristics of Grounding Systems," *IEEE Transactions on Power Delivery*, Vol. PWRD-2, October 1987, pp. 1073-1081.

[12] F. Menter and L. Grcev, "EMTP-Based Model for Grounding System Analysis," *IEEE Transactions on Power Delivery*, Vol. 9, October

1994, pp. 1838-1849; also in in “*Computer Analysis of Electric Power System Transients: Selected Readings*”, Juan A. Martinez-Velasco, Ed., New York: IEEE Press, 1996, pp. 461-472.

[13] L. Grcev, *Computation of Grounding Systems Transient Impedance*, Ph. D. Thesis, University of Zagreb, Croatia (formerly Yugoslavia), 1986.

[14] L. Grcev and F. Dawalibi, “An Electromagnetic Model for Transients in Grounding Systems,” *IEEE Transactions on Power Delivery*, Vol. PWRD-5, No. 4, October 1990, pp. 1773-1781.

[15] L. Grcev, “Computer Analysis of Transient Voltages in Large Grounding Systems,” *IEEE Transactions on Power Delivery,* Vol. 11, No. 2, April 1996, pp. 815-823.

[16] L. Grcev and M. Heimbach, “Frequency Dependent and Transient Characteristics of Substation Grounding Systems,” *IEEE Transactions on Power Delivery,* Vol. 12, No. 1, January 1997, pp. 172-178.

[17] M. Heimbach and L. Grcev, “Grounding System Analysis in Transients Programs Applying Electromagnetic Field Approach,” *IEEE Transactions on Power Delivery,* Vol. 12, No. 1, January 1997, pp. 186-193.

[18] M. Heimbach and L. Grcev, “Simulation of Grounding Structures within EMTP”, *in Proceedings of the 10th International Symposium on High Voltage Engineering (ISH)*, Montreal, August 1997.

[19] K. Berger, “The Behavior of Earth Connections Under High Intensity Impulse Currents”, *CIGRE Session*, Paris, France, 1946, Report 215.

[20] A. L. Vainer, “Impulse Characteristics of Complex Groundings,” *Electrical Technology in URSS*, Vol. 1, 1966, pp. 107-117 (*Electrichestvo*, No. 3, 1966, pp. 23-27).

[21] R. Fieux, P. Kouteynikoff, and F. Villefranque, “Measurement of the Impulse Response of Groundings to Lightning Currents”, *Proceedings of 15th International Conference on Lightning Protection (ICLP)*, Uppsala, Sweden, 1979.

[22] R. Kosztaluk, M. Loboda, D. Mukhedkar, “Experimental Study of Transient Ground Impedances”, *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-100, No. 11, November 1981, pp. 4653-4660.

[23] Saint-Privat-d’Allier Research Group, “Eight Years of Lightning Experiments at Saint-Privat-d’Allier,” *Review Generale de l’Electricite (RGE)*, Vol. 91, September 1982, pp. 561-582.

[24] H. Rochereau, “Response of Earth Electrodes when Fast Fronted Currents are Flowing Out”, *EDF Bulletin de la Direction des Etudes et Recherches*, serie B, no. 2, 1988, pp. 13-22.

[25] H. Rochereau, “Application of the Transmission Lines Theory and EMTP Program for Modelisation of Grounding Systems in High Frequency Range”, *Collection de notes internes de la Direction des Etudes et Recherches*, 93NR00059, 1993, p.21.

[26] S. Bourg, B. Sacepe, T. Debu, “Deep Earth Electrodes in Highly Resistive Ground: Frequency Behavior”, *Proceedings of the IEEE 1995 International Symposium on Electromagnetic Compatibility*, pp. 584-588.

[27] B. Merheim, "Comparison between Modeling and Measurement of Power System Grounding Dynamic Characteristics", Diploma Thesis, Technical University of Aachen, Germany, 1992.

[28] R. G. Olsen and M. C. Willis, “A Comparison of Exact and Quasi-Static Methods for Evaluating Grounding Systems at High Frequencies,” *IEEE Transactions on Power Delivery*, Vol. 11, No. 2, April 1996, pp. 1071-1081.

[29] S. Ramo, J.H. Whinnery, and T. Van Duzer, *Fields and Waves in Communication Electronics*, New York: Wiley, 1965.

[30] A. M. Mousa, “The Soil Ionization Gradient Associated with Discharge of High Currents into Concentrated Electrodes”, *IEEE/PES 1994 Winter Meeting*, IEEE Paper 94 WM 078-6 PWRD

[31] L. Grcev, “Analysis of the Possibility of Soil Breakdown due to Lightning in Complex and Spacious Grounding Systems,” *Proceedings of 22nd International Conference on Lightning Protection (ICLP)*, Budapest, Hungary, 1994, Paper R 3a-07.

[32] L. Grcev, “Computation of Transient Voltages Near Complex Grounding Systems Caused by Lightning Currents”, *Proceedings of the IEEE 1992 International Symposium on Electromagnetic Compatibility*, 92CH3169-0, pp. 393-400.

[33] R. F. Harrington, *Field Computation by Moment Me*thods, New York: IEEE Press, 1993.

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