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IMPROVED EARTHING SYSTEM DESIGN PRACTICES FOR REDUCTION OF TRANSIENT VOLTAGES

by

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Summary:

Earthing system design practices are usually based on requirements for minimization of power frequency ground resistance and touch and step potentials. However, high frequency performance of the earthing systems is essential for the reduction of transient voltages that may appear at terminals of connected sensitive electronic systems. This paper presents results of ongoing research that suggest some simple improvements of the earthing systems design aimed at better high frequency performance.

Keywords: Earthing – Design – Lightning Protection – High Frequency – Transient – Performance

1. INTRODUCTION

Recent international and national EMC standards require maintaining of immunity margins against transient electromagnetic disturbances in different electronic systems, including computers, telecommunication equipment, control systems, etc. Of special interest is lightning, since it is a high-energy phenomenon, which might affect sensitive electronic systems and cause their malfunction or destruction. The efficiency of the protection against unwanted effects of lightning is strongly influenced by the proper design of the electrical systems' earth termination [1].

Many researchers have dealt with the problem of high frequency and transient behavior of earthing systems, from both theoretical [2]–[19] and experimental [20]–[23] points of view. Linear horizontal and vertical grounding electrodes are analyzed in [2]–[4] and more complex arrangements grounding electrodes of are analyzed in [5]–[19]. The most of these works [2]–[11] are based on quasi-static approximation that limit their applicability to lower frequencies, simple geometry, smaller dimensions or more resistive soil [12]. More recently, formulations derived from the full set of the Maxwell' s equations, based on antenna theory, have been developed [13]–[19]. This rigorous approach surpasses the limitations of the previous more simplified approaches, but is more complicated for use. However, it is apparent that the knowledge on this subject is still fragmentary. As a result there are no clear standardized engineering procedures for proper design of different grounding arrangements for better high frequency and transient behavior.

The primary purpose of the study in this paper was to describe results of ongoing research concerning optimization of the earthing systems design that may lead toward an advance in a formulation of such engineering procedures. The first part of the paper describes simple rules for optimization of simple grounding electrode arrangements, while the second part of the paper deals with more complex grounding arrangements such as grids. However, final optimization presently is possible only by using sophisticated computer software, such as [25]. The use of such software is briefly described in the Appendix.

All results in this paper are obtained by computer simulation using the software package [25], based on the rigorous antenna theory model for high frequency and transient analysis of earthing systems [17]. This approach has been extensively validated by comparison with experimental results by the Électricité de France [20]–[24]. Detailed results of the validation are published in [18] and also in [17] where interested reader may find all details on the model.

Analysis in this paper takes into account frequency dependent behavior and neglects the effects of soil breakdown. For large enough currents the electric fields at the ground electrode surface may become greater than the ionization threshold of approximately 300 kV/m [26], and breakdown of the soil may occur. This will decrease the ground impedance of the electrode. The analysis in this paper considers more conservative upper bound of the ground impedance, when breakdown of the soil has not occurred.

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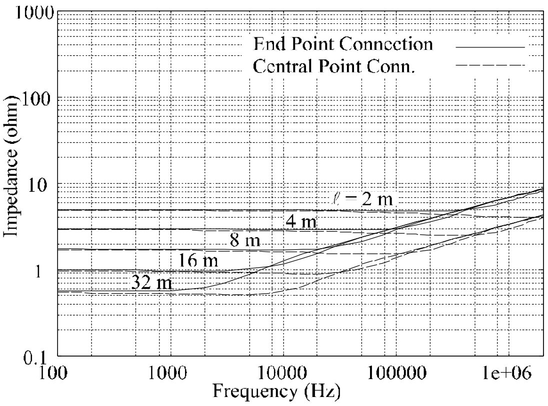
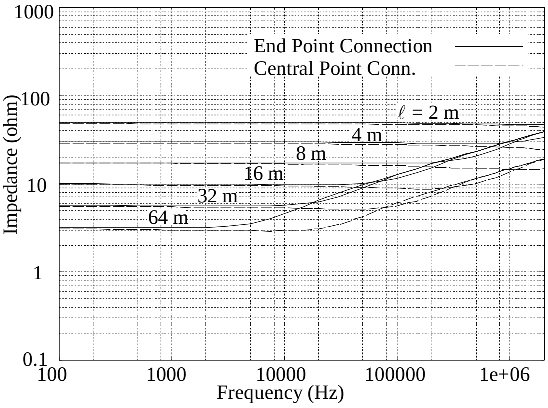
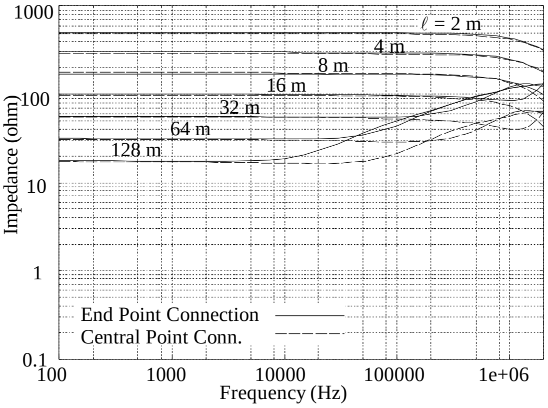


a) ρ = 10 Ω.m



b) ρ = 100 Ω.m



c) ρ = 1000 Ω.m

Fig. 1. Impedance to earth of horizontal linear electrodes of length ℓ buried at 0.5 m depth in soil with resistivity ρ and relative permittivity $\varepsilon_r = 10$.

2. GOAL OF PROPER DESIGN FOR REDUCTION OF TRANSIENT VOLTAGES

The earth termination of the protection against effects of lightning may be constructed by different arrangements of buried conductors, ranging from individual rods or horizontal wires to extended meshed networks of conductors. The primary goal of the corresponding earthing system is to discharge the excessive lightning current impulse into the soil in a very short period of time, ranging in microseconds or milliseconds. During this period, transient processes must not give rise to any danger to the people or any damage to the protected installations. Such goal should be achieved if: the maximal voltage between a point at the earthing system and a point at remote neutral ground, and the voltages between points at and near to the earthing system, are kept below an acceptable limit.

Therefore, proper design procedures should minimize the peak transient voltages on the conductors of the earthing system, for the anticipated worst case of lightning.

3. HIGH FREQUENCY PERFORMANCE OF GROUNDING ELECTRODES

Figure 1 shows results that enable an analysis of the frequency dependent behavior of horizontal grounding electrodes.

From the results in Fig. 1 it can be seen that two frequency ranges may be distinguished: low frequency (LF) range, where the impedance is nearly constant, or frequency independent, and high frequency (HF) range, where impedance is changing with frequency. The limiting frequency of such LF behavior is some characteristic frequency F_c [27]. In observed examples such characteristic frequency F_c is in the kHz range or up to MHz range, depending on the earth resistivity, electrode length and location of energizing point. The characteristic frequency F_c is larger for smaller dimensions of the electrode and larger values of the earth resistivity and for central energizing point.

For frequencies larger than the characteristic frequency F_c, HF ground impedance may be smaller, for example for ℓ from 2-m to 8-m in Fig. 1c, or larger, in all other cases in Fig. 1, than LF ground resistance. Such behavior of grounding electrodes in circuit terms may be specified as capacitive (smaller HF impedance) and inductive (larger HF impedance). Capacitive behavior is highly advantageous since the HF behavior is better than the LF behavior. Unfortunately, such capacitive behavior is typical for electrodes with smaller dimensions and in highly resistive soil, and in nearly all other cases the grounding electrode behavior is inductive.

The grounding electrodes with capacitive behavior have most effective HF performance, while the grounding electrodes with inductive behavior have more effective HF performance if the characteristic frequency F_c is larger.

The position of the energizing point has no effect on the LF performance, however it has very significant influence on the HF performance. The characteristic frequency F_c depends on the distance of the energizing point and the open end point of the electrode and not on the length of the electrode. Consequently, F_c for center driven electrodes is equal to F_c of two times smaller end driven electrode.

Fig. 2 gives the regions of inductive and capacitive behavior of grounding electrode depending from the length and the soil resistivity. Here ”length” is the distance between the energizing and the open end point of the grounding electrode.

4. CRITICAL LENGTH OF GROUNDING ELECTRODES

For every characteristic frequency F_c there is a critical length ℓ_C above which HF impedance is larger than LF impedance [27]. The following formula, based on similar formula in [27], is deducted from the results in Fig. 1:

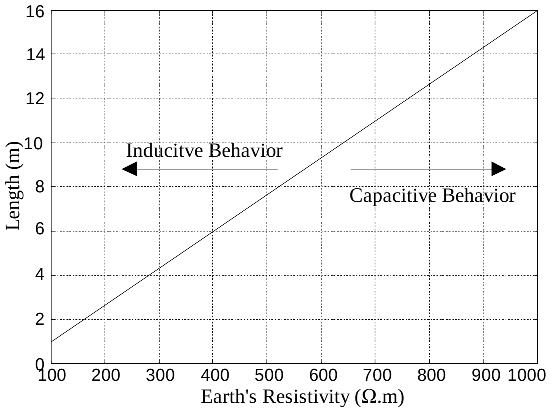


Fig. 2. Regions of inductive and capacitive behavior of grounding electrodes.

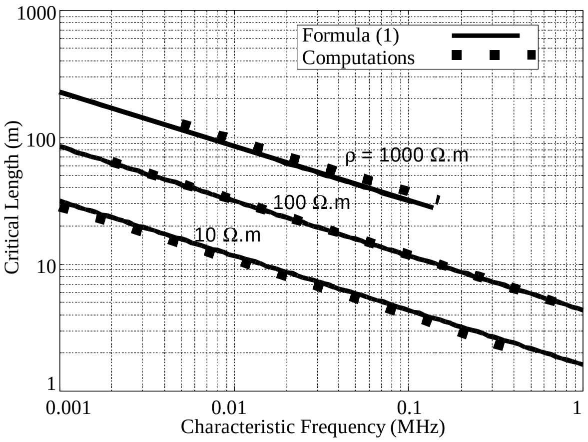
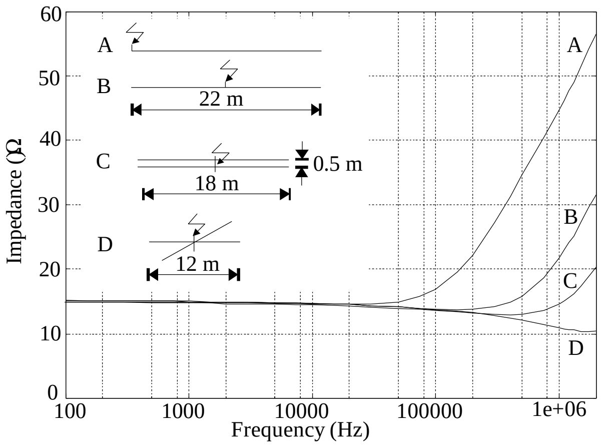


Fig. 3. Critical length of the grounding electrode as a function of characteristic frequency and soil resistivity – comparison between computations in Fig. 1 and formula (1).

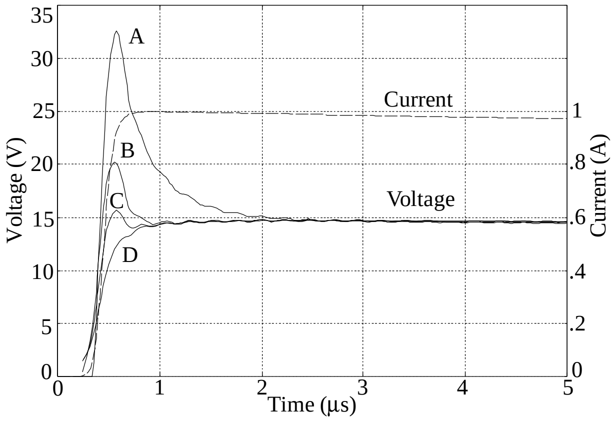
$$\ell_C = 0.6\cdot(\rho/F_C)^{0.43} \tag{1}$$

Another difference between (1) and the formula in [27] is that here ℓ_C is the distance between the energizing point and the open end point of the grounding electrode. Fig. 3 shows comparison between (1) and results of computations presented in Fig. 1.

In most cases the characteristic frequency F_C may be assumed as about 0.1 MHz for lightning first stroke and 1 MHz for return strokes [27].



a) Frequency domain



b) Time domain

Fig. 4. Improvement of the high frequency and transient performance of simple grounding electrode arrangements. (Case A is end-driven and Case B is center-driven 22-m copper wire with 1.4-cm diameter buried at 0.5-m. Case C are two parallel 18-m wires at 0.5-m distance, connected in the center by 1.5-m wire. Case D is four-arm star with 6-m arm and 3-m rod in the center. Soil is with ρ = 200 Ω.m and ε_r = 10. Injected current is T_1/T_2 = 0.25/100 µs return lightning impulse [28]).

5. SIMPLE RULES FOR DESIGN OF GROUNDING ELECTRODE ARRANGEMENTS

It is known that vertical grounding electrodes have similar behavior with for horizontal ones, although, the vertical grounding electrodes are more efficient than the horizontal ones, both in the LF and HF ranges. Therefore, Fig. 2 and (1) may be approximately used for rod electrodes also. Consequently, the following rules are applicable for arrangements of horizontal and vertical electrodes.

Fist choice to achieve for better high frequency and transient behavior is to use grounding electrodes with dominantly capacitive behavior [24]. The region of capacitive behavior may be approximately estimated from Fig. 2 for both horizontal and vertical grounding electrodes. If grounding electrodes with dominantly inductive behavior are used, which is usually the case, their lengths should be smaller than or as near as possible to the critical length for the chosen characteristic impedance. The critical length may be estimated by (1) for chosen characteristic frequency.

The grounding electrode arrangement should be always connected near its middle point and never at its edge point. This is a well-known rule and also obvious from the results in Fig. 2.

In general, as many as possible paths for the current near the connection point should be allowed.

All these rules may be in fact reduced to the following one rule: **High frequency and transient performance is improved by minimizing the length of the current path through the grounding electrodes**.

The application of these rules is illustrated in Fig. 4. To obtain LF ground resistance R = 15 Ω, 22-m horizontal wire is used. However, the worst choice for the transient performance is to connect the wire at the end point (Fig. 4

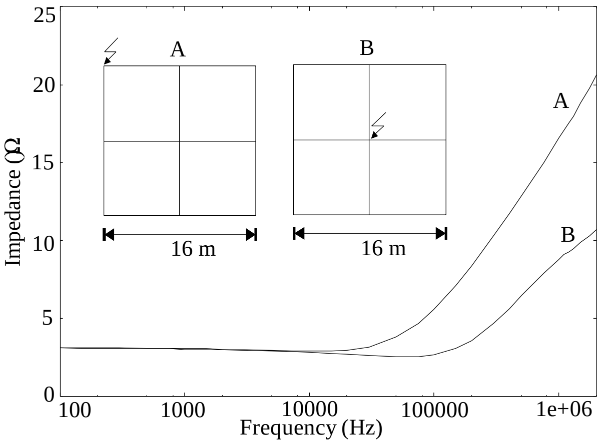


Fig. 5. Improvement of high frequency and transient performance by placement of current feed point away from the edge. (16×16 m^2 grounding grid with 2×2 square 8-m meshes of copper conductor with 1.4-cm diameter buried at 0.5-m in soil with $\rho = 100$ Ω.m and $\varepsilon_r = 10$).

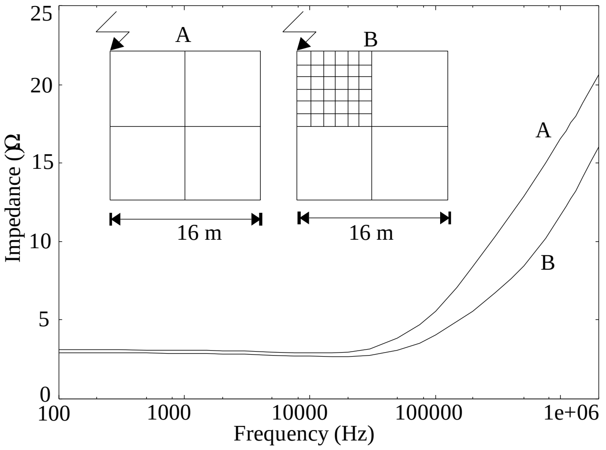


Fig. 6. Improvement of high frequency and transient performance by reduction of conductor separation near current feed point (all dimensions and data are same as in Fig.5).

Case A). Connection at the middle point (Fig. 4 Case B) improves significantly the transient voltages. Case C in Fig. 4 illustrates one possibility to allow additional paths for current. This also reduces the length between the feed point and the open end points of the conductors. Case D, where the length of the electrodes is smaller than the critical length ℓ_C (1), removes transient voltage peak completely. However, better transient performance is achieved at a cost of larger total length of conductors, 37.5 m in Case C and 27 m in Case D compared to 22 m in Cases A and B.

6. OPTIMIZATION OF GROUNDING GRID DESIGN

Previous analysis of transient performance of grounding grids [16] and [19] has revealed that the only two practical ways of improving the transient performance is by placing the current feed point away from the edge (see in Fig. 5), and by reduction of conductor separation near the feed point (see in Fig. 6).

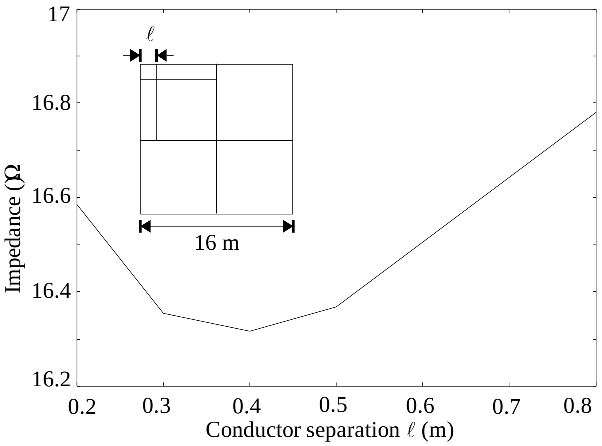


Fig. 7. Optimal conductor separation to minimize impedance at 2-MHz (all dimensions and data are same as in Fig.5).

Results presented in [16] and [17] show large differences of the voltages between points on the grid conductors in the first few microseconds of the transient response. High values of the voltages occur at grid conductors firstly near the injecting point and are further spreading toward the edge of the grid, while the values of the voltages are decreasing. At the time when the maximum of the voltage occurs, the voltage surges have propagated only over a small area around the feed point, so called *the effective area*. During this period there is no interaction with the other parts of the power system. It is clear that minimization of peak value of the voltage impulse at the feed point will lead to accomplishment of the other goal: the minimization of the voltages between points at or near to the earthing system.

Simple rules for improvement of the transient performance does not directly apply to complex arrangements such as grounding grids, and the only way to optimize the design is by means of specialized software, such as [25]. Such optimization process should provide the extent of the effective area and the conductor separation.

The first step is to determine the optimal conductor separation. Figure 7 shows impedance at 2-MHz for different values of conductor separation. As an optimal conductor separation that minimizes impedance 0.4-m may be chosen.

The next step is to investigate the influence of the number of conductors added in the effective area. Figure 8 shows that the largest reduction of the impedance is achieved with two added conductors at optimal separation, while every next addition leads to smaller reduction of the transient impedance.

Figure 9 shows the improvement of the high frequency and transient performance of the analyzed grid by placement of the current feed point at the center and additional conductors with optimal separation near the feed point.

7. CONCLUSIONS

The efficiency of the protection against effects of lightning depends on the electric system earth termination. The proper design of the earthing system should be aimed to prevent any danger to the people and damage to the pro-

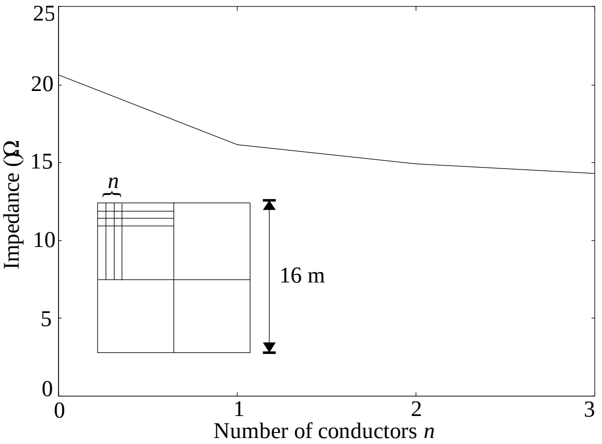


Fig. 8. Reduction of impedance at 2-MHz with addition of 2*n* conductors (all dimensions and data are same as in Fig.5).

tected installations. Such goal should be achieved if the maximal voltages between points at the earthing system and to the ground are kept below an acceptable limit, for the anticipated worst case of lightning.

Generally to reduce transient voltages between points on grounding conductors the lengths of the current paths through the conductors between the feed point and the edge of the grounding system should be minimized. More specifically, for simpler grounding electrode arrangements, the following simple rules should be followed:

- smaller grounding electrodes with dominantly capacitive behavior should be used;
- if that is not possible and grounding electrodes with dominantly inductive behavior have to be used, then their lengths should be smaller than or as near as possible to the critical length for the chosen characteristic impedance;
- current feed point should be placed near the middle point of the grounding system and never at its edge.

Practically the only two ways of improving the transient performance of large meshed grounding systems is by placing the current feed point away from the edge, and by reduction of conductor separation near the feed point.

Recently developed user-friendly software enable an optimization of the earthing system conductors' arrangement concerning the reduction of the transient voltages during an interactive computer session by means of computer graphics and animation.

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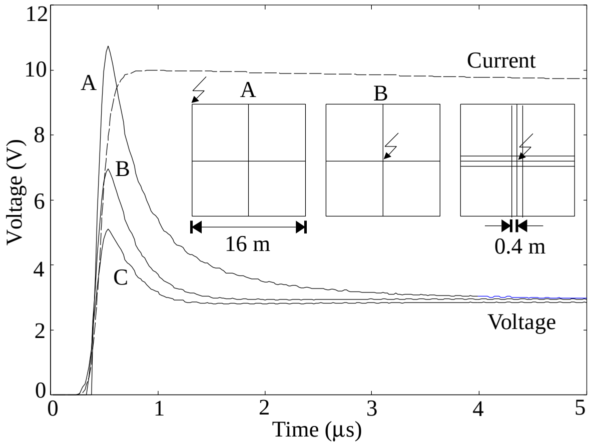

Fig. 9. Reduction of transient voltages on grounding grid (all dimensions and data are same as in Fig.5).

REFERENCES

[1] L. Grcev, "Transient Voltages Coupling to Shielded Cables Connected to Large Substations Earthing Systems due to Lightning," (*1996 CIGRE Session*, Paris, France, Paper 36-201)

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

[3] 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)

[4] 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)

[5] 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)

[6] 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)

[7] 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)

[8] 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, CA, 1996)

[9] 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)

[10] 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)

[11] 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 "Computer Analysis of Electric Power System Transients: Selected Readings," Ed. J. A. Martinez-Velasco, New York: IEEE Press, 1996, pp. 461-472)

[12] 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)

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

[14] L. Grcev and Z. Haznadar, “A novel Approach of Numerical Modeling of Impulse Current Distribution in Grounding Systems,” (Proceedings of 19th International conference on Lighting Protection, Graz, Autria, 1988, pp.165-169)

[15] 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)

[16] L. Grcev, “Transient Performance of Substation Grounding Grids Subjected to Lightning Current Impulse”, (Proceedings of IEEE Stockholm Power Tech International Symposium on Electric Power Engineering, Vol. “High Voltage Technology”, pp. 216-221, IEEE Paper SPT HV 07-06-0671, Stockholm, Sweden, 1995)

[17] 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)

[18] L. Grcev, V. Arnautovski, “Frequency Dependent and Transient Impedance of Grounding Systems: Comparison Between Simulation and Measurement”, (Proceedings of the Second International Symposium: Lightning and Mountains, Chamonix-Mont-Blanc, France, 1997, pp. 239-244)

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

[20] 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, Uppsala, Sweden, 1979)

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

[22] 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)

[23] 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)

[24] 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*, 95CH3577-2, pp. 584-589)

[25] L. Grcev, V. Arnautovski, N. Grcevski, “Software Methods for Analysis of the Efficiency of Different Grounding Arrangements for Lightning Protection”, (Proceedings of the Second International Symposium: Lightning and Mountains, Chamonix-Mont-Blanc, France, 1997, pp. 235-238)

[26] A. M. Mousa, “The Soil Ionization Gradient Associated with Discharge of High Currents into Concentrated Electrodes”, (IEEE Transactions on Power Delivery, Vol. 9, No. 3, July 1994, pp. 1669-1677)

[27] C. Gary, “The Impedance of Horizontally Buried Conductors”, (Proceedings of the First International Symposium: Lightning and Mountains, Chamonix-Mont-Blanc, France, 1994, Paper A6.2, pp. 148-151)

[28] IEC International Standard 1312-1, Protection Against Lightning Electromagnetic Impulse. Part 1: General Principles, 1995.

[29] “CIGRE Guide on Electromagnetic Compatibility in Electric Power Plants and Substations”, CIGRE, Paris, 1998.

APPENDIX

SOFTWARE METHODS FOR OPTIMIZING GROUNDING ELECTRODES ARRANGEMENTS

The optimization of the design of the grounding system to improve its high frequency and transient performance may be completed by simulation during an interactive computer session using the software package, such as [25]. The session may start with an analysis of the initial design of the earthing system. User friendly graphical interface enables definition of the arbitrary geometry of the earthing system by simply drawing on the computer screen. Many of the drawing tasks are automated, such as drawing grids or rods at the edge of the grid. Other parameters are also easily defined via pull-down menus. Potential distributions or voltages between specified points that characterize high frequency and transient behavior of the earthing system may be observed on the computer screen in form of 2D plots or 3D perspectives.

If an improvement of the high frequency or transient behavior is required, the geometry of the earthing system may be easily modified by drawing on the computer screen. By this way, using this “cut-and-try” procedure, one can easily try several modifications of the geometry of the earthing system, while observing the results. Comparison of the corresponding potential and voltage distributions may help in selection of the optimal earthing system arrangement.

Description of available software packages may be found in [29].