Electromagnetic Transients in Large and Complex Grounding Systems

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Abstract - **This paper describes a computer model for simulation of transients in large and complex grounding systems in case of lightning. The grounding system is first modeled by rigorous electromagnetic field theory approach taking into account the frequency-dependence using computational techniques, involving the method of moments and numerical integration of Sommerfeld integrals. Then the model is interfaced to the EMTP, taking into account the interaction between the electric power network and the grounding system. The results of the EMTP analysis are utilized for detailed time-domain evaluation of voltages and currents in elements of the power systems connected to the grounding system. Paper also presents computer model validation by comparisons with measurements and an example of practical lightning protection study.**

Keywords: Electromagnetic Transients, Lightning Protection, Grounding Systems, EMTP, Computer Simulation.

I. INTRODUCTION

Spacious grounding systems with complex configuration of electrodes are often part of the lightning protection system in industrial and power plants. Large currents that flow during a lightning impulse can cause large voltages along control and signal cables placed near grounding systems. These transient voltages may often be a reason for the occurrence of false signals, which may cause malfunction or even destruction of important electronic instrumentation. To determine measures of protection of the instrumentation circuits, lightning protection and electromagnetic compatibility (EMC) studies usually require knowledge of the highest possible elevation of the voltage between the grounding system and the remote neutral earth. At power frequency such potential is a single number, since the grounding systems are usually assumed equipotential. However, in case of lightning or abnormal power system operation, the transient ground potential rise (TGPR) is a complex three-dimensional time-domain function [1].

The first step in the analysis is evaluation of the transient behavior of the grounding system itself. Such analysis was often performed using circuit theory concepts, for example in [2]–[5]. However, all these approaches are based on quasi-static approximation and their validity may be limited to some upper frequency which depends on the size of the grounding system and the electrical characteristics of the earth [6]. More recently, rigorous formulations derived from the full set of the Maxwell's equations are used in [7], [8] and [9].

The second step of the analysis is to model grounding system as a part of the electric power network. The ATP version of the widely used Electromagnetic Transients Program (EMTP) provides proven models for a large number of power system components, but not detailed models of grounding systems. One approach to model frequency-dependent properties of grounding systems within the EMTP is presented in [5]. In order to achieve full electromagnetic approach to the grounding systems, the analysis presented in [9] was interfaced to the EMTP in [10], taking into account the frequency-dependent properties and mutual electromagnetic interactions between parts of the grounding system.

Only a brief description of the underlying computational methodology is presented in this paper. Also the validation of the computer model by comparison with measurements is presented. Finally, an example of a practical lighting protection study is given.

II. THE MATHEMATICAL MODEL

The mathematical model is based on the assumption that the grounding system is a network of straight cylindrical metallic conductors with arbitrary orientation, circular cross section and finite conductivity. The conductors are subject to the thin-wire approximation. The soil is modeled as homogeneous half space with plane boundary, characterized by complex permittivity $\underline{\varepsilon}_1$. First the harmonic excitation is assumed, which yields frequency-domain response of the system.

The complete description of the rigorous electromagnetic approach is given in [8]. The main objective is to evaluate voltages, which necessarily involves determination of the current distribution in the grounding conductors. The model is based on the segmentation of the grounding conductors, which implies the procedures from the moment methods. The electromagnetic interactions between segments is modeled and represented by their mutual impedance. The method of moments enables the reduction of the integral equation to a system of linear equations that may be solved using standard numerical techniques. The effects of the air-soil interference are

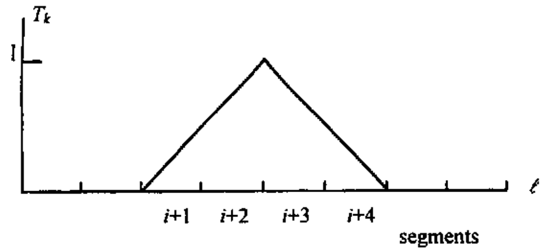

Fig.1a. Triangle expansion function

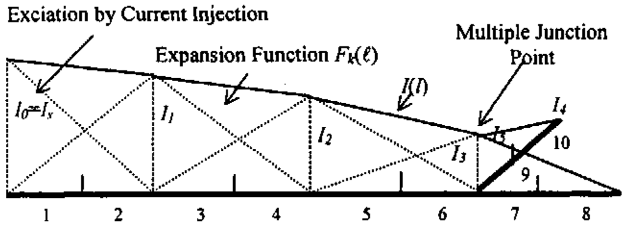

Fig.1b. An Example of the Current Approximation Along Segmented Grounding Conductors

accounted for, which require solution of the Sommerfeld-type integrals.

The first step is to compute the current distribution, as a response to injected current at arbitrary points on the grounding conductors. The axial current distribution in the grounding conductors $I(\ell)$ is approximated by a linear combination of N expansions functions $F_k(\ell)$

$$I(l)=\sum_{k=1}^{N} I_k \cdot F_k(l) \tag{1}$$

where I_k are unknown current coefficients, ℓ is coordinate along conductors axis, and $F_k(\ell)$ are expansion functions of triangle type $F_k(\ell) = T_k(\ell)$, Fig. 1a. These are simple triangle functions of unit height over four consecutive segments, and with value zero over all other segments, Fig. 1a. Successive triangles overlap every two segments except at the ends of the wires, Fig. 1b. Testing functions are also triangle functions $T'_k(\ell)$, but they are located on the wires surfaces instead of the wires axis.

The next step is to solve unknown coefficients I_k in (1) solving the system of N equations. If the excitation current is I_g, the first equation becomes $I_1 = I_g$. The voltage across the i-th segment is a sum of contributions from the currents in all segments. This yields the relation

$$V_i = I_1 z_{i1} + I_2 z_{i2} + \ldots + I_N z_{iN} \tag{2}$$

where z_{mn} are generalized impedances that represent the electromagnetic interaction between the segments. For all segments the relation (2) yields to matrix equation

$$\begin{bmatrix} 1 & 0 & \ldots & 0 \\ z_{21} & z_{22} & \ldots & z_{2N} \\ \vdots & \vdots & \vdots & \vdots \\ z_{N2} & z_{N3} & \ldots & z_{NN} \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} = \begin{bmatrix} I_q \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{3}$$

Extensive number of tests have been performed and all yield well conditioned matrix in (3).

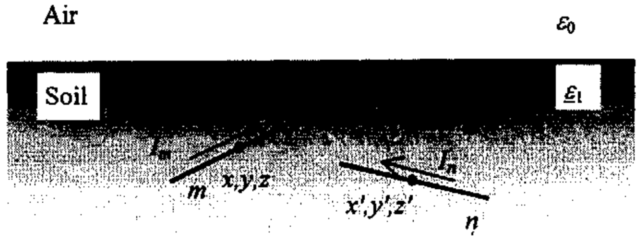

Fig.2. Configuration of two arbitrary current segments

III. EVALUATION OF THE MUTUAL IMPEDANCES

The evaluation of the mutual impedances z_{mn} in (3) is calculated by determining the tangential field at the field current segment surface (segment n) due to a unit current in the axis on the source segment (segment m). Fig. 2. shows simple configuration consisting of two arbitrary oriented current elements, where $\vec{I}_m$ is the source current segment and $\vec{I}_n$ is the field current segment.

The mutual impedance between the two current segments $\vec{I}_m$ and $\vec{I}_n$ is defined as

$$z_{mn} = -\int_n \vec{E}_m \cdot \vec{I}_n dl_n \tag{4}$$

Taking into account the effect of the air-soil interference the mutual impedance is derived by the Sommerfeld formulation. After some mathematical manipulations, the expression for the mutual impedance is

$$z_{mn} = \frac{j\omega\mu_0}{4\pi} \int_n dl_n \int_m dl_m \left[\vec{I}_m \cdot \vec{I}_n P + I_{nz} \left(\frac{dl_m}{dl_m} G_2 - I_{mz} Q \right) \right] + \\ + \frac{1}{j\omega 4\pi\varepsilon_0} \int_n \frac{dl_n}{dl_n} dl_n \int_m dl_m \left[\frac{dl_m}{dl_m} R - I_{mz} G_2 k_1^2 \right] \tag{5}$$

where

$$\underline{\varepsilon} = \underline{\varepsilon}_1 / \varepsilon_0,\ k_1^2 = \omega^2 \mu_0 \underline{\varepsilon}_1 \text{ and } k_0^2 = \omega^2 \mu_0 \varepsilon_0$$

$$P = [G_s - G_i + G_1] \tag{6a}$$

$$Q = -\left[G_3 + \frac{\partial G_2}{\partial z'_A} - G_1 \right] \tag{6b}$$

$$R = [G_s - G_i + \underline{\varepsilon} G_3] \tag{6c}$$

Here, I_{mz} and I_{nz} stand for z-components of the source and field currents.

Notation G_s stands for Green's dyadic function for the electric field of the source current segment, and G_i stands for Green's dyadic function of the image current segment (with respect to interface), for an unbounded medium, suppressing the time-varying exp($j\omega t$) term

$$G_s = \exp(-jk_1 r_1)/r_1, \quad G_i = \exp(-jk_1 r_2)/r_2 \tag{7}$$

where r_1 and r_2 are corresponding distances from the source and image current segment to the field point.

Terms G_1, G_2 and G_3 represent the corresponding correction terms (Sommerfeld-type integrals) which appear in the expressions of the electric field of horizontal and vertical electric dipole in presence of the air-soil interference.

$$G_1 = 2\int_0^\infty \frac{J_0(\lambda\rho)\exp[-\gamma_1(z-z')]}{\gamma_1+\gamma_0}\lambda d\lambda \tag{8a}$$

$$G_2 = \int_0^\infty \frac{\gamma_1-\gamma_0}{k_0^2\gamma_1+k_1^2\gamma_0} J_0(\lambda\rho)\exp[-\gamma_1(z-z')]\lambda d\lambda \tag{8b}$$

$$G_3 = 2\varepsilon_0\int_0^\infty \frac{J_0(\lambda\rho)\exp[-\gamma_1(z-z')]}{\varepsilon_0\gamma_1+\underline{\varepsilon}_1\gamma_0}\lambda d\lambda \tag{8c}$$

with

$$\gamma_1=\sqrt{\lambda^2-k_1^2} \quad \text{and} \quad \gamma_0=\sqrt{\lambda^2-k_0^2}$$

These semi-infinite integrals are integrated numerically.

IV. FREQUENCY-DEPENDENT IMPEDANCES AND INTERFACE TO THE EMTP

The frequency-dependent impedance of a grounding system is defined as

$$Z_{mn}(j\omega)=\frac{V_{mn}(j\omega)}{I_n(j\omega)} \tag{9}$$

where $V_{mn}(j\omega)$ denotes the ground potential rise (GPR) at point m as a response to a steady state current injection $I_n(j\omega)$ at point n. $Z_{nn}(j\omega)$ is the self impedance of the grounding system related to a point n, whereas $Z_{mn}(j\omega)$ represents the mutual impedance between two points: m and n. More details of the procedure for computation of self and mutual impedances are presented in [10].

In transient analyses, however, it is necessary to simulate each element of the electric power system in time-domain. The following technique for rational function approximation permits both the transformation of the frequency-dependent impedances of the grounding system in time-domain and the interfacing with the EMTP.

In order to incorporate self and mutual impedances into the EMTP the frequency-dependent impedances $Z_{mn}(s=j\omega)$ are approximated by rational functions of the following form

$$Z_{mn}(s)\approx Z_{mn,fit}(s)=K\cdot\frac{\prod_{m=1}^{M}(s+z_m)}{\prod_{n=1}^{N}(s+p_n)}=q_0+\sum_{n=1}^{N}\frac{q_n}{s+p_n} \tag{10}$$

Rational functions according to (10) can be incorporated into EMTP without using the inverse Fourier-transform and the storage consuming convolution, which corresponds to multiplication domain. Incorporating the electromagnetic field approach a network according to (3) is implemented into EMTP. After the approximation procedure, self and mutual impedances are passed to the EMTP. Within the EMTP inherent models are used for time domain representation [10] using techniques that reduce the numerical simulation effort drastically.

This approach has been implemented using MODELS in EMTP.

V. COMPARISON WITH MEASUREMENTS

Recordings from extensive field measurements of transient voltages to remote ground performed by the Electricite de France (EDF) are used to verify above described rigorous electromagnetic field model. Impulse

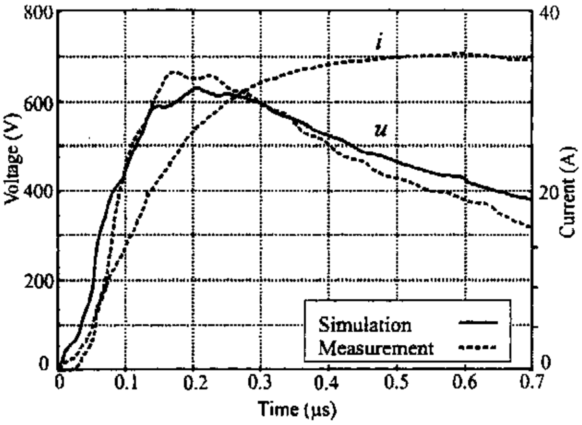

Fig. 3. Measurement and simulation of transient voltages to remote ground at the beginning point of 15m long horizontal wire.

currents have been fed into single- and multi-conductor grounding network 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 [11].

Fig. 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 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 [11], to match low frequency depth. The characteristics of the soil were not separately ground resistance. The simulations were made using the rigorous electromagnetic field approach. The results are compared with the measurements performed by EDF [11]. The simulation results show good consistency with the measurements.

VI. COMPARISON OF DIFFERENT GROUNDING SYSTEM APPROACHES IN EMTP [12]

Important problem that has to be addressed is the accuracy of the modeling of the mutual electromagnetic interactions of the segments of spacious grounding systems with complex geometry. The electromagnetic field approach provides an accurate model of arbitrary grounding systems since simulation is based on the full set of Maxwell's equations. Fig. 4. illustrates transient ground potential rise at a feed point when a surge current (4/20 μs) with a crest value of 1 kA is injected into one end of a 100 m long horizontal electrode with a radius of 10 mm buried in a depth of 0.5 m. The simulations using the approach by Sunde [5], and the electromagnetic field approach interfaced to EMTP [10] show good agreement within the whole displayed frequency range. In time domain, both approaches result in very similar curves representing the results. In Fig. 5. a grounding grid (60 x 60 m^2) consisting of 10 x 10 meshes serves as an example for a complex arrangement. The conductors of radius 7 mm are buried at a depth 0.5 m. Injection position is one corner of the grid. The self impedance by the electromagnetic approach

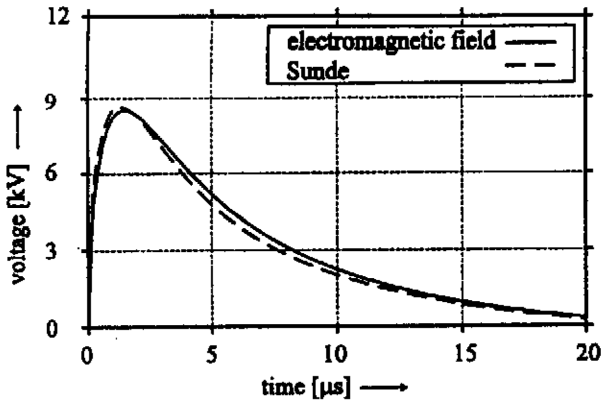

Fig. 4. Comparison of transmission line [5] and electromagnetic field theory approaches [10] for a 100 m long horizontal grounding conductor.

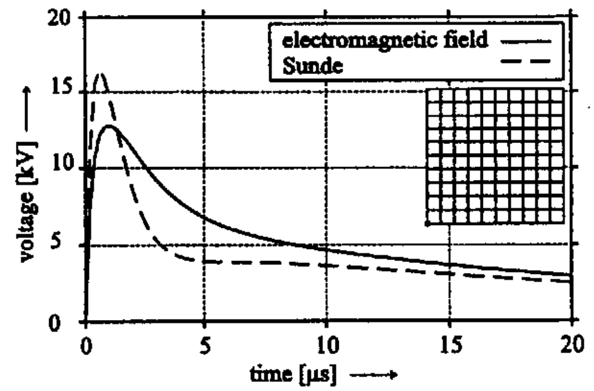

Fig. 5. Comparison of transmission line [5] and electromagnetic field theory approaches [10] for a 60 × 60 m² ground grid with 10 × 10 square meshes.

shows the high influence of the mutual electromagnetic interactions which are neglected leading to strong deviations in the results using the simpler approach which is directly passed to EMTP [5].

VII. PRACTICAL EXAMPLE [1]

A lightning protection study of a 123 kV substation focusing on the TGPR is performed in this chapter. During the transient period mutual coupling between the grounding system and the connected aboveground structures has to be taken into account. In the following the above presented EMTP-based approach is chosen in order to carry out the study. The grounding system of the investigated substation consists of a 60 x 60 m² grid with 6 x 6 meshes, Fig. 6. The copper conductors have a diameter of 14 mm and are buried in a depth of 0.5 m. In order to investigate the influence of the soil parameters on the resulting transients this arrangement is simulated for two different sets of soil parameters. The aboveground electrical components of the substation (voltage transformer, busbar, arrester, and power transformer), as well as the connected overhead transmission line, are modeled within the EMTP and connected to the grounding structure.

A direct lightning stroke hits one phase of the overhead transmission line 300 m before the substation at the phase

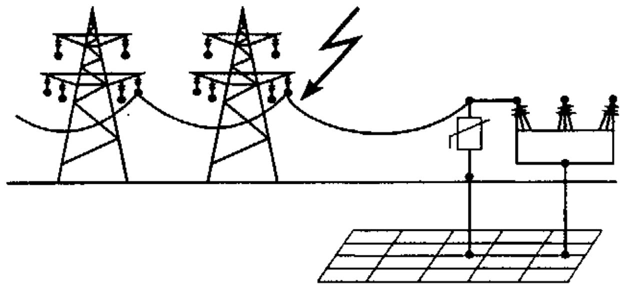

Fig. 6. Lightning Protection Study of a 123 kV Substation.

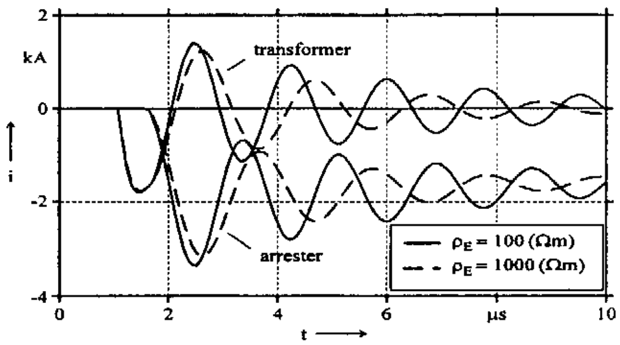

Fig. 7. Injected Current into the Grounding System [1].

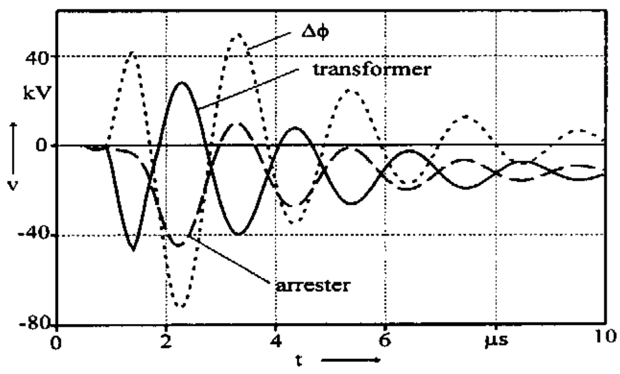

Fig. 8. TGPR at the Arrester and Transformer Connections and the Potential Difference [1].

voltage zero. The lightning stroke has a crest value of -3 kA and an impulse shape (1.2/50 µs). For usual values of the characteristic impedance ($Z_C \approx 370\ \Omega$) a voltage crest value of about 550 kV is expected. It is assumed that a flashover to towers does not occur.

The computed currents injected into the grounding system due to the lightning stroke at the arrester's and the transformer's connection to the grounding system are displayed in Fig. 7., for both sets of soil parameters. After 10 µs the currents approach their DC-distribution. The first transients last the longer the higher soil conductivity is. Additionally both sets of soil parameters produce different transient frequencies: f ≈ 650 kHz in case of ρ_E = 100 Ωm and f ≈ 570 kHz in case of ρ_E = 1000 Ωm, respectively. Comparing self impedances at the feeding points for different soil conductivities it becomes obvious, that for the same grid the imaginary (inductive) part of the self impedances is greater for poorly conductive soil. This means, that the resulting inductivity of the circuit consisting of the surge capacity of the transformer, the inductivity of the busbar and the self impedance of the grounding system related to both feeding points for greater for poorly conductive soil leading to smaller natural frequency of the resulting RLC-circuit. The impact of the coupling between the feeding points, can be neglected in a first approximation due to the limited effective area in the frequency range of the transients.

Fig. 8. presents TGPR at the arrester and transformer connections to the grounding system. Their oscillation is damped toward the even dc distribution, but is mutually in counter-phase. This results in large potential difference $\Delta\phi$ (Fig. 8.) between arrester and transformer connection points during the first few oscillations.

VIII. CONCLUSION

Paper presents integration of the rigorous model for analysis of transients in complex and spacious grounding systems, based on electromagnetic field theory approach, with the EMTP. Advantage of this approach is that frequency dependence and electromagnetic interactions between the parts of the system are rigorously modeled together with the interactions between the grounding system and various components of the power network. This enables computations of overvoltages throughout the electric power system and detailed analysis of the TGPR of large substation grounding system.

IX. ACKNOWLEDGMENT

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