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Grounding Systems Modeling for High Frequencies and Transients: Some Fundamental Considerations

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***Abstract*—In spite of large amount of research work in the last decades on the grounding systems modeling for high frequencies and transients there is no consensus on its practical applicability. This paper points to some issues that may be important in the systematic approach to determine the validity domains of the different existing methods for analysis. In particular, following topics are discussed: the evaluation of the upper frequency of interest in the transient study, the limitations due to the electrical dimensions of the system, and due to the underlying circuit concepts, especially in relation to the definition of impedance to ground. As a basis for the evaluation of the validity domains of more simplified quasi-static and circuit based models a full-wave electromagnetic model is described. Validation by comparison with experiment and illustrative numerical results are presented.**

***Index Terms*—Modeling, Grounding electrodes, Transient analysis, Electromagnetic analysis, Frequency domain analysis, Equivalent circuits.**

I. INTRODUCTION

MODELING of grounding systems for high frequencies and transients, according to a number of recent publications (e.g. [1-20]), attracts considerable interest among different research groups. Such interest stems from a number of actual problems, to name a few: radio base stations in HV towers [21], lightning protection of wind turbines [22], power quality [23], but also from problems of longer-term interest, some of which are: EMC in power plants and substations [24], transients in GIS substations [25], and especially lightning protection of the power lines, the residential buildings and the critical installations [26,27,28]. Contrary to the great number of simulation oriented papers, there is a great deficiency of carefully documented papers on experimental works of which noteworthy examples are [27] and [29-32].

A survey of above literature might leave a novice reader in confusion over the diversity of approaches to modeling, interpretation of the results and validation. Although the simple classification of the approaches might be in only three groups:

- electromagnetic field theory methods [2,3,5,6,7,17,19],
- circuit theory methods (including distributed parameter circuits) [4,8,11,12,13,14,15,16,18], and
- hybrid methods (that combine the previous two) [1,9,10,20],

that would not help in clarification of the models mutual standing. A usual assumption is that the electromagnetic field theory models are based on least neglects and that circuit models are constrained by approximations, but there is a lack of systematic approach that validates different models' capabilities and their applicability domains.

This paper points to some issues that may be important in the process of paving the way for more systematic approach to grounding systems modeling.

II. UPPER FREQUENCY LIMIT FOR MODEL APPLICATION

One of the important fundamental steps in the transient analysis of grounding systems is to determine the highest frequency of interest and to check if the model is applicable in the required frequency range. Practically, there is a frequency limit of the model applicability even for the so-called "full-wave" electromagnetic field models due to unavoidable approximations in the physical model, numerical procedures and limited computer resources. However, such limit is of more importance in more simplified models based on quasi-static approximation. Unwanted case is when such upper frequency limit is lower than the necessary frequencies in the transient study, which might result in application of the model out of its validity domain.

Transients are often related to lightning and in such case a common misconception is that the highest frequency of interest might be determined only by the highest appreciable frequency components of the excitation lightning current waves [33]. It is of course clear that the lightning current wave shape basically influence the highest frequency of interest. One example is given in Fig. 1, which shows two lightning current wave shapes suggested in IEC Standard [34]. The 'subsequent stroke' has higher frequency content than the 'first stroke' wave shape (Fig. 1) due to its faster rise.

However, the upper frequency limit should be also deter-

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mined by the frequency content of the response. For example, usually the sought response is voltage to ground, which is usually needed for determination of the impedance to ground. The problem is that the response is usually not known in advance, and the determination of the upper frequency limit might require trial computations until convergence of results is reached.

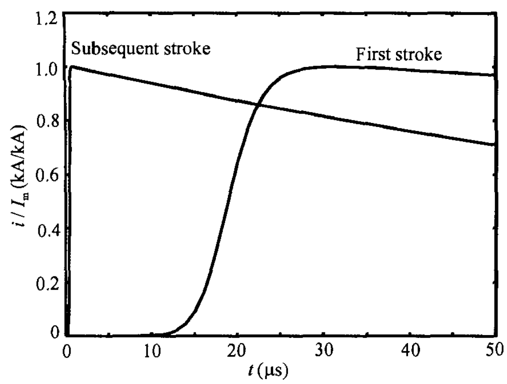

Fig. 1. Two lightning current wave shapes suggested in IEC Standard [34] – normalized to their maximum values (First stroke: T_1 / T_2 = 10-μs / 350-μs; Subsequent stroke: T_1 / T_2 = 0.25-μs / 100-μs)

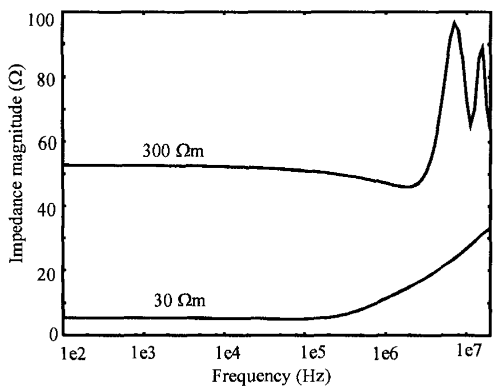

Fig. 2. Harmonic impedance to ground of a 6-m vertical rod in soil with resistivity 30 Ωm and 300 Ωm

We will confine our discussion to the frequency domain approach, that usually uses Fourier or Laplace transforms for the transformation of the solution to the time domain. As an example, Fig. 2 shows the magnitude of the harmonic impedance to ground of a 6-m long vertical rod in a 'conductive' soil with resistivity 30-Ω and in a 'resistive' soil with resitivity 300-Ωm[1]. Figure 2 shows typical frequency independent behavior in the 'lower frequency' region and frequency dependent behavior in the 'higher frequency' region. Please note that in the examples in this paper the breakdown phenomena in the soil related to high intensity currents are not taken into account.

Figure 3 shows results of computation of the voltage to ground at the feed point of the 6-m vertical rod when 'subsequent stroke' current pulse with a peak value of about 11 kA is fed at the upper end of the rod. Discrete Fourier and Inverse Fourier techniques were applied to compute the voltage as response to injected current pulse [6]. Figure 3-a gives results in a soil with resistivity 30-Ω and Fig. 3-b in a soil with resistivity 300-Ωm. For the case in Fig. 2-a a reasonable convergence of results was achieved with a frequency range up to 8 MHz, while for the case in Fig. 2-b, 16 MHz was required. So the frequency range necessary to accomplish the computations determined the upper frequency limit.

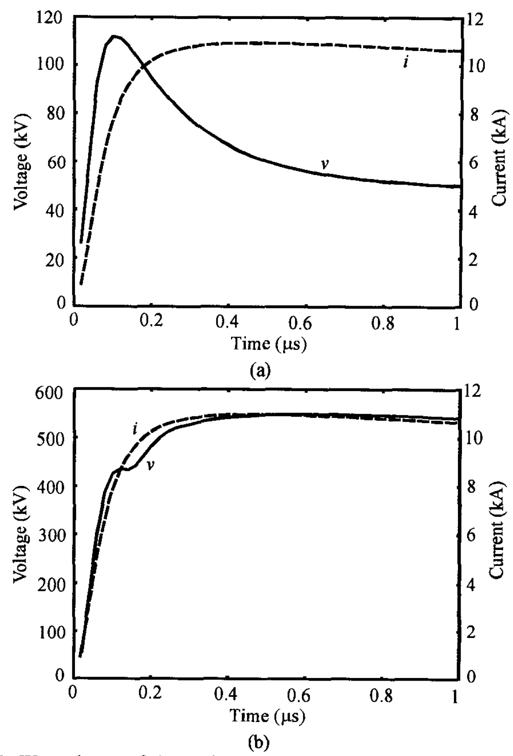

Fig. 3. Wave-shapes of the excitation (current i – broken line) and the response (voltage to ground v – solid line); (a) 6-m rod in 30-Ωm soil; (b) 6-m rod in 300-Ωm soil

III. The Electrical Dimensions Limit

The estimated highest frequency enables to determine the electric dimensions of the system. These are dimensions measured in wavelengths in the ground for the highest frequency. In [7] a criterion for application of quasi-static approximation is established for the system dimensions to be less or equal to one tenth of the wavelength in soil for the highest frequency.

As it is well known the wavelength in ground λ may be much smaller than the corresponding in air, depending on ground electrical parameters (σ – conductivity, ε – permittivity and μ – permeability) [36]:

$$\lambda = \frac{2\pi}{\beta}, \quad \beta = \omega\sqrt{\mu\varepsilon}\left\{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right]\right\}^{1/2} \qquad (1)$$

[1] The value of the relative permittivity of the soil ε_r = 10 was assumed in all examples, unless stated otherwise.

Here, $\omega = 2\pi f$, f being the frequency. As an example, Fig. 4 gives wavelengths in soil for different frequencies and soil resistivities.

If for example we look at the computations illustrated in Fig. 3a and 3b, we can see that the wavelengths for the highest frequencies used are just less than the length of the rod (5.7 m and 5.8 m, respectively). Consequently, the criterion [7] for the application of the quasi-static approximation in the examples in Fig. 3a and 3b is not fulfilled.

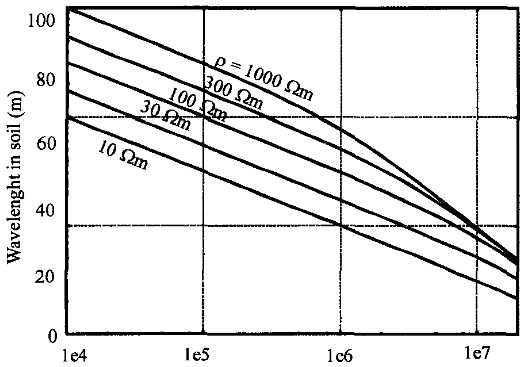

Fig. 4. Wavelengths in soil with different resistivities (ρ)

IV. Problems Related to the Definition of the Impedance to Ground

The grounding systems analysis is inherently linked to the circuit based methods of power system analysis. As it is well known, above ground circuit models with either concentrated or distributed parameters are often applied for modeling the power system elements. However, as mentioned in Section III, bellow ground wavelength is smaller than in the air for the same frequency, making the application of circuit concepts bellow ground questionable.

The quantity used to characterize grounding system behavior is the impedance to ground. The concept of impedance is widely used but its original definition and limitations are often forgotten. It is originally defined for sinusoidal time variations, and generally applies between closely spaced terminals [42]. In grounding analysis at 50/60 Hz static approximation is usually applied and resistance to ground is defined between infinitely distant points, one at the grounding system and the other at remote neutral ground, theoretically at infinity. Problems may arise when this concept is directly transferred to high frequencies.

Classical circuit point of view is that the given system consists of components whose individual behavior and mutual interactions can be completely specified in terms of their terminal voltages and currents [37]. Fig. 5 illustrates an electromagnetic system enclosed by a surface S connected to energy sources and other systems by current carrying wires. Terminal voltages can be defined in a consistent manner at the points at which the wires pierce the surface S as scalar potentials defined on S. In other words, the line integral of the electric field vector between any two points on S have to be, to a reasonable degree of approximation, independent of the path of integration as long the path lies on S [37]. These requirements result from the circuit theory definition of power and its relation to Poynting's theorem.

Therefore, one should carefully examine if the approximations inherent in the circuit approach are justified in the specific analyzed case. The important aspect is path-dependence of the voltage at higher frequencies that might prevent unique definition of impedance to ground.

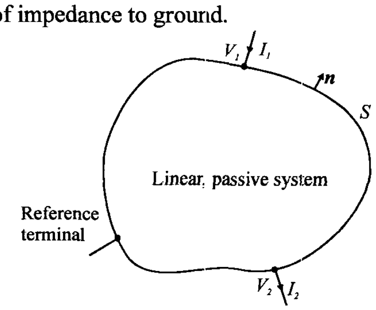

Fig. 5. Terminal voltages and currents from a classical circuit point of view (adapted from [37])

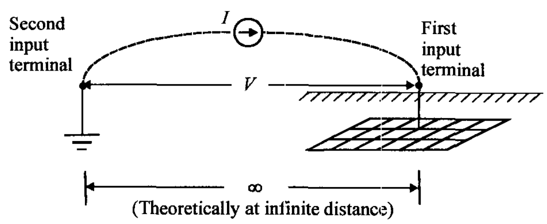

Fig. 6. The current and the voltage required for the definition of the impedance

Figure 6 illustrates the considered situation of a grounding system. When the impedance to ground related to the feed point is defined, the grounding systems are considered as detached from the rest of the system. The excitation of the grounding system may be represented by a current source with one terminal connected to the grounding system and the other at infinity. The influence of the current source connecting leads is ignored. Voltage between the terminals is required for the definition of the impedance (Fig. 6).

This approach is directly related to the static analysis where the voltage between any two points is uniquely defined. However, the voltage at high frequencies (of interest in lightning related studies) might be path-dependent. This is illustrated in the following example in Fig. 7.

Current surge, related to the lightning 'subsequent stroke' (Fig. 1) is fed at the corner point of 60 x 60 m^2 grounding grid with 6 by 6 10 m square meshes buried at 0.8 m depth in soil with $\rho = 1000\ \Omega m$ and $\varepsilon_r = 9$. Voltage between points 1 and 3 is computed. Two alternative paths are considered, one following the grounding grid conductors (1-2-3) and the other going directly between points 1 and 3 (1-3). Such voltage may be expressed as sum of two terms:

$$V_T = \Delta\Phi + V_\ell \tag{2}$$

where $\Delta\Phi$ is scalar potential difference, and is uniquely defined between points 1 and 3, and V_ℓ is path dependent term due to time-varying field. Fig. 7 illustrates the total value and the both components of the transient voltage, for the two paths.

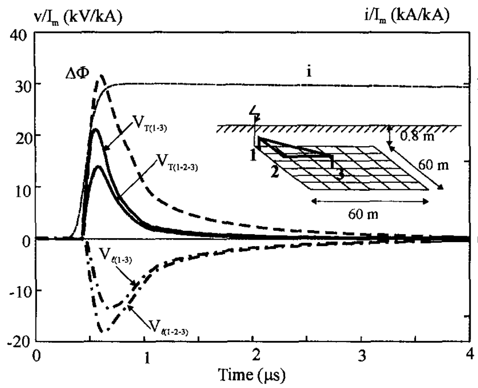

Fig. 7. Transient voltages along different paths between points 1 and 3 at 60 × 60 m^2 grounding grid with 6 by 6 10 m square meshes [24]

It is shown that the effects of the potential difference, in this example, are partially canceled by the induced field. Such effect is larger when the path is along the ground grid conductors (1-2-3) in comparison with path (1-3) resulting in smaller total transient voltage.

This stresses the importance of careful examination of the influence of the voltage path dependence on the definition of the impedance to ground.

V. Electromagnetic Model of Grounding Systems

Model that may be considered with least neglects is the electromagnetic field model. It was first described in [38], following principles developed in antenna theory [39]. To point to the simplifications adopted in more approximate models we will shortly describe the basis of the electromagnetic model.

The solution is in frequency domain and the impulse response is obtained by application of the Fourier or Laplace transform techniques, which imply linear medium. It is based upon the exact solution of the electromagnetic fields due to an electric dipole in lossy half-space [40]. Applying thin-wire approximation the current distribution in the grounding system electrodes may be represented by a distribution of current and charge at the axes of the electrodes. Fulfillment of the boundary conditions at the grounding electrodes surface for harmonic excitation yields the mathematical model.

For simplicity we will consider a horizontal electrode in x direction. In the moment of method solution the electrode is divided in segments with length ℓ [41]. The x-component of the electric field vector at the surface of the segment due to current $I(x')$ and charge $q(x')$ along the axis of the electrode may be expressed in terms of magnetic vector potential $A_x(x)$, and electric scalar potential $\phi(x)$:

$$E(x) = -\frac{\partial}{\partial x}\phi(x) - j\omega A_x(x) \tag{3}$$

where

$$\phi(x) = \int_\ell G_\phi(x,x')q(x')dx' \tag{4}$$

$$A_x(x) = \int_\ell G_{xx}^A(x,x')\cdot I(x')dx' \tag{5}$$

$$q = \frac{-1}{j\omega}\frac{dI}{dx'} \tag{6}$$

Here, G_ϕ is the Green's function of the scalar potential and G_{xx}^A is the component of the dyadic Green's function of the magnetic vector potential:

$$G_\phi = \frac{1}{4\pi\underline{\varepsilon}}\left\{G_{11} + \frac{k_1^2 - k_0^2}{k_1^2 + k_0^2}G_{12} + k_1^2 V_{11}'\right\} \tag{7}$$

$$G_{XX}^A = \frac{\mu_0}{4\pi}\{G_{11} + W_{11}\} \tag{8}$$

$$G_{11} = \exp(-jk_1r_1)/r_1,\ G_{12} = \exp(-jk_1r_2)/r_2 \tag{9}$$

where r_1 and r_2 are distances from source point at the segment axis and the image point above the ground to the point at the segment surface. Here also:

$$k_0^2 = \omega^2\mu_0\varepsilon_0,\quad k_1^2 = \omega^2\mu_0\underline{\varepsilon}$$

$$\underline{\varepsilon} = \varepsilon - j\sigma/\omega,\quad \gamma_1 = \sqrt{\lambda^2 - k_1^2},\quad \gamma_0 = \sqrt{\lambda^2 - k_0^2}\,.$$

Terms W_{11} and V'_{11} in (7) and (8) are obtained by Sommerfeld integrals:

$$V_{11}' = S_0\{\tilde{V}_{11}'\} = S_0\{\frac{2k_1^2}{k_0^2 + k_1^2}\frac{\gamma_1 - \gamma_0}{k_0^2\gamma_1 + k_1^2\gamma_0}\frac{1}{\gamma_1}\exp[-\gamma_1|z + z'|]\} \tag{10}$$

$$W_{11} = S_0\{\tilde{W}_{11}\} = S_0\{\frac{\gamma_1 - \gamma_0}{\gamma_1 + \gamma_0}\frac{1}{\gamma_1}\exp[-\gamma_1|z + z'|]\} \tag{11}$$

$$S_0\{\tilde{g}(\lambda)\} = \int_0^\infty \tilde{g}(\lambda)J_0(\lambda\rho)\lambda d\lambda\,. \tag{12}$$

where J_0 denotes Bessel function of first kind and zero order.

Applying classical moment method techniques [41], the generalized impedance matrix may be constructed using (3):

$$Z_{mn} = -E_m\cdot\ell_m/I_n \tag{13}$$

where subscripts m and n denote segment numbers and E_m is the tangential field at the central point at the surface of the segment m due to constant current I_n in the axis of the segment n. Then the unknown current distribution $[I]$ may be determined by solution of the matrix equation:

$$[Z]\cdot[I] = [Z_S I_S] \tag{14}$$

where $[Z]$ is generalized impedance matrix and $[Z_S I_S]$ is excitation matrix where I_S is current injected at a point in the grounding electrode and Z_S is impedances between the injection segment and other segments [6].

When the current distribution is known we can compute the scalar potential at the injection point V_S and the impedance to ground related to injection point may be determined:

$$Z_g = \frac{V_S}{I_S} = \frac{1}{I_S}[I]\cdot[Z_s] = [Z]^{-1}\cdot[Z']\cdot[Z_s] \quad (15)$$

By this way mutual electromagnetic interaction between parts of the grounding system and the influence of the earth's surface are taken rigorously into account. This rigorous approach may be further applied to compute fields, potentials and voltages [2].

VI. Some Simplifications

The complexity of the electromagnetic model stresses the importance of reliable simplified models. Following are some of the usual simplifications. These greatly simplify the mathematical model in Section V, however systematic analysis of the validity domain of such simplifications has not been performed so far.

A. Image theory

Image theory disregards Sommerfeld's integrals in (7) and (8). Electrostatic image theory is used in all circuit models, which modifies (7) into:

$$G_\phi = \frac{1}{4\pi\underline{\varepsilon}}\{G_{11} + G_{12}\} \quad (16)$$

Modified image theory use instead:

$$G_\phi = \frac{1}{4\pi\underline{\varepsilon}}\left\{G_{11} + \frac{k_1^2 - k_0^2}{k_1^2 + k_0^2}G_{12}\right\} \quad (17)$$

B. Quasi-static approximation

Quasi-static approximation disregards the propagation effects and instead of (9) use:

$$G_{11} = 1/r_1, \quad G_{12} = 1/r_2 \quad (18)$$

C. Decoupling of the electric and magnetic field

Circuit and some hybrid models are based on decoupled electric and magnetic fields, considering charges as sources of electric field and currents as sources of magnetic field.

D. Analogy with static field

The circuit parameters are usually determined based on static analysis based on analogy of high-frequency field with the static one.

VII. On Comparisons between Electromagnetic and Circuit Models

In this section we present as an example some comparisons between the electromagnetic and simplified models. More work is necessary for detailed and systematic comparison between different existing models.

Figure 8 shows transient voltage to remote ground at three points 'A', 'B' and 'C' in 60 x 60 m^2 grid with 10 m long ground rods at the corners, subjected to T_1/T_2 = 1 μs/20 μs with 1 kA crest current pulse injected at the point 'A' [6]. Electromagnetic [6] and hybrid-circuit model [1] are compared. Relatively good agreement is reached for the transient voltages at the feeding point. On the other side, hybrid-circuit model [1] tends to largely overestimate voltages at the edge points B and C of the grid in comparison with the electromagnetic model.

Another example is shown in Fig. 9. Circuit model [13] is compared with the electromagnetic model [6] for the computation of scalar potentials along a profile at the earth's surface above the illustrated grounding system. The results at 50 Hz are in good agreement; while at 100 kHz circuit model largely overestimate the results. It could be expected that at 1 MHz this discrepancy of the results would be considerable larger.

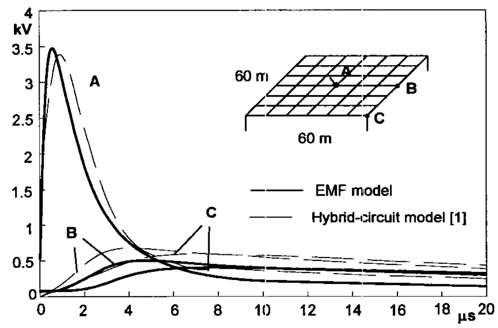

Fig. 8. Transient voltage response of 60m × 60m grounding grid to a 1/20 μs 1 kA current impulse [6]

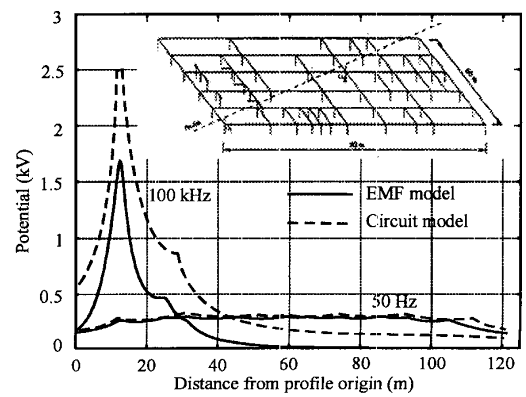

Fig. 9. Comparison of the potential distribution along a profile at the earth's surface computed by circuit [13] and electromagnetic [6] models

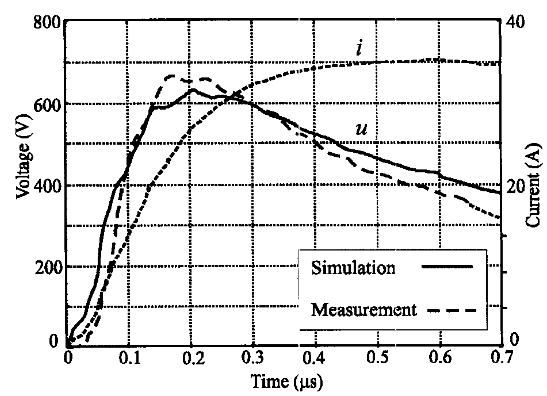

Fig. 10. Measurement and simulation of transient voltages to remote ground at the beginning point of 15-m long horizontal wire.

VIII. Model Validation by Experiment

The most important step in model development is its validation and comparison with experimental results is crucial for this task.

As a example, Fig. 10 shows the oscillograms of the recorded current pulse injected at the end point of 15 meters horizontal ground wire and transient voltage to remote ground at the same point [13,17]. The simulation results show good consistency with the measurements.

However, more work is necessary for experimental characterization of the high frequency and transient behavior of more complex grounding electrode arrangements. This could be of crucial importance in the effort to establish the validity domains of different simulation models and determine their practical applicability.

IX. Conclusions

Recently a number of simulation models for grounding systems at high frequencies and transients have been described. However, there is no consensus on the practical applicability of different approaches, interpretations of results and their validation. On the other side, there is a deficiency in reliable carefully documented experimental data suitable for model validation.

The need for simplified circuit based models stems from the necessity to interface them with the power system circuit based analysis methods. On the other hand, it also stems from the complexity of the electromagnetic field models. However, it is most important to determine the validity domains of the simplified models, taking into account, highest frequency, dimensions, electromagnetic characteristic of the soil, and limitations of the circuit concepts. Considering a systematic approach to determine the validity domains of different models, following conclusions could be drawn.

First important step is evaluation of the upper frequency needed in the transient study. This upper frequency cannot be evaluated solely from the analysis of the frequency content of time functions, but is also dependent on the computational techniques. Frequency range necessary to accomplish the computations might determine the upper frequency limit.

A criterion for application of the quasi-static approximation requires that dimensions of the grounding system are less than one tenth of the wavelength in soil for the highest frequency. When the upper frequency is estimated applicability of simplified models might be checked.

Impedance to ground is usually used for characterization of the grounding systems at high frequencies and transients. Uniquely defined impedance requires uniquely defined voltage between the feed point and remote neutral earth. Since the voltage at high frequencies is path dependent careful examination of the influence of this effect on the definition of the impedance to ground is required.

The rigorous full-wave electromagnetic field model is based on least possible neglects. It may be considered as a starting point for evaluation of the validity domains of other more simplified models.

One conclusion from the comparisons between the electromagnetic and circuit based models is that circuit models overestimate computed fields, potentials and voltages in the grounding systems vicinity.

The most important step in model development is its validation and comparison with experimental results is crucial for this task. More work is required to provide carefully developed and documented experiments that would be basis for validation and evaluation of applicability domains of simulation models.

X. Acknowledgment

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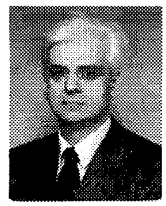
XII. BIOGRAPHIES



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