Grounding System Analysis in Transients Programs Applying Electromagnetic Field Approach

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***Abstract*—Lightning protection studies of substations and power systems require knowledge of the dynamic behavior of large grounding grids during electromagnetic transients. This paper presents strategies which allow to incorporate complex grounding structures computed using a rigorous electromagnetic model in transients programs. A novel technique for rational function representation of frequency-dependent grounding system impedances in the EMTP is described. An arbitrary number of feeding points can be modeled as mutual coupling is taken into account. Overvoltages throughout electrical power systems and the transient ground potential rise in the surroundings of grounding structures can be computed.**

KEYWORDS - Electromagnetic Transients, Lightning, Grounding System, Rational Function Approximation, EMTP, EMC.

I. INTRODUCTION

Grounding systems play an important role in power system protection. This contribution deals with the grounding system as part of the electrical network during abnormal conditions.

The behavior of grounding systems at nominal frequency is well understood. Modeling the transient performance of grounding systems, however, is more complicated as it involves frequency-dependence. This applies especially to complex geometrical arrangements such as large grounding grids. Three basic analytical concepts are used to simulate the transient behavior of grounding arrangements: circuit approach [1,2], transmission line approach [3,4], and electromagnetic field approach [5,6,7]. The electromagnetic field approach describes the problem in frequency domain rigorously applying the full set of Maxwell's equations with the minimum possible neglects. An estimation of the overvoltages in power systems during fault conditions, however, can effectively be performed in time domain. In a stand-alone simulation this can be achieved by inverse Fourier-transform. Modeling of grounding systems as part of the electrical network, i.e. direct feed-back to the network during the run-time simulation is mandatory, requires methods to incorporate the grounding system into transients programs. The widely used EMTP is chosen here, as it provides proven models for a large number of power components. One attempt to model the frequency-dependent properties of grounding systems within the EMTP was presented in [3]. The approach [3] is a transmission line approach, neglecting the mutual electromagnetic coupling between the parts of the grounding structure. In order to achieve both full electromagnetic coupling between the parts of the grounding structure and the interface to the EMTP the electromagnetic field approach is chosen here and connected to the EMTP. The inductive and capacitive coupling between the grounding system and the aboveground metallic structures, however, is neglected in contrast to [8,9].

The interface to the EMTP is realized by defining the grounding impedances related to the feeding points considered and the mutual impedance between them in form of a frequency-dependent transfer function as suggested in [10]. The main advantage of this method is that the transfer function is independent of the kind of excitation and depends merely on geometrical arrangement of the system and soil's parameters.

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II. FREQUENCY-DEPENDENT IMPEDANCES OF GROUNDING SYSTEMS

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

$$Z_{mn}(j\omega):=\frac{V_{mn}(j\omega)}{I_n(j\omega)} \tag{1}$$

where $V_{mn}(j\omega)$ denotes the ground potential rise (GPR) at point m as response to a steady state current injection $I_n(j\omega)$ at point n (Fig. 1). Details of the underlying theory and computer modeling of the frequency-dependent impedances of complex grounding systems can be found in [3,5,6]. Appendix provides a brief description of the basic steps of the

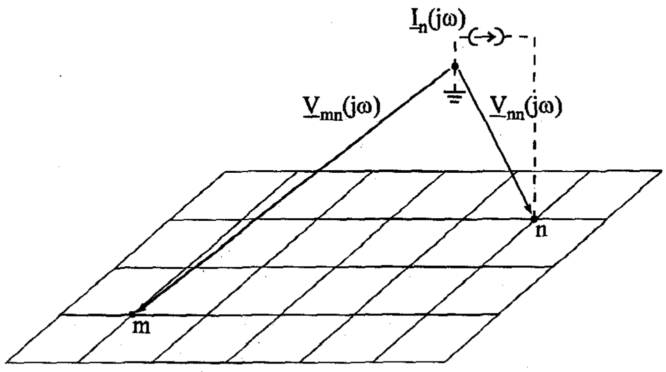

Fig. 1. Computation of self and mutual impedances

solution and a more detailed set of key references. $Z_{nn}(j\omega)$ is the self impedance of the grounding system related to a certain point n, whereas $Z_{mn}(j\omega)$ ($m \neq n$) stands for the mutual impedance between two points m and n. The coupling between these points is described by the mutual impedances $Z_{mn}(j\omega)$ with $Z_{mn}(j\omega) = Z_{nm}(j\omega)$ due to the reciprocal theorem.

The GPR $V_{mn}(j\omega)$ is determined using the computation method presented in [5], which is based on a rigorous electromagnetic model. In frequency domain analysis non-linear phenomena such as soil ionization cannot be taken into account. Soil ionization appears at very large currents, if the electrical field at the conductors surface exceeds the ionization threshold of approximately 3 kV/cm. Regarding large grounding grids, however, the impact of soil ionization is small due to the length of the buried conductors and the relatively low current densities.

Fig. 2 shows magnitude and phase function of the self impedance of a 60 x 60 m^2 grid with 6 x 6 meshes for corner and center injection, respectively. The copper conductors have a diameter of 14 mm and are buried in a depth of 0.5 m. In this paper the geometrical arrangement is considered with two different soil parameters: Firstly, a specific conductivity of 0.01 $(\Omega m)^{-1}$ corresponding to a relative permittivity of 36 ("wet soil") and, secondly, a specific conductivity of 0.001 $(\Omega m)^{-1}$ corresponding to a relative permittivity of 9 ("dry soil"). The same soil parameters were assumed in [5,11,12] and are chosen here for comparison reasons. In the low frequency range the self impedance is independent of the feeding point and proportional to soil conductivity, whereas in the higher frequency range the self impedance of corner injection exceeds the one of center injection due to the smaller effective area. Depending on the position of the feeding point and the soil conductivity the impedances show a slightly capacitive behavior in the low frequency range changing to an inductive behavior in the higher frequency range. This is indicated by the positive phase function and the strong increase of the magnitude function in the higher frequency range. Additionally, the magnitude function of the self impedance is no longer directly proportional to soil conductivity, since the impedance is no longer resistive in the high frequency range.

Fig. 3 displays the mutual impedance for a soil conductivity of 0.001 $(\Omega m)^{-1}$. For the same soil conductivity

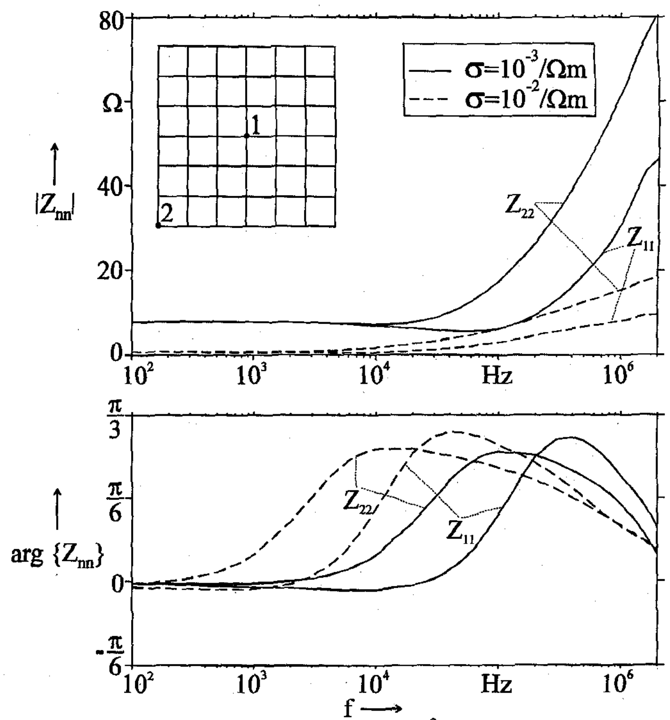

Fig. 2. Self impedance of 60 x 60 m^2 grounding grid

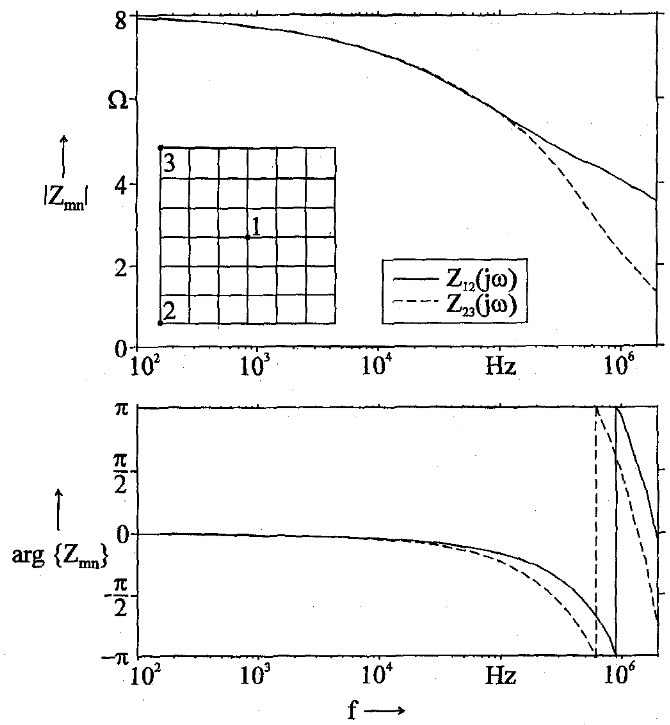

Fig. 3. Mutual impedances of 60 x 60 m^2 grounding grid

the resistive low frequency values of mutual impedance and self impedance are equal independently of feeding and observation position, since in DC-case a current injected anywhere in the grid produces the same GPR in the whole grid. At higher frequencies the magnitude function of the mutual impedance decreases depending on the distance between feeding and observation position and the soil conductivity. The strong variation of the phase function in the high frequency range indicates, that the voltages $V_{mn}(j\omega)$ are not computed at the same point where the currents $I_n(j\omega)$ are injected. This results in a shifting of the phase function, as discussed in section III. The mutual impedances are non-minimum-phase-shift functions.

III. INCORPORATION OF THE GROUNDING SYSTEM INTO THE EMTP

In transients analyses, it is mandatory to simulate each element of the network in time domain. In the following a strategy is presented, which permits both the transformation of the frequency-dependent impedances of the grounding system in time domain and the interfacing with the EMTP by means of rational approximation.

In lightning protection studies usually several connections of the live parts to the grounding system have to be considered. Consequently, a sophisticated time domain model of the grounding system has to take into account coupling between feeding points. The simulation method is based on superposition of the potential rises produced by the currents injected into the different feeding points. For J feeding points (denoted by 1,2,..,J) the impact of the grounding system on the electrical network is described in frequency domain by the following equations:

$$\begin{bmatrix} V_1(j\omega) \\ V_2(j\omega) \\ \dots \\ V_J(j\omega) \end{bmatrix} = \begin{bmatrix} Z_{11}(j\omega) + Z_{12}(j\omega) + \dots + Z_{1J}(j\omega) \\ Z_{21}(j\omega) + Z_{22}(j\omega) + \dots + Z_{2J}(j\omega) \\ \dots \\ Z_{J1}(j\omega) + Z_{J2}(j\omega) + \dots + Z_{JJ}(j\omega) \end{bmatrix} \cdot \begin{bmatrix} I_1(j\omega) \\ I_2(j\omega) \\ \dots \\ I_J(j\omega) \end{bmatrix} \quad (2)$$

where $Z_{mn}(j\omega)$ is given by (1). The following paragraphs deal with the incorporation of (2) into the EMTP. Within the EMTP the voltages and currents of (2) are then simulated in time domain taking into account both the aboveground parts and the grounding system.

A. Rational Approximation Technique

For time domain representation every complex-valued, frequency-dependent impedance $Z_{mn}(s = j\omega)$ is considered as transfer function approximated by a rational function of the form:

$$Z(s) \approx K \cdot \frac{\prod_{m=1}^{M}(s+z_m)}{\prod_{n=1}^{N}(s+p_n)} = q_0 + \sum_{n=1}^{N} \frac{q_n}{s+p_n} \quad (3)$$

This procedure is valid, if the system is stable and minimum-phase-shift [13]; every zero $s = -z_m = -2\pi f_{z,m}$ and every pole $s = -p_n = -2\pi f_{p,n}$ are placed on the negative, real axis. A partial fractional expansion is applied to reduce the numerical problems of the run-time simulation. Rational functions according to (3) can be incorporated in time domain simulations without using the inverse Fourier-transform and the storage consuming convolution, which corresponds to multiplication in time domain.

A method determing the poles and zeros of rational functions was proposed by Bode [14] and applied by Marti [15] for representation of overhead transmission lines. This algorithm available within the EMTP, however, is not adapted to the highly frequency-dependent parameters of grounding systems. Therefore the algorithm applied in this paper is based on an asymptotic method adjusted to grounding structures [3]. This algorithm is further improved, as for two reasons an asymptotic method can only be an estimate. Firstly, the asymptotic representation of every pole and zero is a rough approximation and, secondly, the impact of every pole and zero in the higher frequency range is neglected. In the method presented the approximation is optimized by shifting the position of every pole and zero along the frequency axis until the deviation is minimized. The optimization is based on the least-square fitting technique. In a loop the position of every pole is iteratively improved using the following expression.

$$\begin{aligned} O(s,p_n) &= \min \int_{\Omega_{p,n}} w_{p,n}(\omega) \cdot \left| Z(s) - Z_{fit}(s) \right|^2 d\omega \\ &= \min \int_{\Omega_{p,n}} w_{p,n}(\omega) \cdot \left| Z(s) - \frac{Z^*_{fit}(s)}{(s+p_n)} \right|^2 d\omega \end{aligned} \quad (4)$$

where

$Z^*_{fit}(s) = Z_{fit}(s) \cdot (s+p_n)$

$w_{p,n}(\omega) = \left| \omega - \omega_{p,n} \right|^{-\alpha}$ weighting function,

$\Omega_{p,n}$ frequency range in the surroundings of the n-th pole

The expressions for zeros are equivalent. The deviation integral $O(s,p_n)$ is numerically solved and minimized. The algorithm stops when corner frequencies remain unchanged within a given tolerance band.

The accuracy of the applied rational approximation technique is influenced by the frequency-dependence of the investigated curve and the number of poles and zeros used for approximation. Approximating the magnitude functions of self and mutual impedances presented in Fig. 2 and Fig. 3 it was found out that for a given number of poles and zeros the results of the rational approximation show the strongest deviations for $Z_{11}(j\omega)$ with a soil conductivity of 0.01 $(\Omega m)^{-1}$. The maximum relative deviation between the approximated and the original curve for this case is displayed in Table 1 for

number of poles	number of zeros	rel. deviation before optim.	rel. deviation after optim.
7	7	15.6 %	2.5 %
16	16	10.8 %	0.9 %

Table 1: Maximum relative deviation before and after optimization

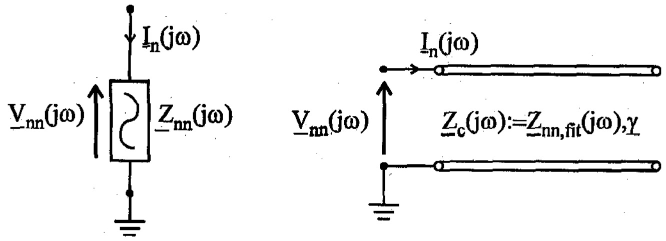

Fig. 4. Incorporation of the self impedance into the EMTP

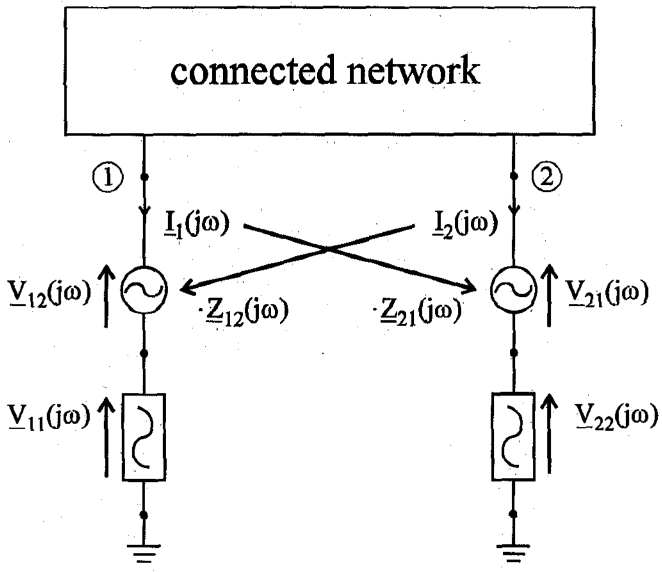

Fig. 5. Circuit representation of the grounding system

two different orders N of the approximation function before and after applying the above described optimization algorithm. The results underline the efficiency of the optimization.

B. Interface to the EMTP

In the following the incorporation of (2) into the EMTP is described. In the first step a method to incorporate self impedances of grounding systems is presented. Complementary, in a second step a strategy to introduce the mutual couplings by additional incorporation of the mutual impedances is proposed.

In order to incorporate frequency-dependent self impedances into the EMTP, the frequency-dependent EMTP model of an overhead transmission line based on Marti's model [15] is used in a special way. Due to the fact, that the surge impedance of transmission lines is represented by the characteristic impedance as long as no reflections arrive, the frequency-dependent impedance of the feeding point is considered to be the characteristic impedance of a long transmission line (Fig. 4). The residues q_n and the poles $-p_n$ of the characteristic impedance according to (3) are determined by the above described rational approximation technique and passed to Marti's EMTP model. Within the EMTP the so-called recursive convolution technique is applied for simulating the characteristic impedance [16].

The mutual impedance $Z_{mn}(j\omega)$ describes the coupling between two points situated at a distance d. Due to the finite velocity of propagation of the electromagnetic waves the mutual impedance can be expressed in time domain as

$$z_{mn}(t)=z^{0}_{mn}(t-\tau_{mn}), \tag{5}$$

where τ_{mn} denotes the traveling time of the fastest frequency response. τ_{mn} is achieved by computing the step response using the inverse fast Fourier-transform (IFFT) of the mutual impedance as outlined in section IV. Resulting from the shifting property of the Fourier-transform, (5) is described in frequency domain by

$$Z_{mn}(j\omega)=Z^{0}_{mn}(j\omega)\cdot e^{-j\omega\tau_{mn}}, \tag{6}$$

where $|Z_{mn}(j\omega)| = |Z^0_{mn}(j\omega)|$. $Z^0_{mn}(j\omega)$ is the corresponding minimum-phase-shift function, which can be approximated by rational functions according to section III-A. Firstly, the terms $Z_{mn}(j\omega)\cdot I_n(j\omega)$ of (2) are replaced by $Z^0_{mn}(j\omega)\cdot I_n(j\omega)$. Using the EMTP tool *models*, $Z^0_{mn}(j\omega)$ are considered as transfer functions with the currents $I_n(j\omega)$ as input quantities. The approximated impedances (3) are passed to the *models'* section [17] for representation of arbitrary rational transfer functions. In an auxiliary network the outputs are represented by ideal voltage sources. Secondly, in order to achieve a time-delay corresponding to the traveling time of the fastest frequency component between the points transmission lines with an ideal transfer characteristic are added to the ideal voltage source in the auxiliary network. Finally, the signals are transferred to voltage sources $V_{mn}(j\omega)$ in the simulated network. These voltage sources represent the complete terms $Z_{mn}(j\omega)\cdot I_n(j\omega)$ and are in series with the frequency-dependent self impedances of the feeding points. Fig. 5 shows the circuit representation according to (2) in frequency domain for J = 2 feeding points. The algorithm computing the voltage within the EMTP is based on the trapezoidal rule.

The procedure modeling the coupling between the different feeding points is applicable to an arbitrary number of feeding points. Additionally, the transient ground potential rise (TGPR) at any point of the grid can be simulated within the EMTP using the presented method, by considering these points as feeding points according to (2) with an injection current zero (I = 0).

The methods presented to incorporate the self and mutual impedances into the EMTP perform the transformation to time domain within the EMTP using techniques, that reduce the numerical simulation effort drastically. For further details on the numerical techniques applied within the EMTP the reader is referred to [19].

IV. VALIDATION OF THE SIMULATION TOOL

A. Validation of the Interface to the EMTP

For validation of the self impedance representation, a 1 kA step current is fed into a corner of the grid with a

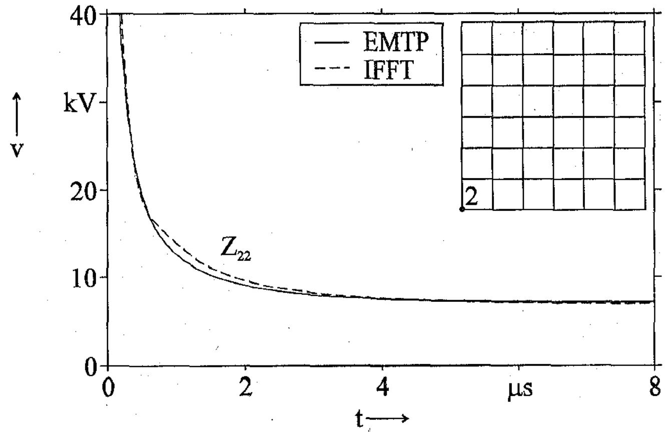

Fig. 6. Step response of self impedance using different representations

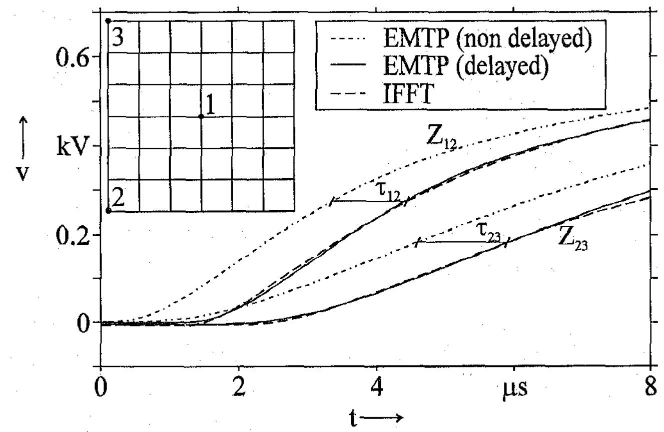

Fig. 7. Step response of mutual impedance using different representations

specific soil conductivity of 0.001 $(\Omega m)^{-1}$. Fig. 6 shows the step response voltage at the feeding point for both the EMTP and the IFFT representation. The curves are in good agreement. In the EMTP computation displayed in Fig. 6 only a small number (N = 4) of poles and zeros according to (3) are used, in order to make errors caused by a limited number of poles and zeros visible. The resulting deviation can be further reduced by increasing the accuracy of the approximation procedure.

Fig. 7 displays the step responses of two mutual impedances to an 1 kA current for different computation methods. The specific soil conductivity is chosen as 0.01 $(\Omega m)^{-1}$. In both examples (Z_{12}, Z_{23}) the dash-dotted curves show the results of the EMTP simulation based on the rational approximation of $Z^0_{mn}(j\omega)$, whereas the results of the IFFT are given by the dashed line. The traveling time of the fastest frequency response τ_{mn} is taken from comparison of time domain results, since the IFFT curve is shifted by τ_{mn} along the time axis. τ_{mn} can also be determined by comparison of the phase functions corresponding to $Z_{mn}(j\omega)$ and the result of the rational approximation of $Z^0_{mn}(j\omega)$ according to (6). This time-delay is introduced into the EMTP

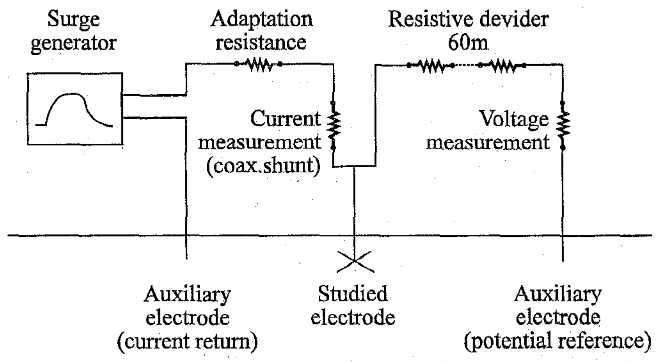

Fig. 8. Measuring set-up

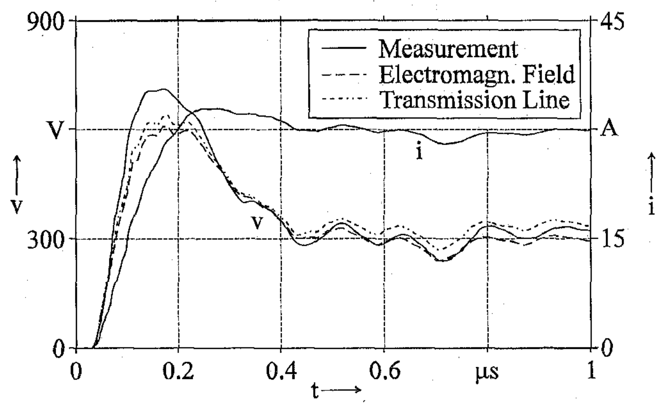

Fig. 9. Comparison between measurement and simulation

as outlined in section III. For both examples the results of the complete EMTP representation are shown by the solid line, being good in accordance with the IFFT results. Again the accuracy can be increased by using an approximation of higher order.

Investigating the time delays τ_{12} and τ_{23} according to Fig. 7 it becomes obvious, that τ_{12} is smaller than τ_{23}. This results from the smaller distance between points 1-2 compared to 2-3 although the shortest connection along the grid's segments is of the same length.

B. Comparison to Measurement and Previously Published Models

A short horizontal copper conductor of 8 m length and a 12 mm diameter is used to validate the model. The conductor is buried in a depth of 0.6 m in soil with a specific conductivity of 0.0167 $(\Omega m)^{-1}$. The relative permittivity is assumed to 15 as data on the soil permittivity during the measurements are not available. The value of 15 is within the range of the relative permittivities usually assigned to earth. The model is compared to field measurements performed by the Electricite de France (EdF) and a previously published model based on the transmission line approach [3]. The current is fed into one end of the conductor. The voltage to remote ground was measured using a 60 m long resistive divider with a bandwidth of 3 MHz. The measuring set-up is displayed in Fig. 8. The reader is referred to [18] for more

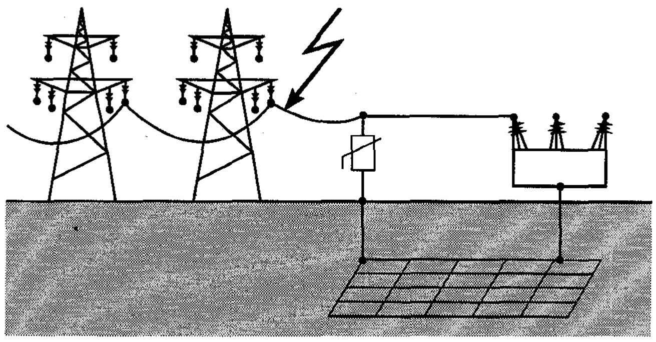

Fig. 10. Lightning protection study of a 420 kV substation

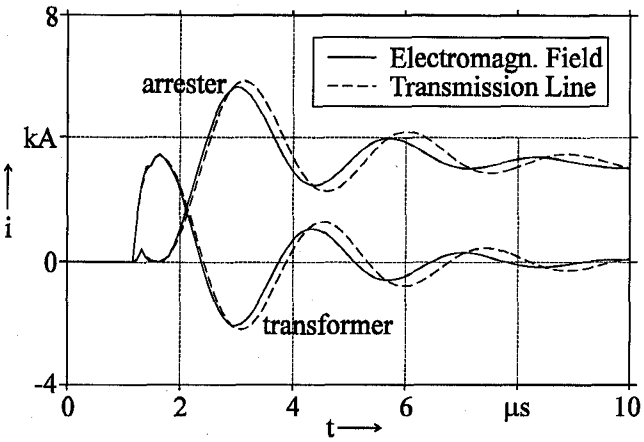

Fig. 11. Injected current into the grounding system

detailed information concerning the measurements. The transmission line model [3] considers each conductor of the grounding system as a lossy transmission line with frequency-dependent parameters, but neglects the mutual electromagnetic coupling between the segments of the grounding system. The model [3] is an accurate and efficient tool for simulating straight horizontal conductors. In case of large grounding grids the neglect of the coupling causes errors depending on size of the arrangement as pointed out in section V.

Fig. 9 presents the results of the comparison. The simulated voltages are in good agreement, whereas the measured voltage shows higher values in the steep front of the current impulse. This deviation for higher frequencies was found in all other comparisons [3,5] and is related to the inductive voltage drop along the divider for very high frequencies.

V. LIGHTNING PROTECTION STUDY FOR A 420 KV SUBSTATION

As an example a lightning protection study for a 420 kV substation is performed. A direct lightning stroke is assumed to hit one phase of an overhead transmission line 300 m in front of the substation at the phase voltage zero. The lightning stroke has a crest value of 6 kA and an impulse shape (1.2/50 µs). For an usual overhead transmission line a maximum potential of about 1000 kV is expected; it is

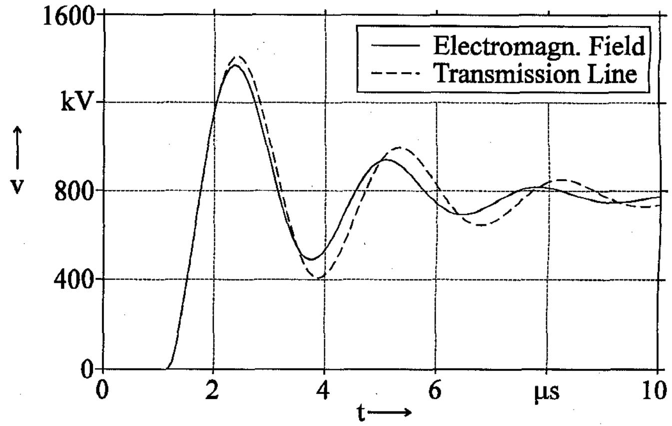

Fig. 12. Voltage across the transformer's terminals

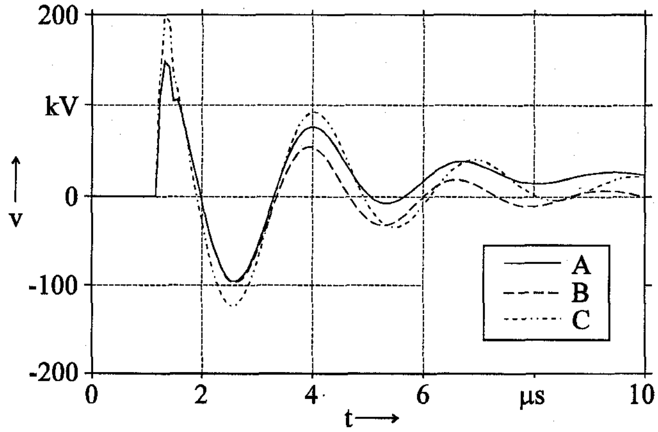

Fig. 13. TGPR at the transformer connection

assumed, that flashover to towers does not occur. The overhead transmission line as well as the switchyard (voltage transformer, surge arrester, busbar, and power transformer) are simulated using the EMTP (Fig. 10). As this paper focuses on grounding system the power transformer is modeled by its surge capacity. The inductive and capacitive coupling between the aboveground structures is neglected. The soil conductivity is taken to 0.001 $(\Omega m)^{-1}$. In order to underline the impact of the grounding system model on the resulting transients, the lightning protection study is carried out by means of two different models. The presented model is compared to the transmission line model [3].

The currents injected into the grounding system at the feeding points are displayed in Fig. 11. The first transients last about 10 µs. After that period the currents approach the DC-distribution. The electromagnetic field theory yields a transient frequency of about 360 kHz. This frequency can be estimated in a first approximation with the aid of the transformer's surge capacity and the inductivity of the busbar connecting the arrester and the power transformer. Additionally, the impact of the inductive part of the self impedances has to be taken into account for the estimation. Compared with the electromagnetic field approach the transmission line approach computes a transient frequency of about 330 kHz. This results from an overestimation of the self impedances and here especially of the imaginary part. The amplitudes, however, are hardly influenced by that overestimation.

Consequently, both approaches compute nearly the same values for the maximum voltage between the transformer's high voltage terminal and the transformer's connection to the grounding system (Fig. 12). The computed voltage oscillates around the clamp voltage of the metal oxide arrester.

The coupling between the different feeding points is discussed using Fig. 13. Curves A and B display the results of the electromagnetic field approach. The coupling between the feeding points is taken into account (curve A) and neglected (curve B), respectively. In the first 3 μs the influence of the current injected at the arrester can be neglected compared to the TGPR evoked by the current injected into the grounding grid at the transformer. For increasing times, however, the TGPR is more and more determined by the impact of the coupling. Firstly, this can be explained by the increase of the mutual impedance and the decrease of the self impedance from high to low frequencies. Secondly, nearly the whole current is fed into the grounding system at the arrester, due to the increasing DC-content of the current. The transmission line approach [3] (curve C) clearly overestimates the TGPR in the first few microseconds, due to the above mentioned overestimation of the self impedance. Additionally, this approach results in an underestimation of the coupling between the feeding points.

VI. CONCLUSIONS

The electromagnetic field approach was used to compute the grounding system as integral part of the electrical network by defining self and mutual impedances. The impedances were considered as transfer functions, and the interface with the EMTP was verified using IFFT. For a simple grounding rod, comparison between electromagnetic field and transmission line approach [3] to measurements showed good agreement. In the performed lightning protection study, i.e. in case of large grounding grids, deviations between both approaches occur in transient frequency and TGPR simulation.

Using the transmission line approach [3] each segment of the grounding grid has to be modeled separately in the EMTP independently of the number of the feeding points. Applying the electromagnetic field approach preprocessing is needed for which simulation effort depends on size and complexity of the system. Within the EMTP, however, the simulation effort depends highly on number of the feeding points but is nearly independent of size of the grounding structure. Consequently, when all self and mutual impedances are precomputed by the electromagnetic field theory, different lightning protection studies can be efficiently computed within the EMTP by means of the electromagnetic field approach. Additionally, the electromagnetic field approach provides an improved accuracy especially for large grounding grids.

VII. ACKNOWLEDGMENTS

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APPENDIX - COMPUTATIONAL METHODOLOGY FOR FREQUENCY-DEPENDENT IMPEDANCE OF GROUNDING SYSTEMS

The computational methodology is based on the general method of moments [20]. This methodology was first developed for antennas near to and penetrating the earth [21], and later applied to grounding systems [6]. More details on modifications of antenna solutions for grounding systems can be found in [22].

The grounding system is assumed to be a network of connected straight cylindrical metallic conductors with arbitrary orientation [6]. The first step is to compute the current distribution, as a response to injected current at arbitrary points on the conductors network. The conductor network is divided into a number of fictitious smaller segments. Then axial current distribution in the network I(l) is approximated by a linear combination of M expansion functions $F_k(l)$ [5]:

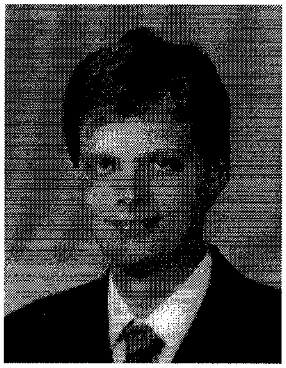
$$I(l) = \sum_{k=0}^{M} I_k \cdot F_k(l) \tag{A1}$$

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

$$[Z] \cdot [I] = [V] \tag{A2}$$

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. [5] provides all details on evaluation of the elements of [Z], and [3] gives 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 [3], voltage [5], and impedance [6].



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