Grounding System Modeling in EMTP/ATP Based on its Frequency Response

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***Abstract*—The aim of this paper is to present a grounding system modeling using a circuit network synthesized from its frequency response. This circuital representation allows simulating the grounding system in EMTP/ATP program considering its frequency dependent effects. Also, any electrical component may be included in the simulation, such as power system equipments or electronic devices.**

The frequency response was obtained by means of both an electromagnetic model based on the Moments Method (MM) and a Hybrid Electromagnetic Model (HEM). The results were compared with previous works and field measurements, finding a good agreement.

***Index Terms*—Circuital Synthesis, EMTP/ATP, Frequency response, Grounding system, Hybrid Electromagnetic Model, Moments Method.**

I. INTRODUCTION

THE transient behavior of grounding system influences greatly the performance of electrical systems under fault conditions. This fact has led the authors to present a modeling technique which represents the characteristic of the grounding system for a wide frequency range.

In the last years the research program on Acquisition and Analysis of Signals PAAS-UN is involved in grounding systems studies with the aim of getting more accurately models that represents the behavior of those systems when they are subjected to transients. Traditionally these studies have been conducted using modeling techniques which are restricted to low frequencies ranges and fixed geometries. In this work the authors present a novel technique based on circuit synthesis whose behavior is highly accurate for a wide frequency range.

The frequency domain response may be measured directly using specialized equipment or, in the other hand, it may be obtained theoretically by means of electromagnetic models. In this paper, two models were used to compute and compare the frequency response. One of them is the well know Moments Method using ramp functions to approximate the current in each conductor segment and the another one is a Hybrid Electromagnetic Model which uses a constant value to approximate the current in each conductor segment.

Once the characteristics in frequency domain were found, the Vector Fitting technique was used to obtain a rational function that matches the frequency spectrum. After that, a Circuit Synthesis technique was used in order to obtain an electric circuit model which was implemented in EMTP/ATP program to get time domain responses.

This document presents firstly the electromagnetic models, Vector Fitting and Circuit Synthesis techniques applied to a couple of grounding systems. Thereafter, the simulation results, analysis and final conclusions are presented.

II. ELECTROMAGNETIC MODELS

To compute the frequency response of grounding systems for any arrangement and different soil parameters, two different methods were implemented: Moments Method (MM) and Hybrid Electromagnetic Model (HEM). Both solutions are frequency-based and the Fourier transform is applied to get the time domain response. A brief description of MM and HEM is presented below.

A. Moments Method Solution - MM

In order to obtain the solution of the Electric Field Integral Equation (EFIE), the method of moments was used in frequency domain [1], [2]. For this purpose, the grounding system was approximated to thin wires which were divided into N small segments. With the aim of calculate the longitudinal current distribution, the tangential electric field is computed on the surface of each segment due to each current sample (unknown) placed in the conductors axis. This current can be approximate to a constant value, piecewise sinusoidal or a ramp function, being the latest two approximations more suitable by virtue that they do not show discontinuities between segments. For this work the ramp was chosen in order to get an expansion function to approximate the current and an electric dipole approximation such as antennas theory was used [3]. Ramp dipoles are electric line sources extended over the adjacent segments. The current is zero at the end

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points of the dipole and maximum at the segment's join point. Dipoles are illustrated in next figure where i_n is the maximum dipole current.

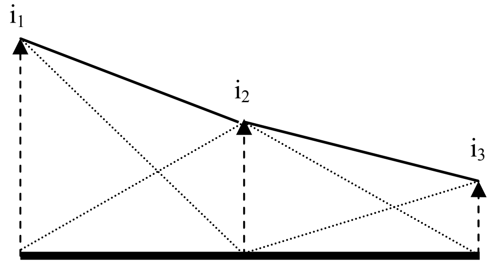

Fig. 1. Ramp dipole

The expansion function for the current ($F(l)$) is presented in Ec. (1) where l_1 and l_2 denote the end points of the segment and d is its length. (see figure 2) .

$$F(l) = i_1\left(\frac{l_2 - l}{d}\right) + i_2\left(\frac{l - l_1}{d}\right) \quad (1)$$

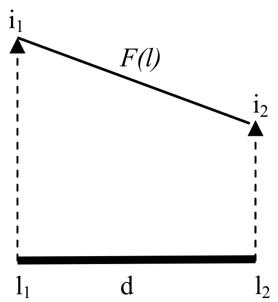

Fig. 2. Current distribution with ramp approximation

From the electromagnetic interaction among segments, a linear equation system is found with N unknown currents, one for each dipole. The system solution gives the current distribution of the segments, allowing to calculate the electric field and potential in any point and the system impedance as a voltage-current relation.

B. *Hybrid Electromagnetic Model - HEM*

A methodology for describing the electromagnetic behavior of structures which may be represented by cylindrical conductors was used [4]-[7]. Conductors of the grounding system are partitioned in a number of segments using the thin-wire approximation. Each one of them is considered as a source of electromagnetic field produced by two current components: a transversal current (I_T) and a longitudinal current (I_L) which are constant along each segment (Figure 3).

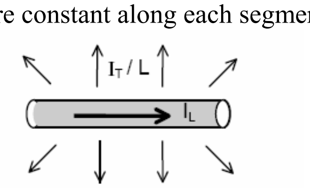

Fig. 3. Current Components in HEM

The electromagnetic coupling between each pair of segments is calculated using the expressions for the scalar and magnetic vector potentials and assuming an average potential of the segment V and a voltage drop along it ΔV, as shown in equations (2) and (3). In this way, coupling impedances matrixes Z_T and Z_L are calculated.

$$V = Z_T I_T \quad (2)$$

$$\Delta V = Z_L I_L \quad (3)$$

Once it is done, circuital relations between voltages and currents allow the system to be represented in a compact form and solved for its nodal voltages (unknown). Once these voltages are known, the current distribution along the grounding system can also be known.

Since all the calculations involved in this methodology are carried out in the frequency domain, the frequency dependence of the soil parameters, skin effect and propagation effects are easily included. In this paper, this methodology is used to find the frequency response of the input impedance of a grounding system by means of the voltage-current relation.

III. Electromagnetic Models Validation

The field measurements of two grounding systems, presented in [1], were used for the validation of MM and HEM solution models. The table 1 presents the dimensions of grounding systems and other data used for the simulations.

TABLE I
GROUNDING SYSTEMS DATA

	Counterpoise	Rod
Length [m]	15	6
Radius [mm]	12	8
Resistivity [Ω-m]	70	50
Relative Permittivity	15	15
Depth [m]	0.6	-

The MM and HEM models were applied to the grounding systems shown in Table I. The injected current for each configuration is depicted in figure 4, and the resultant transient voltages at injection point are compared with field measurements in figures 10 and 11.

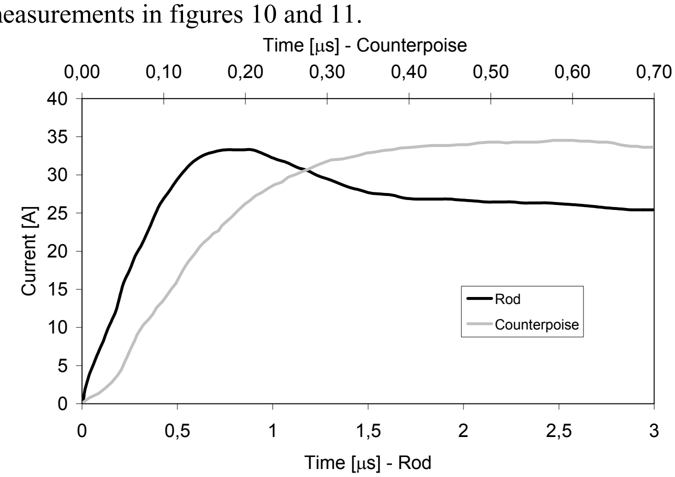

Fig. 4. Injected Currents

As it may be seen in figures 10 and 11, the results applying MM and HEM are quite comparable. Besides, the frequency responses of both methods are similar in magnitude and phase. For this reason it was decided to obtain the Circuital Synthesis with HEM frequency response due to its lower computation time.

IV. Vector Fitting - VF

The frequency response of the grounding system up to 2 MHz is computed by means of the HEM. After this, an approximation of frequency response by Vector Fitting – VF - is made, which enables to get a transfer function of specific order.

VF is a numerical method for the fitting of Frequency Domain Responses – FDR, measured or calculated, by means of the rational function approximation shown in (4). It allows identifying state space models directly from the FDR of any single or multiple input-output systems, and it may be applied to high order systems and wide frequency range. A more complete theory of this method is presented in references [8]-[10] and a general description is mentioned below.

$$F(s) = \sum_{n=1}^{N} \frac{c_n}{s - a_n} + d + sh \tag{4}$$

The residues c_n and the poles a_n are either real quantities or complex conjugate pairs, while d and h are real. This approximation is a nonlinear problem because a_n appears in the denominator. For this reason a pole relocation technique is used to express the function as a linear problem and solve it, by improving iteratively the known poles.

This procedure is carried out in two stages. In the first one, a function $\sigma(s)$, whose poles are equally spaced over the frequency range of interest, is introduced and the problem is expressed in a linear form $Ax=B$ as shown in (6).

$$\sigma(s) = (\sum_{n=1}^{N} \frac{\bar{c}_n}{s - \bar{a}_n} + 1) \tag{5}$$

$$\sigma(s) * f(s) = \sum_{n=1}^{N} \frac{c_n}{s - \bar{a}_n} + d + sh \tag{6}$$

In (6) $f(s)$ is the real FDR (measured or calculated) and the unknowns are d and h and the residues c_n and $\bar{c}_n$. By calculating the zeros of $\sigma(s)$ an improved set of poles for fitting $f(s)$ is found. In the second stage the new poles found in the previous stage are replaced in (4) and the new residues are calculated. This iterative procedure is repeated with the new starting poles up to the expected accuracy between $F(s)$ and $f(s)$ would be reached.

V. Circuit Synthesis - CS

Once the transfer function of the system is expressed as the sum of partial fractions (4), each one can be represented as a branch network with a defined admittance value. Finally, all the branches are connected in parallel, obtaining the synthesized circuit.

In (4) c and a can be real or complex quantities, while d and h are real quantities and may be optional. The branch components are calculated by the following rules:

1) The terms $1/d$ and h represent a grounded resistance and a grounded capacitance, R_0 and C_0 respectively.

2) In case of real poles and c is real positive, the equivalent component is a RL series branch, whose admittance is:

$$F_i(s) = \frac{1/L}{s + R/L} \tag{7}$$

Where L and R are calculated with (8) and (9):

$$L = 1 / c_i \tag{8}$$

$$R_1 = -a_i / c_i \tag{9}$$

3) In case of real poles and c is real negative, the equivalent component is a RC series branch, and the admittance is approximated to:

$$F_i(s) = \frac{s/R}{s + 1/CR} \tag{10}$$

Where C and R are calculated with (11) and (12):

$$C = -c_i / a_i^2 \tag{11}$$

$$R_2 = a_i / c_i \tag{12}$$

In this case the term d is modified as shown in (13).

$$d = d - (c_i / a_i) \tag{13}$$

4) If c and a are included in a conjugated complex pair as in (14), the equivalent component is a R_aL_1 series branch connected in series with a R_bC_1 parallel branch, whose total admittance is given by (15).

$$F(s) = \frac{cr + jci}{s + (ar + jai)} + \frac{cr - jci}{s + (ar - jai)} \tag{14}$$

$$F(s) = \frac{s/L + 1/CLR_b}{s^2 + s(1/CR_b + R_a/L) + 1/CL} \tag{15}$$

Where the values of C_1, L_1, R_a, and R_b are calculated as follows:

$$L_1 = \frac{1}{2 \cdot cr} \tag{16}$$

$$R_a = \left(-2 \cdot ar + 2(cr \cdot ar + ci \cdot ai)L\right)L \tag{17}$$

$$C_1 = \frac{1}{\left(\left(ar^2 + ai^2 + 2(ar \cdot cr + ai \cdot ci)R_a\right)L\right)} \tag{18}$$

$$R_b = \frac{1}{\left(-2(ar \cdot cr + ai \cdot ci)C \cdot L\right)} \tag{19}$$

Figure 5 shows a schematic representation of the circuit synthesis.

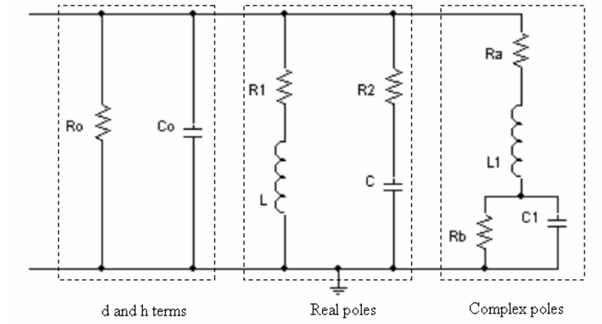

Fig 5. Circuit Synthesis Schematic

VI. Simulation Results

A public domain Matlab routine, *vectfit.m*, was used for the VF (available at http://www.energy.sintef.no/Produkt/VECTFIT/MENU.htm). The routine needs as inputs the frequency response data, the starting poles and kind of the rational function to be used: Proper, strictly proper or improper. As outputs, this routine gives the adjusted rational function, its zeros, poles and residuals, and the fitting error between the original data and the obtained function. Besides, this routine is able to give results of a synthesized circuit composed by R, RL, RC and/or RLC parallel branches.

In all the cases simulated in this work, it was used a 4 order rational function because for this case the results shown a better agreement with the original data. The starting poles were located equally spaced on a logarithmical scale and assumed as complex quantities.

A. *Case 1: Counterpoise*

After 5 iterations, it was obtained an improper function given by Eq. (20).

$$F(s) = \frac{-2.09e7}{s + 2.05e6} - \frac{2.16e8}{s + 1.31e7} + \frac{4.08e3 - j1.22e3}{s + (1.26e4 - j2.03e3)} + \frac{4.08e3 + j1.22e3}{s + (1.26e4 + j2.03e3)} + 1.9e-7s + 1.55e-1 \qquad (20)$$

Figures 6 and 7 show the synthesized circuit for the counterpoise, and the comparison of its frequency response with the one obtained by means of HEM.

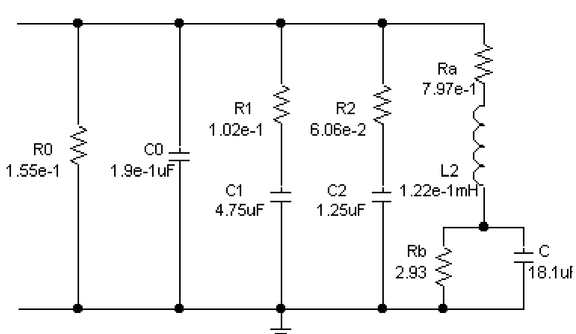

Fig 6. Circuit Synthesis for Counterpoise

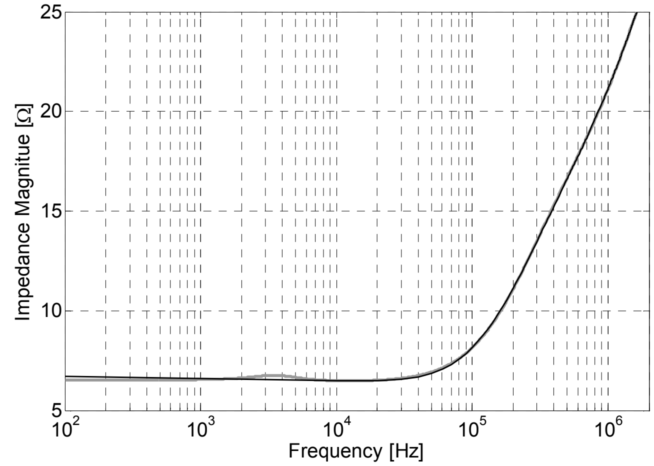

Fig. 7. Frequency Response of Counterpoise. (Gray: Synthesized)

B. *Case 2: Rod*

After 5 iterations, it was obtained an improper function given by Eq. (21).

$$F(s) = \frac{-2.29e8}{s + 1.20e7} + \frac{4.41e5}{s + 7.18e5} + \frac{2.27e4}{s + 7.82e4} + \frac{1.35e2}{s + 2.14e3} + 2.42e-7s + 3.66e-2 \qquad (21)$$

Figures 7 and 8 show the synthesized circuit for the rod, and the comparison of its frequency response with the one obtained by means of HEM.

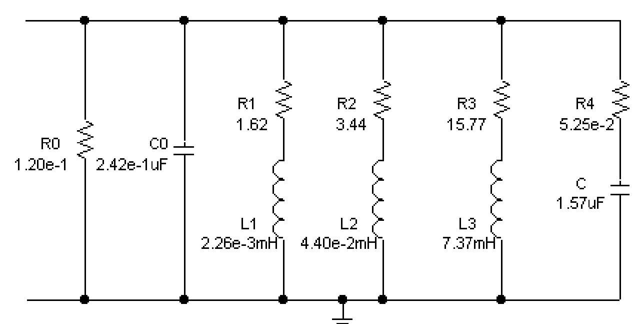

Fig 8. Circuit Synthesis for teh Rod.

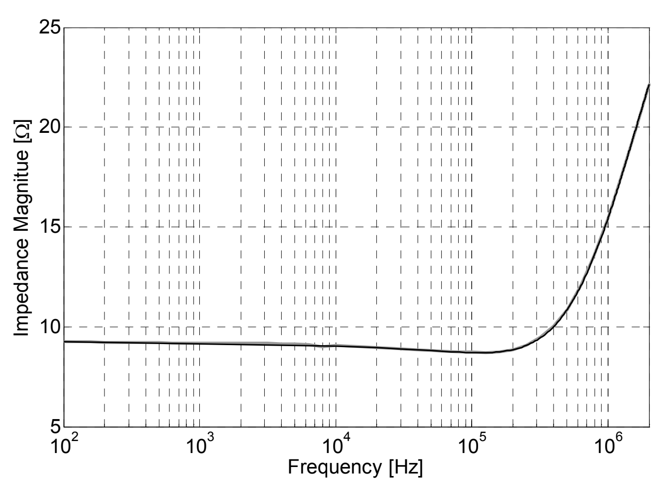

Fig. 9. Frequency Response of Rod. (Gray: Synthesized)

The synthesized circuit was used to simulate the transient voltages of the grounding systems in EMTP/ATP program. The same current waves depicted in figure 4 were injected to the circuits and the results are presented in figures 10 and 11. The comparison of field measurements, MM, HEM and circuital model verified that the electromagnetic models have a good agreement with the actual results.

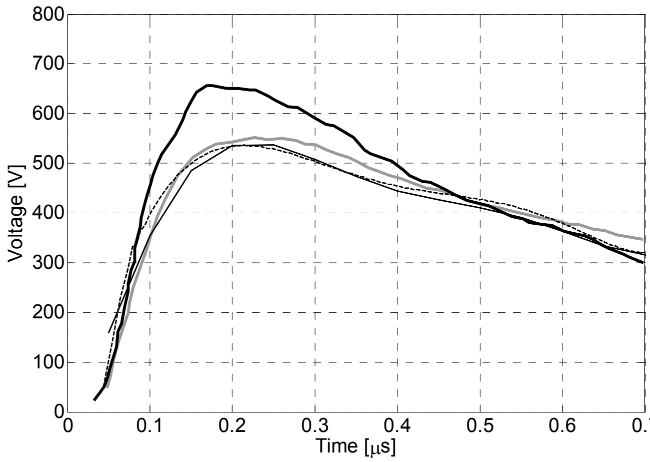

Fig. 10. Voltage at Injection Point - Counter poise. (Thick Black: Measurement, Gray: MM, Thin Black: HEM and Dashed: Synthesized).

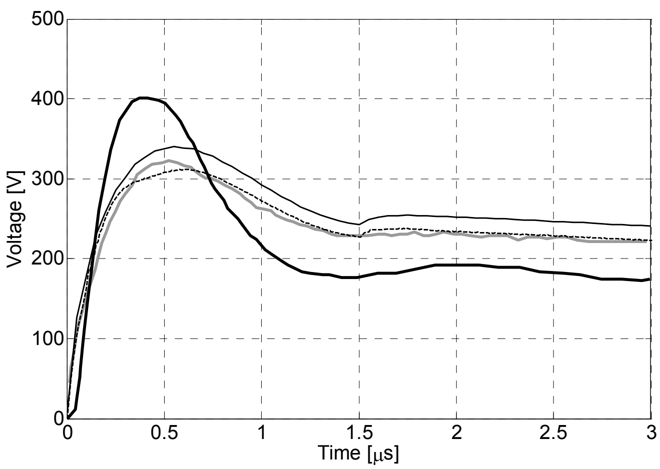

Fig. 11.Voltage at Injection Point - Rod. (Thick Black: Measurement, Gray: MM, Thin Black: HEM and Dashed: Synthesized).

VII. Analysis

It was found similar results for both electromagnetic models described above. The Vector Fitting and the Circuit Synthesis were calculated using the frequency characteristic found with HEM because this method spent less processing time due to it presents simpler equations.

Despite of the agreement between the theoretical results, the models are not able to reproduce exactly the experimental measurements. These differences can occur because in the simulation it is not taken into account the measurement system and other effects associated to the transient behavior of the ground.

As can be seen from the results, the higher differences are presented when the injected current has a short rise time. In this case the difference can get values up to 25%. For the case when the rise time is higher, the error diminishes. This can occur due to the inductive effect present in the feeding cables of the experimental setup.

VIII. Conclusions

The new proposed model of grounding system presented in this paper is a good approach of its electrical behavior.

The major advantage of using equivalent synthesized circuits is the possibility to easily model the transient behavior of a grounding system or any electrical component together with other electrical components models, such as transmission lines, transformers, machines, etc. Also, the simulation time is reduced considerably which is an advantage when it is necessary to carry out many simulation cases.

Frequency characteristic was found using two electromagnetic methodologies. Due to both methodologies present similar results it was decided to use HEM results because it spent less computational time.

Results in time domain for MM, HEM and CS are in good agreement. It was concluded that using Circuit Synthesis allows obtaining similar result in a wide frequency range in a very straightforward way. Nevertheless, the circuital network can not be assumed as the physical electric model of the grounding system.

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