Broad-Band Equivalent Circuit of Grid-Grounding System Considering Frequency Dependence of Electrical Parameters of Soil through Modified Vector Fitting Method

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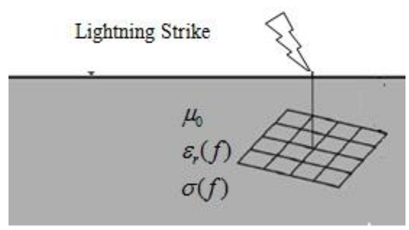
ABSTRACT:
In this paper, wide band circuit model based on modified vector fitting method are proposed for the grid-grounding system. At first, the input impedance of the grid-grounding system in the frequency domain is computed by accurate methods such as the method of moments (MoM). The circuit models are then achieved through converting input impedance of the problem to rational functions via modified vector fitting method. These functions are formed in such a way that at first a set of starting poles in the frequency range of interest are chosen, and then the exact locations of poles are found via an iteration process by least square method. Finally, these rational functions are converted to equivalent circuits in time domain and then imported into EMTP software for modeling the ground system so that transient voltage of overhead lines subjected by lightning strikes is also efficiently evaluated.

KEYWORDS: Grounding system; EMTP; modified vector fitting.

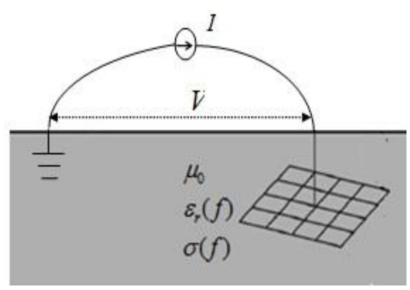
1. INTRODUCTION

Grounding systems such as vertical, horizontal and grid electrodes are often used in power systems to discharge lightning current into earth without any damage to people and installations [1, 2]. Figure 1(a) shows schematic diagram of grid grounding systems under lightning strike. Transient voltage of grounding system (defined electrical potential of the grounding electrodes with respect to a reference point at infinite as shown in figure 1(b)) is of great practical importance, because firstly it is able to reveal the maximum voltage level that is submitted to the ground, secondly it is evaluates the time that the ground is subjected to certain levels of transient voltage. Safety criteria are based upon minimizing this parameter.

This parameter is usually computed by transient solvers such as EMTP (Electromagnetic Transient Program) software [3, 4] through importing grounding system as equivalent circuit into EMTP. This equivalent circuit in evaluating lightning-induced voltage across surge arresters as shown in figure 1(c) is also of importance. It is well known that to compute transient voltage of both grid grounding system and arresters, this equivalent circuit should be correctly extracted and imported into EMTP.



(a)



(b)

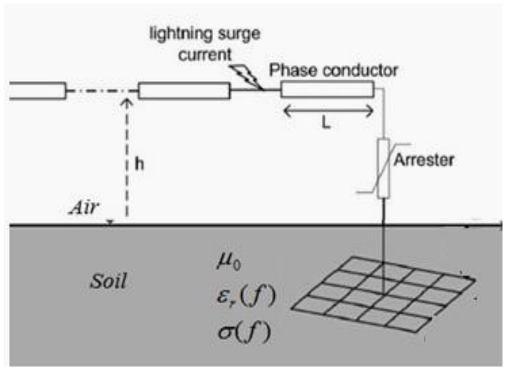


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Fig. 1. (a): Schematic diagram of grid-grounding system, (b): definition of transient voltage and input impedance, (c): an overhead line terminated to grid-grounded arrester.

Most often, the equivalent circuit of grid grounding system is represented as lumped resister or combination of resistors, inductances and capacitances [5-8] which their values are based upon quasi-static assumption and thus these models at high frequencies created by lightning strikes are inaccurate.

To remove this restriction, equivalent circuit of different grounding systems based on finite difference time domain (FDTD) was extracted [9], but these circuits firstly include too many lumped elements, secondly cannot consider frequency dependence of the electrical parameters of soil [10] and thirdly suffer from time consuming computations, and fourthly they cannot consider ionization of soil.

Although recently transient voltage of grounding systems by finite element method (FEM) [11] and combination of method of moments (MoM) and conventional nodal analysis method [12] has been carried out, they are not led to extracting equivalent circuit of grounding systems.

In contrast with the existing circuit models, the efficient vector fitting method (VF) [13-15] could be used. In this method, at first, the input impedance of the grid-grounding system in the frequency domain is defined as (1) and computed by accurate methods such as MoM [16].

$$Z(j\omega)=\frac{V(j\omega)}{I(j\omega)} \tag{1}$$

Where $V(j\omega)$ and $I(j\omega)$ are electrical potential and electrical current in the frequency domain respectively as shown in figure 1(b).

The circuit models are then extracted via converting input impedance of the problem to rational functions by means of the VF. These functions are formed through choosing at first a set of starting poles in the frequency range of interest, and then the locations of poles are modified via an iteration process. As a result, these rational functions are converted to equivalent circuits and imported into EMTP software for modeling the ground system. Also in figure 1(b), $I(t)$ is related to the two current waveforms for lightning strikes, that is, first and subsequent strokes which are expressed in [8].

To the best our knowledge, there is no broad-band equivalent circuit for grid-grounding system considering frequency dependence of electrical parameters of soil (dispersive soil). Figure 2 shows that how the electrical parameters of soil at high frequencies created by lightning strikes are rapidly changed with frequency. In this figure, σ_0 is low-frequency conductivity of soil.

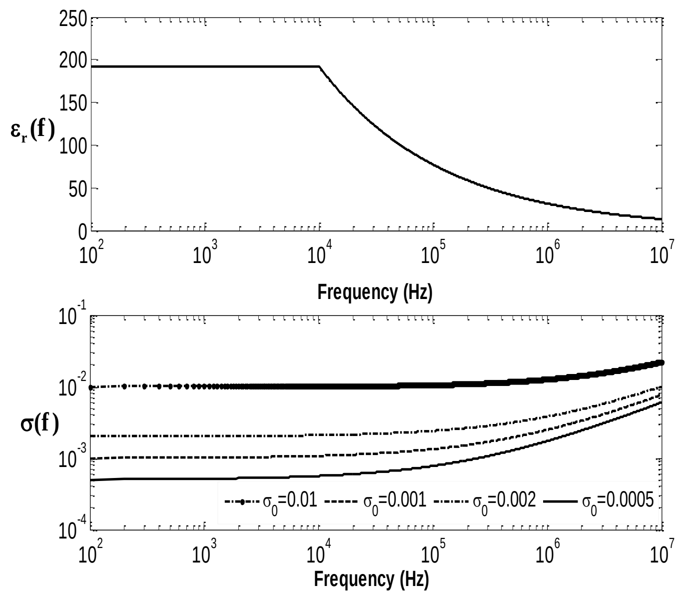

Fig. 2. Frequency-dependent behavior of electrical parameters of lossy soil.

The aim of this paper is to extract broad-band equivalent circuit for grid network buried in a dispersive soil.

This paper is organized as follows. In section 2, principle of the MVF is explained. In following, in section 3, it is assumed that the electrical parameters of soil are frequency dependent, hence the MVF is applied to a grid-grounding system and the equivalent circuit is then extracted. After then, in this section, the effect of previous equivalent circuits and MVF-based one in this study on the lightning-induced voltage across surge arresters is investigated by EMTP. Finally conclusion is given in section 4.

2. MODIFIED VECTOR FITTING METHOD

Extracting equivalent circuit of electrical networks is based on approximating frequency response with rational functions of the following form:

$$f(s)=\sum_{n=1}^{N}\frac{c_n}{s-a_n}+d+sh \tag{2}$$

Where residues c_n and poles a_n are either real quantities or come in complex conjugate pairs, while d and h are real.

The aim is to approximate these coefficients using least square technique. Also note that the equation (2) is a nonlinear problem versus unknown coefficients. Vector fitting method solves this problem as a linear problem under assumption of known poles in an iteration process as follows.

At the first stage, a set of starting poles are assumed and multiply $f(s)$ by an unknown function $\sigma(s)$. Also a rational function for $\sigma(s)$ is introduced as following:

$$\begin{bmatrix}\sigma(s)f(s)\\ \sigma(s)\end{bmatrix}=\begin{bmatrix}\sum_{n=1}^{N}\frac{c_n}{s-\tilde{a}_n}+d+sh\\ \sum_{n=1}^{N}\frac{\tilde{c}_n}{s-\tilde{a}_n}+\tilde{d}\end{bmatrix} \tag{3}$$

Note that in the above equation, $\sigma(s)$ has the same poles as $f(s)\sigma(s)$.

Multiplying the second row of (2) by $f(s)$ gives:

$$\left(\sum_{n=1}^{N}\frac{c_n}{s-\tilde{a}_n}+d+sh\right)=\left(\sum_{n=1}^{N}\frac{\tilde{c}_n}{s-\tilde{a}_n}+1\right)f(s) \tag{4}$$

Rewriting the above equation gives:

$$\left(\sum_{n=1}^{N}\frac{c_n}{s-\tilde{a}_n}+d+sh\right)-\left(\sum_{n=1}^{N}\frac{\tilde{c}_n}{s-\tilde{a}_n}\right)f(s)=f(s) \tag{5}$$

Writing the equation (5) for a given frequency s_k ,

we obtain

$$A_k x=b_k \tag{6}$$

where

$$A_k=\begin{bmatrix}\frac{1}{s_k-\tilde{a}_1} & \cdots & \frac{1}{s_k-\tilde{a}_N} & 1 & s_k & -\frac{f(s_k)}{s_k-\tilde{a}_1} & \cdots & -\frac{f(s_k)}{s_k-\tilde{a}_N}\end{bmatrix} \tag{7}$$

$$x=\begin{bmatrix}c_1 & \cdots & c_N & d & h & \tilde{c}_1 & \cdots & \tilde{c}_N\end{bmatrix}^T \tag{8}$$

$$b_k=f(s_k) \tag{9}$$

Equation (5) is linear in terms of its unknowns c_n , d , h , and $\tilde{c}_n$. If each sum of partial fractions in equation (5) is written as fraction:

$$(\sigma.f)(s)=h\frac{\prod_{n=1}^{N+1}(s-z_n)}{\prod_{n=1}^{N+1}(s-a_n)} \tag{10}$$

$$\sigma(s)=h\frac{\prod_{n=1}^{N+1}(s-\tilde{z}_n)}{\prod_{n=1}^{N+1}(s-a_n)} \tag{11}$$

From the two above equations, we get

$$f(s)=\frac{(\sigma.f)(s)}{\sigma(s)}=h\frac{\prod_{n=1}^{N+1}(s-z_n)}{\prod_{n=1}^{N+1}(s-\tilde{z}_n)} \tag{12}$$

Equation (12) shows that the poles of $f(s)$ is equal to zeros of $\sigma(s)$. Therefore, by computing the zeros of $\sigma(s)$, a set of starting poles can be chosen. According to [13], the zeros are computed through computing eigenvalues of the following matrix:

$$H=A-b\tilde{d}^{-1}\tilde{c}^T \tag{13}$$

Where A is a diagonal matrix including staring poles, and b is column vector of ones. $\tilde{c}$ is a row vector including residues of $\sigma(s)$.

Note that the zeros calculation by (13) is only applicable with nonzero $\tilde{d}$. If the absolute value of is found to be smaller than $tol=1E-8$, the solution is discarded and the LS problem is solved again with a fixed value for $\tilde{d}$ in (3). That is $tol=tol.(\tilde{d}/abs(\tilde{d}))$.

To obtain more accurate result for unknowns, one should substitute these zeros in equation (6) as new poles, and this process is continued up to predefined error is achieved. Finally, once the iteration process is finished, equivalent circuit as explained in [17] is achieved.

3. EQUIVALENT CIRCUIT OF GRID-GROUNDING SYSTEM

In this section, the MVF model is applied to extract equivalent circuit of grid grounding system which is equally spaced $2m\times 2m$ square at depth of $1m$.

Figure 3 shows the amplitude and phase of the input impedance grid network for different values of low-frequency conductivity.

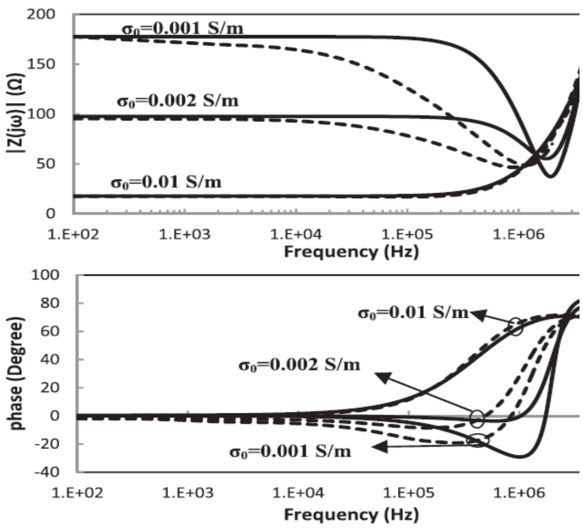

Fig. 3. Frequency dependence behavior of the input impedance of grid-grounding system [11].

Figure 4 compares the exact (MoM) and the MVF models. As it is seen, excellent fitting is achieved. Accordingly the equivalent circuits without and with considering frequency dependence of soil for $\sigma_0 = 0.001S/m$ are extracted as shown in figure 5 and 6 respectively. From now on the extracted equivalent circuit in figure 6 can be imported to EMTP for modeling grounding system.

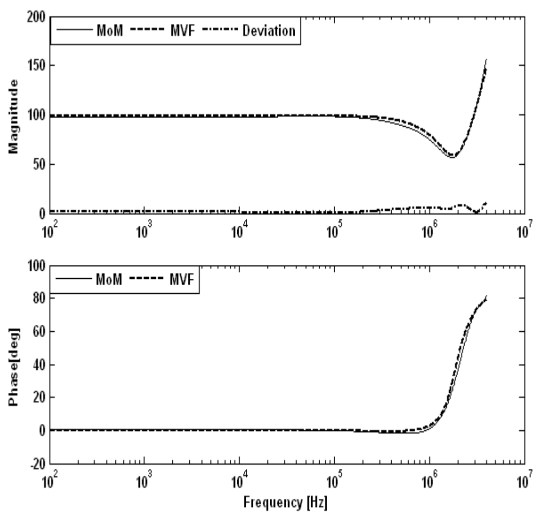

Fig. 4 Modeled input impedance by the MoM and MVF for $\sigma_0 = 0.001S/m$.

Finally to know how the frequency dependence of electrical parameters of soil affects the transient voltage of surge arrester connected to overhead lines, an overhead line above ground of height h=10m (figure 1) is investigated.

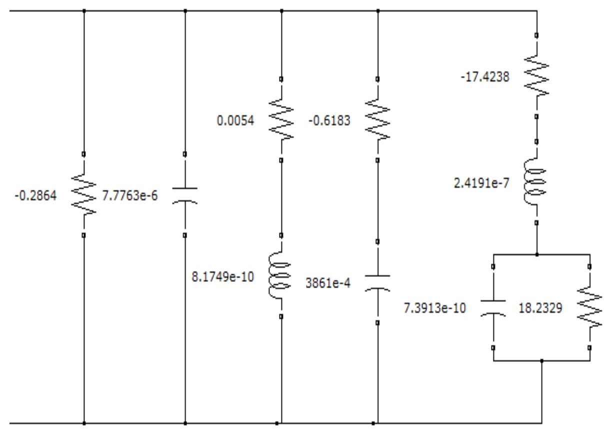

Fig. 5. Equivalent circuit of grid-grounding system without considering frequency dependence of soil for $\sigma_0 = 0.001S/m$.

The arrester is a nonlinear load of the following characteristic:

$$i = p\left(\frac{v}{v_{ref}}\right)^q \tag{14}$$

Where p is an integer, q is an exponent, and v_{ref} reference voltage for avoiding overflow. Note that in figures 5 and 6, all resistance, inductances and capacitances are in Ω, H and F respectively.
As it is seen in the figures 7, when the frequency dependence of soil is included, the transient voltage of grounding system affects the rise time and peak value. It is well known that this influences the insulation coordination study of power system and choosing proper lightning arresters [18].

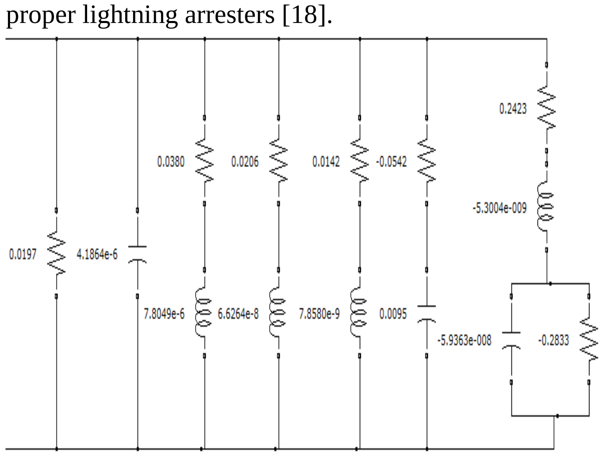

Fig. 6. Equivalent circuit of grid-grounding system with considering frequency dependence of soil for $\sigma_0 = 0.001S/m$.

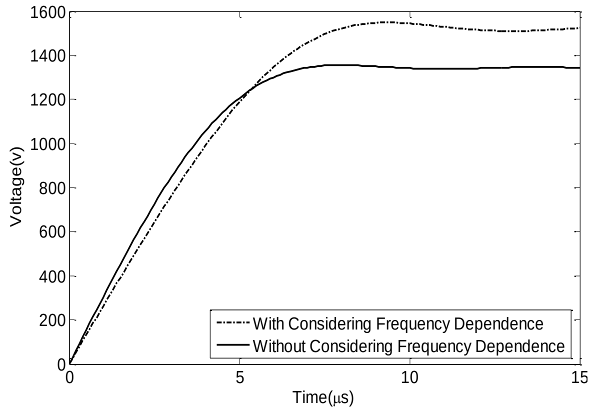

Fig. 7 lightning-induced voltage of surge arrester with and without considering frequency dependence of electrical parameters of soil.

4. CONCLUSION

In this paper assuming the electrical parameters of soil are frequency-independent, the transient voltage across arrester was evaluated. The achieved results show that this affects rise time and peak value of lightning-induced voltage and accordingly these affect study of insulation coordination of power system and selecting proper arresters. Transient analysis of multi-conductor overhead line terminated to arrester is another study that is under way.

5. ACKNOWLEDGMENT

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