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The Impact of the Grounding System on the Lightning Performance of Transmission Lines: a Sensitivity Analysis

K. Sheshyekani[1,2], Ali. A. Ghadimi[1], H. R. Karami[2], S. H. H. Sadeghi[2], R. Moini[2], F. Rachidi[3] and M. Paolone[4]

k-sheshyekani@araku.ac.ir, a-ghadimi@araku.ac.ir, hamidr_karami@aut.ac.ir, sadeghi@aut.ac.ir, moini@aut.ac.ir, farhad.rachidi@epfl.ch, mario.paolone@unibo.it
[1]Faculty of engineering, Arak university, Shahid Beheshti Ave, Arak 38156, Iran.
[2]Electromagnetics Research Laboratory of Amirkabir University of Tech, 424 Hafez Ave., Tehran 15914, Iran
[3]Swiss Federal Institute of Technology, Lausanne 1015, Switzerland
[4]Bologna University, Bologna, 40136, Italy

ABSTRACT

The paper presents some numerical studies aiming at investigating the effect of different grounding system structures on the lightning performance of transmission lines equipped with surge arresters. The model takes into account the frequency dependence of the grounding system. The transmission line is treated in frequency domain by use of the BLT (Baum-Liu-Tesche) equations while the grounding system, is simulated using general electromagnetic model solved by means of the Method of Moment (MoM) in frequency domain. The lightning-originated overvoltages in presence of the surge arrester are then calculated in frequency domain using the Arithmetic Operator Method (AOM). A sensitivity analysis has been done studying the effect of different parameters including soil electromagnetic properties, grounding system structure and injection point on the lightning-originated overvoltages.

1. INTRODUCTION

The performance of transmission lines against lightning surge currents is an important issue in the protection and insulation coordination study of power systems. However, most often the grounding system to which shielding wires and lightning arresters are connected is treated in a simplified fashion disregarding its frequency dependence. It is noted that a detailed model of grounding system is desirable for a more accurate estimation of the back-flashover rate of transmission lines which is an important parameter in the protection of transmission line against lightning generated overvoltages. The lightning protection performance is dominantly affected by the frequency dependence of the grounding system. For instance, in the case of high values of grounding impedance at higher frequencies, the overvoltages might exceed the Lightning Impulse Withstand Level (LIWL) of power system apparatuses.

In this paper a sensitivity analysis is done to investigate the effect of various grounding system structures including rods, grids, etc., as well as soil parameters on the lightning performance of transmission lines. The importance of this study stems from the wide range of soil parameters that transmission lines might envisage along their profile in jungles, deserts or mountains. In particular, it is always a vexing problem for engineers to design an effective grounding system with a proper impedance in rocky soils where transmission line is prone to experience a high back-flashover rate. The method used in this paper has been recently presented in [1,2]. In this method, the transmission line is represented in frequency domain by making use of the BLT (Baum-Liu-Tesche) equations while the grounding system, to which the arrester station is connected, is simulated using general electromagnetic model solved by means of the Method of Moment (MoM) in frequency domain. The lightning-originated overvoltages in presence of the surge arrester are then calculated in frequency domain using the Arithmetic Operator Method (AOM).

2. THEORETICAL MODELING

Consider the single-phase transmission line above a lossy ground shown in Fig.1 in which the lightning surge is originated by a direct strike to the phase conductor. As shown in Fig.1, the considered line geometry assumes a surge arrester connected to the grounding system at the end of the transmission line ($x=L$).

For such a configuration, the arrester could be considered in series with the transient impedance of the grounding system $Z_g(f)$. This transient impedance represents the frequency-dependence of the grounding system. It is determined by means of a rigorous electromagnetic model (EFIE numerically solved by means of the MoM) [3]-[6].

2.1 EFIE for grounding system

The grounding system conductors are divided into small segments. The conductors are considered as thin wires, assuming that their radii are much smaller than the wavelength and their length are greater than the radii. Consequently, the current is considered to flow in a filamentary line on the wire axis, with zero values on the endpoints of the wire segment (e.g., sinusoidal basis functions) [3]. This axial current produces an electric field in the surrounding media which can be calculated by multiplying the current by the Green's function and integrating along the wire. The boundary condition requires that the total tangential electric field be zero on a perfect conductor, namely,

$$u\cdot(\boldsymbol{E}^i + \boldsymbol{E}^s) = 0 \quad (1)$$

where E^i is the incident electric field by an external source, and E^S is the scattered electric field produced by the induced currents on the conductor. Applying the boundary condition along the thin wire, the related EFIE can be derived [7],

$$u.E^i = -\frac{j\omega\mu_1}{4\pi}\int_l I_l(r')G(r,r')dl \quad (2)$$

where $G(r,r')$ is the dyadic Green's function for the electric field at r due to a current element at r'. $I_l(r')$ is the unknown induced current along the wire [3]-[5].

MoM is the most popular standard numerical method to treat integral equations of the kind given by (2). Using the MoM, the integral equation is converted into a system of linear equations whose solution can be obtained in a straightforward way. This procedure requires the grounding conductors to be divided into small segments to determine the current distribution at each segment through the numerical solution [4]. The effect of the soil layers can be taken into account by using the Sommerfeld integrals [3]. Since the computation of the Sommerfeld integrals is time demanding, several simplified methods - such as the image theory - are utilized to circumvent this problem [5].

2.2 Nonlinear Circuit Formulation

Fig. 2 shows a circuit representation of the model in which two distinct parts can be identified, namely: i) the terminal non-linear load formed by the arrester and the frequency-dependent ground impedance, and ii) the transmission line which is assumed to be linear.

The transmission line is characterized by a length L, a propagation constant γ, and a characteristic impedance Z_c. As shown in Fig. 3, this linear portion of the model can be represented by an equivalent Norton equivalent circuit. In frequency domain, the input admittance of the circuit is given by $Y_{in}=1/Z_{in}$, where Z_{in} is the input impedance of the line. The short-circuit current is defined as $I_{sc}=V_{oc}/Z_{in}$, where V_{oc} is the open-circuit voltage [8]. For the determination of Y_{in} in Fig. 3, the line is supposed to be open-circuited at its end ($x=L$) and matched at its beginning ($x=0$). The use of the BLT equations allows to evaluate the load voltage $V(L)$. The ratio of this open-circuit voltage to the excitation current provides the input impedance:

$$Z_{in} = \frac{V(L)}{I_O} = Z_c\,\frac{1+\rho_1 e^{-2\gamma L}}{1-\rho_1 e^{-2\gamma L}} \quad (3)$$

in which the reflection coefficient $\rho_1 = 0$, hence the input impedance is identical to the characteristic impedance of the line.

Similarly, the open-circuit voltage can be determined by calculating $V(L)$ due to a single lumped voltage source at x=0 and setting the reflection coefficient at the line end $\rho_2 = 1$:

$$V_{oc} = V_o\,\frac{e^{-\gamma L}(1-\rho_1)}{1-\rho_1 e^{-2\gamma L}} = V_o e^{-\gamma L} \quad (4)$$

By making reference to the simple model shown in Fig 1, the lightning current is divided in two equal parts traveling in both directions of the line.

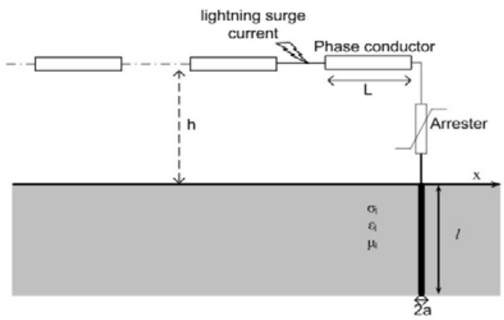

Fig. 1. Schematic diagram of the analyzed problem: a single conductor transmission line above a lossy ground with a grounded surge arrester placed at one line termination connected to a vertical grounding rod.

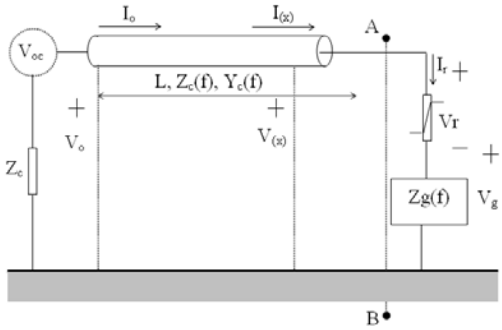

Fig. 2. Circuit representation of the problem shown in Fig.1.

Before reflected surges reach the strike point, the injected voltage can be easily calculated by multiplying the characteristic impedance of the line by the injected lightning current. Thus the short-circuit current in Fig. 3, is given by,

$$I_{sc} = \frac{V_{oc}}{Z_{in}} = \frac{I_P Z_c e^{-\gamma L}}{Z_c} = I_P e^{-\gamma L} \quad (5)$$

where I_P, is the injected lightning impulse current.

Given the input impedance and the short circuit current, the Norton equivalent circuit is treated in frequency domain using the AOM.

With reference to Fig. 3, let $\overline{V}_r$ and $\overline{V}_g$ represent the arrester voltage (henceforth called arrester residual voltage) and the grounding system voltage, respectively.

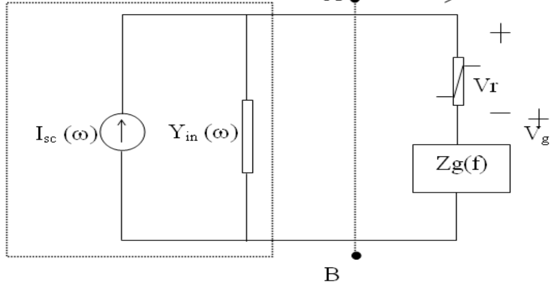

Fig 3. . Equivalent circuit model of the problem shown in Fig. 2.

Applying the Kirchhoff Current Law (KCL) to the surge arrester and the grounding system leads to

$$-\bar{I}_{\mathrm{sc}} + \bar{Y}_{\mathrm{in}}(\bar{V}_r + \bar{V}_g) + \bar{I}_{\mathrm{r}} = 0 \quad (6)$$

where

$$\bar{V}_{\mathrm{r}} = \left[V_{\mathrm{r},0}, V_{\mathrm{r},1}, V_{\mathrm{r},2}, \ldots V_{r,2P-1}, V_{r,2P}\right]^T \quad (7)$$

$$\bar{I}_{\mathrm{sc}} = \left[I_0, I_{\mathrm{sc},1}, -I_{\mathrm{sc},2}, I_{\mathrm{sc},3}, -I_{\mathrm{sc},4}, \ldots, I_{\mathrm{sc},n}, -I_{\mathrm{sc},n+1}, \ldots\ldots 0,0\right]^T \quad (8)$$

$$\bar{I}_{\mathrm{r}} = \left[I_{\mathrm{r},0}, I_{\mathrm{r},1}, I_{\mathrm{r},2}, \ldots I_{\mathrm{r},2P-1}, I_{\mathrm{r},2P}\right]^T \quad (9)$$

$$\bar{Y}_{in} = \begin{bmatrix} 0 & 0 & . & . & . & 0 & 0 \\ 0 & Y_{r1} & -Y_{i1} & & & & \\ & Y_{i1} & Y_{r1} & & & & \\ & & & Y_{r2} & -Y_{i2} & & \\ & & & Y_{i2} & Y_{r2} & & \\ 0 & & & & & & \\ 0 & & & & & & \end{bmatrix} \quad (10)$$

where

- P is the number of frequencies in the output spectral vector, and n is the number of excitation frequencies.
- Y_{rk} and Y_{ik} are the real and imaginary parts of $Y_{\mathrm{in}}(\omega_k) = Y_{rk} + \mathrm{j}Y_{ik}$,
- $V_{r,k}, I_{r,k}$ are the k-th components of arrester terminal voltage waveform, $vr(t)$, and arrester current waveform, $ir(t)$ respectively.

$$v_r(t) = V_{\mathrm{r},0} + \sum_{k=1}^{P}\left\{V_{\mathrm{r},2k-1}\cos\omega_k t + V_{\mathrm{r},2k}\sin\omega_k t\right\} \quad (11\text{-a})$$

$$i_L(t) = I_{\mathrm{r},0} + \sum_{k=1}^{P}\left\{I_{\mathrm{r},2k-1}\cos\omega_k t + I_{\mathrm{r},2k}\sin\omega_k t\right\} \quad (11\text{-b})$$

-$I_{\mathrm{sc},k}$ (k=1,2..n) is the k-th component of the short-circuit current waveform $i_{sc(t)}$:

$$i_{\mathrm{sc}}(t) = I_1\cos\omega_1 t + I_2\cos\omega_2 t + \ldots + I_K\cos\omega_K t \quad (11\text{-c})$$

Note that the Isc is calculated only at the excitation frequencies.

To take into account the surge arrester *V-I* characteristic ($i=f_n(vr)$), Equation (6) can be written as:

$$\bar{I}sc = \bar{I}r + \bar{Y}in\bar{Z}g\bar{I}r + \bar{Y}in\bar{V}r \quad (12)$$

where $\bar{Z}g$ is the matrix form of the grounding system transient impedance.

$$\bar{Z}_g = \begin{bmatrix} 0 & 0 & . & . & . & 0 & 0 \\ 0 & Z_{r1} & -Z_{i1} & & & & \\ & Z_{i1} & Z_{r1} & & & & \\ & & & Z_{r2} & -Z_{i2} & & \\ & & & Z_{i2} & Z_{r2} & & \\ 0 & & & & & & \\ 0 & & & & & & \end{bmatrix} \quad (13)$$

Z_{rk} and Z_{ik} are the real and imaginary parts of $Zg(\omega_k) = Z_{rk} + jZ_{ik}$.

It should be noted that for given excitation frequencies and the maximum order of arrester nonlinearity (of order 7), the so-called Basic Intermodulation Product Description (BIPD) table defines the basis for the spectral vectors by determining all of the non-negative combinations or weightings of these frequencies up to the maximum order of arrester nonlinearity. A detailed description of the BIPD table is found in [9].

To solve (12) for $\bar{V}_{\mathrm{r}}$, we need to expand $\bar{I}_{\mathrm{r}}$ in terms of $\bar{V}_{\mathrm{r}}$. This is done by converting the arrester *V-I* characteristic in frequency domain. Recall from the theory of the Fourier transform that repeated multiplication of time-domain functions corresponds to repeated convolution in the frequency-domain, *i.e.*,

$$\left[v(t)\right]^n \overset{F}{\Rightarrow} \underbrace{V(f) * V(f) * \ldots * V(f)}_{n \text{ times}} \quad (14)$$

We can now use the Arithmetic Operator Method (AOM) to describe the convolution operations as matrix vector operations. The AOM uses basic arithmetic operations on signal spectra in the frequency-domain [9]. The use of AOM for calculating $V_{\mathrm{r}}(\omega)$ at each harmonic frequency is described in [10].

3. NUMERICAL ANALYSIS

We consider the case of a lightning strike to the mid-span of a transmission line terminated with an arrester (Fig. 1). The conductor diameter is d=5.62 cm and the vertical height at mid-span is h=22 m. The conductor is lossy and its parameters (resistance, inductance and capacitance) are considered to be frequency dependent. The arrester is connected to a vertical grounding rod of circular cross-section of radius r=12.5 mm, buried in a soil with a conductivity σ_1=0.01 S/m and a relative permittivity ε_r=10. Following the method presented in preceding section the whole system is then analyzed in the frequency domain. A sensitivity analysis is conducted to show the effect of the various grounding system structures and different soil parameters. Soil parameters including its conductivity and relative permittivity together with grounding system structures are changed to see the their effects on the lightning-generated overvoltages. For the sake of simplicity, it is assumed that soil ionization does not occur around grounding electrodes, and hence, soil is selected to be a linear medium.

Fig. 4 shows the input impedance (henceforth called the harmonic impedance to ground) of the vertical grounding rod for various rod lengths, computed using the general electromagnetic approach.

The proposed approach is validated by comparing its results to those obtained using the Electromagnetic Transient Program (EMTP-RV [11]) in which the grounding system is properly modeled using an equivalent RLC circuit [2].

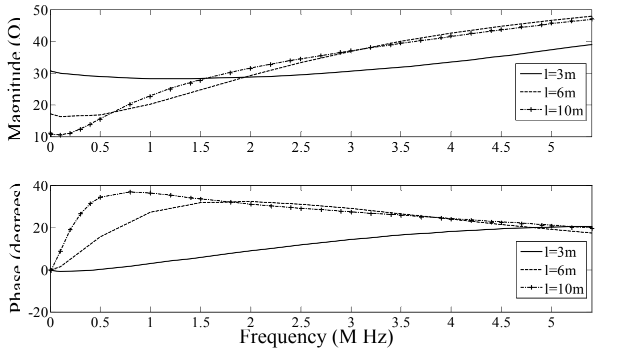

Fig. 4. Harmonic impedance to ground for a vertical grounding rod of various length l=3 m, 6m, 10m and circular cross-section of radius r=12.5 mm, buried in a soil with a conductivity σ_1=0.01 mho/m and a relative permittivity ε_r= 10.

It can be seen that the harmonic impedance shows a frequency independent behavior in the low frequency (LF) range, where the magnitude of harmonic impedance is equal to the static resistance at low frequencies. It is also seen that harmonic impedance takes different values at higher frequencies accentuating the frequency dependence of the grounding system. A 20-kA, 2/20 μs lightning current is supposed to directly hit the transmission line at a point far from the both ends of the line; hence, the line could be considered with a match load at one propagation direction. This is quite different from the static model of the grounding system which fails in providing accurate results at high frequencies when used for the calculation of the transmission line overvoltages. Fig. 5 shows the transmission line overvoltages (for a line length of 400 m) considering two different grounding rod lengths, 3 and 6 m. Also shown in this figure are the overvoltages obtained by EMTP. It can be seen that the results provided with the proposed model are in good agreement with the ones provided by the EMTP model. One might be interested in understanding the effect of the grounding system frequency dependence on the transmission line vervoltages. At higher frequencies, the grounding system might be dominantly either inductive or capacitive. If the inductive behavior prevails the capacitive one, the harmonic impedance is likely to have a sharp increase for higher frequencies resulting in higher value overvoltages. This behavior is clearly confirmed in the results shown in Fig.4. The harmonic impedance of the grounding system at higher frequencies is dramatically affected by the electromagnetic properties of the soil, the geometry of the grounding system as well as current injection point [12].

To further understand the grounding system behavior, the harmonic impedance of a vertical rod of length l=6m and a circular cross-section of radius r=12.5 mm, buried in a ground characterized by different values for the soil conductivity (0.1, 0.01, 0.001 S/m) are shown in Fig. 6. It can clearly be seen that for soils with low conductivity the harmonic impedance takes smaller values at higher frequencies resulting in smaller value overvoltages. This is due to the fact that for low conductivities, grounding system dominantly behaves capacitively which results in a smaller harmonic impedance.

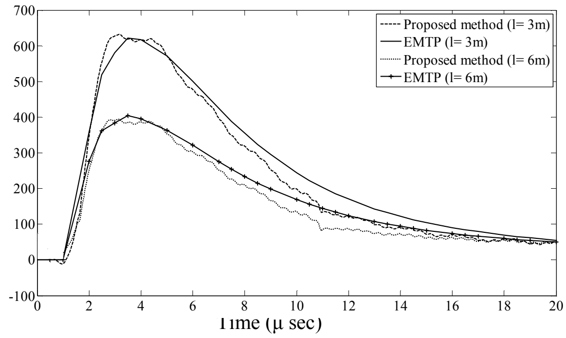

Fig. 5. Lightning overvoltage at the end of the transmission line of length L=400 m considering two different grounding rod lengths, 3 m and 6 m and circular cross-section of radius r=12.5 mm, buried in a soil with a conductivity σ_1=0.01 mho/m and a relative permittivity ε_r= 10.

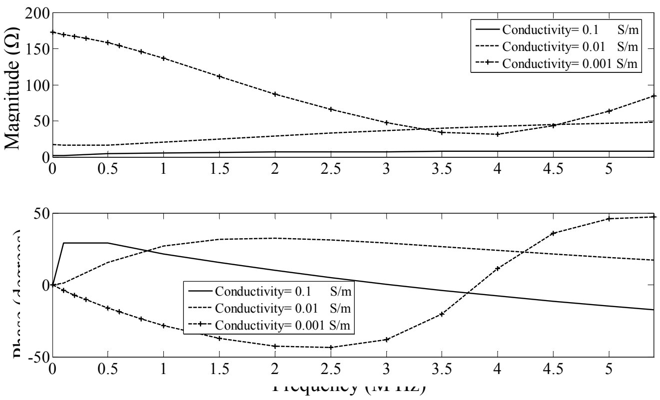

Fig. 6. Harmonic impedance to ground for a vertical grounding rod of length l=6 m, and circular cross-section of radius r=12.5 mm, buried in a soil with various conductivity σ1= 0.1, 0.01, 0.001 mho/m and a relative permittivity εr= 10.

In another study we investigated the effect of the injection point i.e., the point where the lightning current flows through the grounding system. To this aim a horizontal electrode of length l=12m and a circular cross-section of radius r=7 mm, buried in depth of h=0.5m in a ground characterized by soil conductivity of σ= 0.01 S/m as shown in Fig. 7 has been studied. The harmonic impedances of the horizontal grounding electrode when the lightning current is injected in the middle and the corner of the electrode are shown in Fig. 8. It is clearly seen that the injection point can dramatically change the harmonic impedance of the grounding system at higher frequencies. It is an important issue in the sense that one can modify the lightning performance of the grounding system of transmission lines by connecting the ground accessories (either the tower, shielding wire or lightning arrester) to a point far from the edge of the grounding system.

Finally the effect of the frequency dependence of a complex grounding systems is studied. Fig. 9 shows the results when the arrester is connected to a grounding grid.

The considered grounding grid is an equally-spaced 20m×20m square. The depth of the grid is 1m and the conductors are of radius r=7mm. Soil conductivity and permittivity are respectively, σ_1=0.01 mho/m and ε_r= 10.

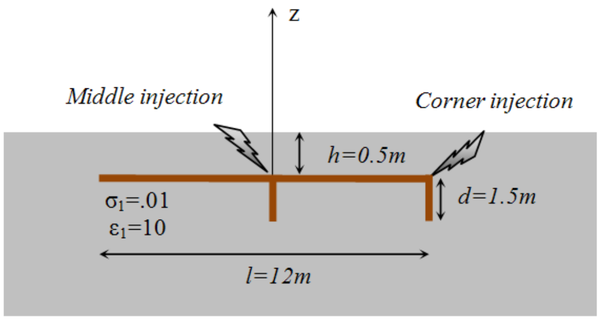

Fig. 7. Schematic diagram of the horizontal grounding electrode with two injection points.

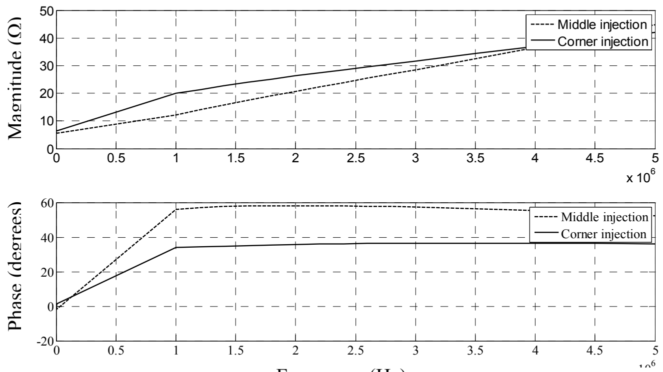

Fig. 8. Harmonic impedance to ground for a horizontal grounding rod shown in Fig. 6 buried in a soil with a conductivity σ_1=0.01 mho/m and a relative permittivity ε_r= 10.

The results are compared with those obtained adopting a static model for the grounding system and show that it is important to take into consideration the frequency dependence of the grounding system. It is seen that the inclusion of the frequency dependence of the grounding system affects primarily the early-time response of the overvoltages, namely their risetime and peak value. These parameters play an important role in the insulation coordination study and the selection of lightning arresters.

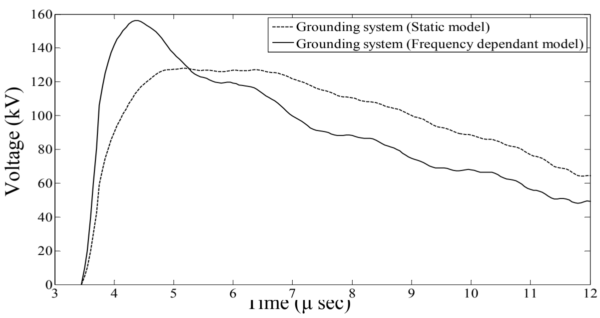

Fig.9. Overvoltages at the end of the transmission line. Arrester connected to a grounding grid.

Table. 1 shows the effect of different grounding system parameters on the low/high frequency part of harmonic impedance as well as lightning-generated overvoltages. It is seen from this Table that various parameters including, soil electromagnetic properties, grounding system structure and injection point are of great importance in the lightning overvoltages of transmission line.

Table.1: Effect of grounding system parameters on the low/high frequency part of harmonic impedance as well as lightning transient over-voltages

	Harmonic impedance (Low Frequency)	Harmonic impedance (High Frequency)	Lightning transient over-voltages
Soil resistivity	Significant	Significant	Significant
Soil permittivity	Dispensable	Rather important	Rather important
Electrode length	Significant	Significant	Significant
Injection point	Dispensable	significant	significant

4. CONCLUSION

We presented several numerical studies in order to investigate the effect of grounding system frequency dependency on the lightning overvoltages of transmission lines. The analyses have been done using the MoM-AOM approach.

It has been shown that the frequency dependency of grounding systems has a significant effect on the lightning overvoltages of transmission lines. A sensitivity analysis has been done studying the effect of different parameters including soil electromagnetic properties, grounding system structure and injection point. It is shown that these parameters can remarkably change the transient performance of the grounding system affecting the respective lightning overvoltages.

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From: "ICLP 2010 Tecnical Program Committee" <2010.iclp@gmail.com>
To: <k-sheshyekani@araku.ac.ir>
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ICLP 2010 Summary #1139 - Impact of Grounding Systems on the Lightning Performance of Transmission Lines: a Sensitivity Analysis

On behalf of the Scientific Committee of the International Conference on Lightning Protection, we are pleased to inform that your Summary has been accepted to be presented at the next ICLP, Cagliari, Italy - September 13-17, 2010.

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Sincerely,

Alberto Borghetti
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COMMENTS TO THE AUTHORS:

The topic of the paper is very important. Although the abstract is very short, the expected contribution appears to be useful. As the work is presented in frequency domain, the final version of the paper is expected to clearly show how the nonlinear behavior of surge arresters is taken into account.