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Influence of frequency-dependent characteristics of grounding and line models on transient overvoltages in overhead lines

***Abstract**. This paper assesses the influence of the frequency-dependent characteristics of line and grounding models, along with the effect of the frequency dependence of the electrical parameters of soil, on developed lightning overvoltages in overhead lines. It is shown that in most cases the frequency dependence of soil parameters can be disregarded in the line model. On the other hand, the frequency-dependent characteristics of grounding markedly impacts the developed transient voltages, and in accurate studies a grounding static model should be avoided.*

***Streszczenie.** Oszacowano wpływ charakterystyk częstotliwościowych modelu linii i uziomu, włącznie z zależnością od częstotliwości parametrów gruntu, na przepięcia pochodzenia piorunowego w liniach napowietrznych. W większości przypadków w modelu linii zależność parametrów gruntu od częstotliwości może być pominięta. Charakterystyki częstotliwościowe uziomu mają natomiast znaczący wpływ na wyznaczane przepięcia, zatem w przypadku dokładnych analiz należy unikać stosowania statycznego modelu uziomu. (**Wpływ charakterystyk częstotliwościowych uziemienia i linii na przepięcia piorunowe w liniach napowietrznych**).*

Keywords: frequency-dependent line model, frequency-dependent grounding model, overhead line, lightning transients.
Słowa kluczowe: model linii zależny od częstotliwości, model uziomu zależny od częstotliwości, linia napowietrzna, przepięcia pochodzenia piorunowego.

Introduction

Direct lightning strikes to the transmission line towers or to the shielding wires can result in severe overvoltages across insulators leading to short circuits and line outages [1, 2]. Lightning impulse currents are usually characterized by a wideband frequency content ranging from dc to several megahertz over which the power system components can show different behaviour at different frequency intervals. In particular, in accurate evaluation of the lightning performance of transmission lines, it is important to consider the frequency-dependent characteristics of line parameters and grounding systems.

Traditionally, the lightning performance of transmission lines is assessed using the widely accepted time-domain electromagnetic transient tools (for instance, ATP-EMPT, EMTP-RV, and PSCAD), due to their capability to deal with complex networks and different system apparatus, along with non-linear devices such as surge arresters [3, 4]. However, in these time-domain tools, the frequency-dependent behaviour of grounding system is disregarded and it is often modelled as a simple lumped resistance [5]. Also, the soil conductivity and permittivity strongly vary along the typical frequency range of lightning currents being this effect not included in the aforementioned time-domain tools [6]. Recent works, for instance [7, 8, 9], show that such frequency dependence of soil parameters markedly impacts the lightning performance of grounding systems. Furthermore, in [10] it is shown that the consideration of frequency-dependent soil parameters can be relevant in the simulation of high-frequency transients on transmission~~s~~ lines if the ground is a poor conductor.

Within this context, this work aims to investigate the influence of the accurate representation of the frequency-dependent characteristics of grounding system and line parameters on the lighting overvoltages calculation. To this aim, the grounding system admittance matrix is first calculated over the frequency range of interest using an accurate electromagnetic model. Then, a rational approximation of the grounding system admittance matrix is obtained using the vector fitting method [11]. Finally, the obtained rational approximation is interfaced with the time-domain tool by means of an equivalent circuit. A wideband model is also obtained for the transmission line from its nodal admittance in the frequency domain, including the frequency dependence of soil parameters. Then, a rational approximation is obtained and the model is interfaced with the time-domain tool in a similar way done for the grounding system.

Frequency-dependence of electrical parameters of soil modelling

According to classical laboratorial measurements and recent field experimental results [12, 13], there is a significant frequency dependence of soil conductivity σ_s and permittivity ε_s in the typical frequency range of lightning currents (0 Hz to few MHz). The soil magnetic permeability is, in general, basically constant and almost equal to vacuum permeability, μ_0 [13].

Recently, Alipio and Visacro proposed (1) and (2) to compute the frequency dependence of soil conductivity σ_s and permittivity ε_s based on a large number of field measurements and on the causal Kramers-Kronig's relations and Maxwell Equations [13].

(1) $$\sigma_s = \sigma_0 + \sigma_0 \times h(\sigma_0)\left(\frac{f}{1\,MHz}\right)^{\gamma}$$

(2) $$\varepsilon_s = \varepsilon'_\infty + \frac{\tan(\pi\gamma/2)\times 10^{-3}}{2\pi(1MHz)^{\gamma}}\sigma_0 \times h(\sigma_0)\,f^{\gamma-1}$$

where: σ_s – soil conductivity in mS/m, σ_0 – low-frequency conductivity (100 Hz) in mS/m, ε_s – soil permittivity, ε'_∞ – soil permittivity at higher frequencies, f – frequency in Hz.

According to [13], the following parameters of model (1) and (2) are recommended to obtain mean results of measurements for the frequency variation of σ_s and ε_s: γ = 0.54, ε'_∞ = 12ε_0 and $h(\sigma_0)$ = 1.26×$\sigma_0^{-0.73}$, where ε_0 is the vacuum permittivity (ε_0≅8.854×10^{-12} F/m).

It is worth mentioning that using (1) and (2) to take the frequency dependence of soil parameters into account proved to be consistent based on extensive field tests in different soils and on the experimental results of the impulse response of grounding electrodes [13].

Line Modelling

The transmission line is represented via the well-known nodal admittance matrix $\boldsymbol{Y_n}$ [14]. $\boldsymbol{Y_n}$ defines the relation between port voltages and currents at the lines ends. For a line length l, the characteristic admittance $\boldsymbol{Y_c}$ and propagation matrix $\boldsymbol{A}$, which are calculated using the line-impedance per unit of length $\boldsymbol{Z}$ and the line admittance per unit length $\boldsymbol{Y}$, are defined as [14]

(3) $$\boldsymbol{Y_c} = \boldsymbol{Z}^{-1}\sqrt{\boldsymbol{ZY}}$$

(4) $$\boldsymbol{A} = \exp\left(-l\sqrt{\boldsymbol{ZY}}\right)$$

For transmission lines, $\boldsymbol{Z}$ can be written as

(5) $$\boldsymbol{Z} = \boldsymbol{Z_i} + \boldsymbol{Z_{ext}} + \boldsymbol{Z_g}$$

where: $\boldsymbol{Z_i}$ – the internal conductor impedance, $\boldsymbol{Z_{ext}}$ – ideal external impedance, $\boldsymbol{Z_g}$ – ground return impedance, all matrices per unit length.

The line parameters were calculated according [15]. In particular, in the calculation of $\boldsymbol{Z_g}$, the frequency-dependent soil parameters are considered using the complex plane method where the ideal soil is at a depth $d_e = 1\Big/\sqrt{j\omega\mu_0\left(\sigma_s + j\omega\varepsilon_s\right)}$ below the actual soil in a procedure similar to the one presented in [16], but now replacing σ_s by $\sigma_s + j\omega\varepsilon_s$ [14]. For each frequency, σ_s and ε_s are determined using (1) and (2). The nodal admittance is calculated directly in the phase domain and is given by [14]

(6)
$$\boldsymbol{Y_n} = \begin{bmatrix} \boldsymbol{Y_c}\left(\boldsymbol{U}+\boldsymbol{A}^2\right)\left(\boldsymbol{U}-\boldsymbol{A}^2\right)^{-1} & -2\boldsymbol{Y_c}\boldsymbol{A}\left(\boldsymbol{U}-\boldsymbol{A}^2\right)^{-1} \\ -2\boldsymbol{Y_c}\boldsymbol{A}\left(\boldsymbol{U}-\boldsymbol{A}^2\right)^{-1} & \boldsymbol{Y_c}\left(\boldsymbol{U}+\boldsymbol{A}^2\right)\left(\boldsymbol{U}-\boldsymbol{A}^2\right)^{-1} \end{bmatrix}$$

where: $\boldsymbol{U}$ – identity matrix.

The nodal admittance matrix $\boldsymbol{Y_n}$ is calculated in a frequency range from dc to several megahertz. Then, a rational approximation of $\boldsymbol{Y_n}$ is obtained using the vector fitting method [11], which was further expanded to deal with rational approximation of frequency dependent admittance matrices. Finally, from the rational approximation of the nodal admittance, it is possible to synthesize an electrical network, which can be promptly included in time-domain electromagnetic tools.

Grounding system modelling

In lightning studies, it is important to consider the frequency-dependent characteristics of grounding, along with the frequency dependence of soil parameters, in order to accurately determine the resultant overvoltages. To this aim, a wideband model of the grounding system is obtained as follows. First, the harmonic impedance $Z(j\omega)$ of the grounding system is determined using the accurate Hybrid Electromagnetic Model (HEM) [17], in a frequency range from dc to several megahertz. As detailed [17], the HEM model solves Maxwell's equations numerically via the vector and scalar potentials using the thin wire approximations. In calculations, the frequency dependence of soil parameters is taken into account based on (1) and (2). After determining the harmonic impedance $Z(j\omega)$, a pole-residue model of the associated admittance $Y(j\omega)$=1/$Z(j\omega)$ is obtained using the vector fitting method [11]. Finally, in a similar approach as the one adopted for line modeling, from the obtained passive pole-residue model of the grounding admittance, an electrical network is synthesized, which can be promptly included in time-domain simulations.

Developments

We consider a 132-kV overhead line with a single ground wire, as illustrated in Fig. 1. It is assumed that the ground wire is hit directly by a lightning stroke in a point 800 m away from the substation entrance. At the substation end, the ground wire is connected to the grounding system, which consists of a square grid of 30 m × 30 m, composed of square meshes with space between conductors of 5 m. The 7-mm-radius copper electrodes are buried at a depth of 0.8 m in soil. Three values of low-frequency soil resistivity ρ_0=1/σ_0 are considered: 100, 1000 and 10000 Ωm. The equivalent representation of the system under study is depicted in Fig. 2. At the substation end, the phase conductors are connected to capacitances of 470 pF which represent in a simplified way the substation components, according to [18]; in the other end, the phase conductors are impedance matched.

The discharge striking the ground wire is represented by a ramp-type current waveform, with a rise-time of 2-μs according to IEEE Guide for Improving the Lightning Performance of Transmission Lines [1].

In order to assess the influence of the frequency-dependent characteristics of line and grounding models, along with the effect of the frequency dependence of the electrical parameters of soil, the following assumptions were adopted in simulations.

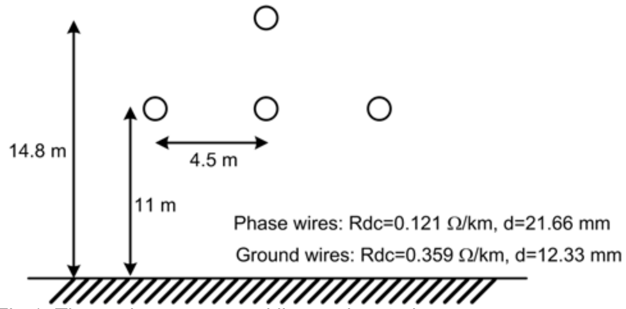

Fig.1. Three-phase overgead line under study

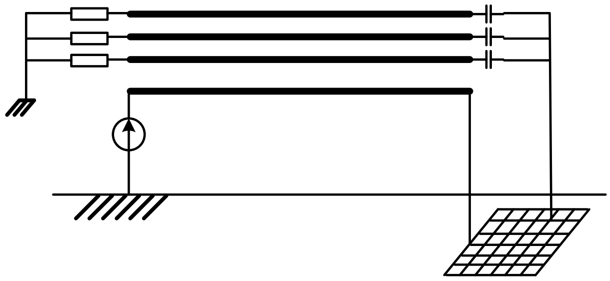
Fig.2. Equivalent representation of the system under study

Two models are adopted to represent the line. Model 1 corresponds to the nodal admittance matrix considering the frequency dependence of soil parameters, as described in Section III. Model 2 corresponds to the line model proposed by Marti [19], which is possibly the most popular model for the digital simulation of electromagnetic transients on overhead lines. Briefly, it is a distributed-parameter model that includes the variation of the line parameters with frequency. The solution of the transmission line equations is performed in the modal domain, considering a constant and real transformation matrix. Marti model disregards the frequency dependence of soil parameters in the calculation of the ground return impedance.

Two models are adopted to represent the grounding system. Model 1 corresponds to a static model, which consists of representing the grounding system by a lumped resistor with value equal to the low-frequency grounding resistance. This simplified model is commonly used in studies of lightning overvoltages developed in transmission lines and substations [3, 4]. Model 2 corresponds to the frequency-dependent model described in Section IV.

The frequency-dependent line and grounding models were obtained, respectively, according to Sections III and IV. In both cases, the electrical parameters of soil were assumed to be frequency-dependent according to the causal model presented in Section II. Also, it is worth mentioning that both the pole-residue model and the electrical network of the line and grounding models were obtained using the public domain calculation package for rational approximation of frequency dependent admittance matrices available in [20]. The passivity of the pole-residue models is enforced by perturbation of model parameters [21]. All time-domain simulations presented in the next section were developed in the Alternative Transients Program (ATP) [22].

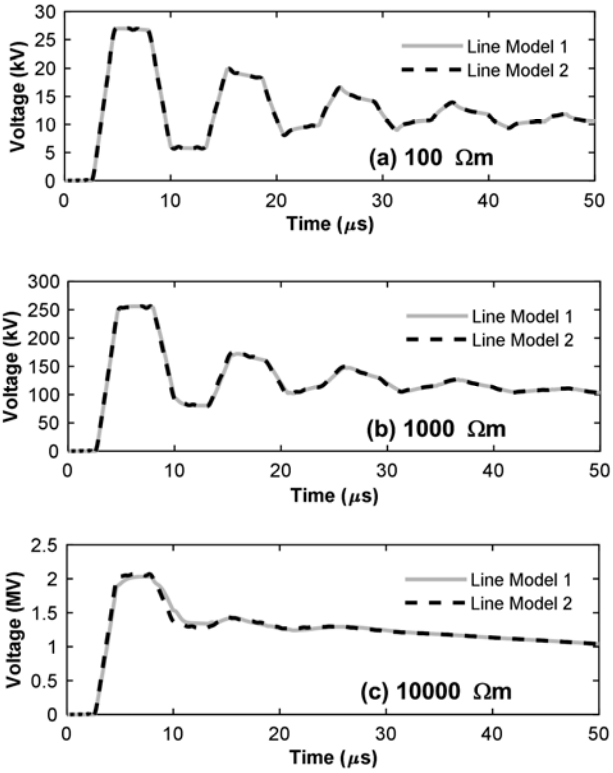

Fig.3. Voltage at the substation end of the ground wire, considering soil resistivity of (a) 100 Ωm, (b) 1000 Ωm, and (c) 10000 Ωm. Line model 1 corresponds to the nodal admittance matrix considering the frequency dependence of soil parameters, as described in Section III. Model 2 corresponds to the traditional Marti line model. In all simulations, the grounding system is represented by a lumped resistance R_G with value equal to the low-frequency resistance of the grounding grid (R_G is equal to 1.49, 14.91 and 149.11 Ω, respectively for the grounding grids buried in soils of 100, 1000 and 10000 Ωm)

Influence of Line Model

Fig. 3 illustrates the voltage calculated at the substation end, considering three values of soil resistivity, 100, 1000 and 10000 Ωm. In order to focus on the influence of line model, in all cases the substation grounding grid is represented by a simple lumped resistance with value equal to the low-frequency grounding resistance of the grid.

By analysing the voltage waveforms illustrated in Fig. 3, it is seen that the curves obtained considering the two line models are basically coincident. Only in case of high-resistivity soil, slight differences are observed in the voltage waveforms in the first microseconds. If very accurate results are not required, the frequency dependence of the electrical parameters of soil can be neglected, and the line model by Marti leads to good results.

Influence of grounding model

Fig. 4 illustrates the voltage calculated at the substation end, considering the grounding system represented as a simple lumped resistance with value equal to the low-frequency grounding resistance of the grid (static model—model 1), and as an equivalent circuit determined according to Section III (frequency-dependent model—model 2). In all simulations, the line is rigorously represented including the frequency dependence of soil parameters.

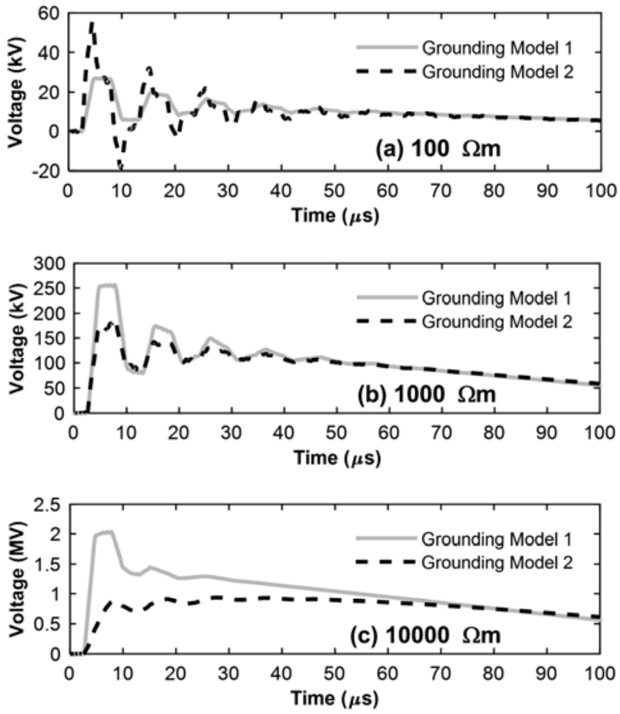

Fig.4. Voltage at the substation end of the ground wire, considering soil resistivity of (a) 100 Ωm, (b) 1000 Ωm, and (c) 10000 Ωm. Grounding model 1 corresponds to a static model, which consists of representing the grounding system by a lumped resistor with value equal to the low-frequency grounding resistance R_G (R_G is equal to 1.49, 14.91 and 149.11 Ω, respectively for the grounding grids buried in soils of 100, 1000 and 10000 Ωm). Grounding model 2 corresponds to the frequency-dependent model described in Section IV. In all simulations, the line is rigorously represented including the frequency dependence of soil parameters (described in Section III)

By analyzing the voltage waveforms illustrated in Fig. 4, it is seen that the two models lead to quite different results. In case of high-resistivity soils (1k and 10k Ωm), the calculated overvoltages considering the static model (model 1) show higher values, in comparison with the voltages calculated taking into account the frequency-dependent characteristics of grounding (model 2). This is due to fact that, considering the area of the grounding grid under analysis, the impulse performance of the grounding is better than its low-frequency performance, for soils of 1000 Ωm and 10 kΩm, according to [23]. The frequency-dependent model of grounding captures its wideband behavior, while the static model captures only its low-frequency behavior. Since in case of 1k and 10k Ωm the low-frequency performance of grounding is worse than its impulse performance, it is expected to have higher overvoltages in the conductor end connected to the grounding grid, when considering the static model (model 1).

On the other hand, in case of low-resistivity soil, 100 Ωm, the impulse performance of the grid is worse than its low-frequency performance [23]. In this case, the voltages determined taking into account the frequency-dependent characteristics of grounding are larger and the waveform presents an oscillatory behavior due to the significant modification of the reflection coefficient at the junction between the ground wire and substation grounding grid.

It is to be noted that in the slow portion of the voltage waveforms, no relevant differences are observed between the curves, since in this region the voltage behavior is dominated by the low-frequency grounding resistance and the frequency-dependent characteristics of grounding are not important.

Finally, it is worth mentioning that the observed differences between the waveforms along the fast transient period are valid for the case analyzed in this paper. Such differences between the two grounding models depend, among other aspects, on the grid area, soil parameters and front-time of current wave. Anyway, irrespective to the way the developed overvoltages are influenced, they strongly depend on the frequency-dependent characteristics of grounding.

Summary and conclusions

This paper assessed the influence of the frequency-dependent characteristics of line and grounding models, along with the effect of the frequency dependence of the electrical parameters of soil, on developed lightning overvoltages in overhead lines. It was shown that the frequency dependence of the electrical parameters of soil can be disregarded in the line model. Only in very high-resistivity soils such effect should be considered if highly accurate results are required. The frequency-dependent characteristics of grounding system markedly impact the developed lightning overvoltages and the use of a grounding static model should be avoided.

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