DOI: 10.2478/bhee-2018-0003

Original scientific paper/Izvorni naučni rad

MODELLING OF THE ELECTROMAGNETIC TRANSIENTS ON THE GROUNDING SYSTEMS

MODELIRANJE ELEKTROMAGNETSKIH TRANZIJENATA NA UZEMLJIVAČKIM SISTEMIMA

Nedis Dautbašić[1], Adnan Mujezinović[1]

Abstract: This paper deals with the mathematical model based on the transmission line (TL) approach for the simulation of grounding system behaviour at high frequency electromagnetic transients. This paper discusses the possibility of application transmission line approach, when conducting electromagnetic transient analysis of grounding systems. These analyses are important for electromagnetic compatibility (EMC) problems as well as for lightning protection (LP) system efficiency evaluation. Within this paper transmission line model of grounding system with taking into account mutual interactions between grounding system segments is presented.

Keywords: electromagnetic transients, grounding system, transmission line approach

Sažetak: U ovom radu predstavljen je matematski model za modeliranje visokofrekventnih elektromagnetskih tranzijenata na uzemljivačkom sistemu baziranom na teoriji prijenosnih linija. U radu se razmatra mogućnost primjene teorije prijenosnih linija u analizi elektromagnetskih tranzijenata na uzemljivačkim sistemima. Ove su analize važne za razmatranje problema elektromagnetne kompatibilnosti kao i za evaluaciju učinkovitosti sistema za zaštitu od atmosferskih pražnjenja. Prezentiran je model uzemljivačkog sistema baziran na teoriji prijenosnih linija koji u obzir uzima međusobne utjecaje između segmenata uzemljivačkog sistema.

Ključne riječi: elektromagnetski tranzijenti, uzemljivački sistem, pristup baziran na prijenosnim linijama

INTRODUCTION

The purpose of the grounding system in the high voltage facilities is to provide the safety of the personnel and equipment inside and outside the facilities during the short-circuit and lightning discharge [1]. Also, parameters of the grounding system of high voltage transmission lines have a significant impact on the magnitude of the lightning overvoltage and insulation coordination [2], [3]. Knowledge of the grounding system behaviour under high frequencies phenomenon is essential for the electromagnetic compatibility studies within high voltage facilities as well as for lightning protection system efficiency evaluation [4], [5]. The grounding systems are performed by a system of uninsulated galvanically connected conductors which are buried in soil. These conductors must be connected in such a way to prevent together with the surrounding soil all harmful effects that can be caused by high frequencies events such as lightning discharges [6].

When designing grounding systems of high voltage facilities, it is important to consider their impulse characteristics, i.e. their characteristics when they are exposed to fast electromagnetic transients such as lightning and switching transients. Due to the predominantly inductive character of the grounding system at high frequencies, overvoltage in certain points of the grounding system can reach high values, which can impact the operation of the protection devices and communication systems [7]. The response of grounding system to the lightning current can be represented using impulse impedance [8], [9]. The impulse impedance of the grounding system can be defined as a ratio of peak value of the voltage and current at the feeding point of the grounding system [10]. Therefore, in order to evaluate behaviour of the grounding system at high frequencies it is necessary to know the exact voltage and current values on the grounding system.

High frequency excitation analysis of the grounding system can be conducted by using different mathematical models based on the basic circuit theory, transmission line theory and full-wave approaches, based on the numerical techniques such as finite difference time domain method, finite element method and boundary element method [11]-[13]. The grounding system transient analysis can be conducted in frequency domain [14] and in time domain [15].

In this paper, for the calculation of the electromagnetic transients on the grounding system, numerical model

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Paper submitted: October 2018 Paper accepted: December 2018

based on the transmission line theory was used. The application of the presented numerical model was demonstrated on two simple geometry grounding systems taken from the literature.

1. MATHEMATICAL MODEL OF THE GROUNDING SYSTEM

1.1. Calculation of the grounding system parameters

The mathematical model given in this paper is derived under assumption that a grounding system can be subdivided into a certain number of straight thin-wire elements. Each straight thin-wire structure represents one segment of the grounding system and can be modelled by concentric parameters using the corresponding equivalent scheme (π, Γ, T - elements). Figure 1 shows a division of the grounding system on the straight thin-wire elements and representation of the one straight thin-wire element by π element.

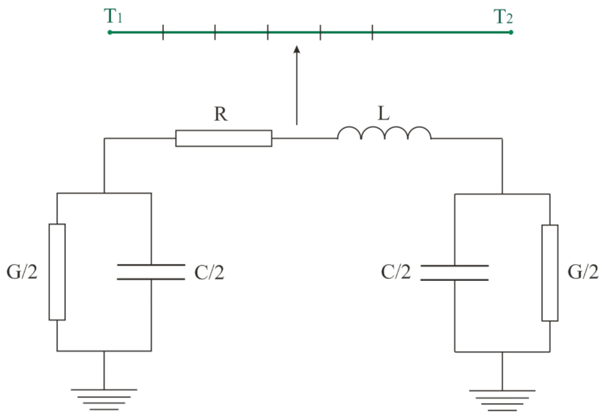

Figure 1: π equivalent circuit of the grounding segment [7], [16]

As can be seen from Figure 1, every π - element is composed of:

R – self per-unit length resistance of the grounding element,
L – self per-unit length inductance of the grounding element,
C – shunt per-unit length capacitance of the grouning element, and
G – shunt per-unit length conductance of the groundg element.

When determining the π equivalent circuit parameters, it is necessary to take into account [7], [16]:

- geometrical characteristics of the analysed segment,
- characteristics of the surrounding soil,
- electrical properties of the analysed grounding segment, and
- characteristics of the injected electric current.

1.1.1. Calculation of the π element per-unit length parameters

For the calculation of the grounding segment's self per-unit length resistance and inductance it is necessary to firstly determine the internal per-unit length impedance of the conductor and its self per-unit length impedance of the return path. The internal per-unit length impedance of the conductor is determined by applying the following expression [7], [17]:

$$Z_c = \frac{\rho_c m_c}{2\pi r}\coth(0.777 m_c r) + \frac{0.356\rho_c}{\pi r^2} \tag{1}$$

where:

$$m_c = \sqrt{\frac{j\omega\mu_c}{\rho_c}} \tag{2}$$

Z_c – internal impedance of the grounding conductor (Ω/m),
r – thin-wire segment radius (m),
ω – angular frequency (rad),
ρ_c – grounding conductor resistance (Ωm),
μ_c – permeability (H/m).

Self impedance of the return path through the ground, Z_s, is given by the following expression [7], [17]:

$$Z_s = \frac{j\omega}{2\pi}\left(-\ln\left(\frac{\gamma m_s r}{2}\right) + \frac{1}{2} + \frac{4 m_s h}{3}\right) \tag{3}$$

where:

$$m_s = \sqrt{\frac{j\omega\mu_s}{\rho_s}} \tag{4}$$

Z_s – impedance of the return path through the ground (Ω/m),
γ – Euler's constant (0.57722),
h – burial depth (m),
ρ_s – electrical resistivity of the soil (Ωm), and
μ_s – soil permeability (H/m).

Therefore, the frequency dependent per-unit length impedance of a grounding system segment can be determined by applying the following expression [7], [16]:

$$Z_T(\omega) = Z_c(\omega) + Z_s(\omega) \tag{5}$$

From the previous expression, it is possible to determine the frequency dependent per-unit length resistance and inductance of a particular grounding system segment, where the per-unit length resistance of *i*-th segment is equal to:

$$R_i = \Re\{Z_T(\omega)\} \tag{6}$$

The per-unit length inductance of *i*-th grounding system segment can be determined by applying the following equation:

$$L_i = \frac{\Im\{Z_T(\omega)\}}{\omega} \tag{7}$$

The following relation can be used for the calculation of a per-unit length shunt conductance [7], [17]:

$$G_i = \frac{\pi}{\rho_s \ln\sqrt{\dfrac{\rho_s}{rh\omega\mu_s}}} \tag{8}$$

The per-unit length capacity can be determined by applying the following approximate equation [7], [17]:

$$C_i = \frac{2\pi\varepsilon_0\varepsilon_{rs}}{\ln\dfrac{2l}{\sqrt{2hr}} - 1} \tag{9}$$

where:

C – per-unit length capacity of thin-wire segment grounding (F/m),
l – thin-wire segment length (m),
ε_0 – free space dielectric constant (F/m), and
ε_{rs} – relative dielectric constant of soil.

1.1.2. Calculation of reciprocal coupling interactions of grounding segments

Many authors, due to simplicity of calculation, neglect the interaction between individual grounding segments. Such approximation introduces the error in calculation and is permissible only when the distance between ground segments is large.

In order to obtain a complete picture of the behaviour of grounding system during flow of transient currents, it is necessary to take into account the coupling between the grounding system segments. Generally, coupling effects can be divided into three groups:

- mutual resistance,
- mutual capacity, and
- mutual inductance.

The illustration of the coupling between two grounding system segments (*i*-th and *j*-th segments) and the equivalent electrical circuit is given on Figure 2.

First two types of a mutual coupling mechanism are associated with the existence of potential difference between the grounding system segments, while the third, mutual inductance is caused by the flow of current through the grounding system segment that creates the magnetic field and couples the other segments [19], [20]. Also, when calculating the mutual resistance and capacity between two segments, it is necessary to consider that the soil in which the grounding system is placed is considered as half-infinite medium. Therefore, image theory approach was used in this paper [21].

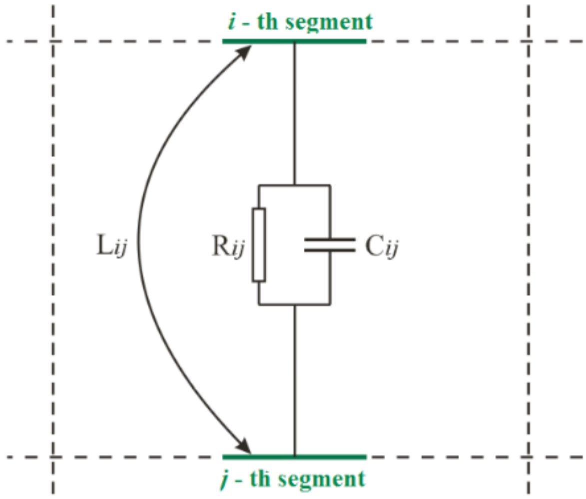

Figure 2: Grounding elements coupling mechanisms and their representation [18], [19]

The per-unit length mutual resistance between the *i*-th and *j*-th grounding segments can be calculated using the following equation [21]:

$$R_{ij} = \frac{\rho_s}{4\pi l_j}\left(\int_{l_j}\int_{l_i}\frac{1}{D_{ij}}dldl + k\int_{l_j}\int_{l_{i'}}\frac{1}{D'_{ij}}dldl\right) \tag{10}$$

where:

R_{ij} – is per-unit length resistance between the *i*-th and *j*-th segments (Ω/m),
D_{ij} – is distance between *i*-th and *j*-th segments (m),
D'_{ij} – represents the distance between the image of the *i*-th segment located above the ground surface at a height equal to the depth of burial of the *i*-th segment and *j*-th segment (m),
k - reflection coefficient and is calculated as follows:

$$k = \frac{\rho_a - \rho_s}{\rho_a + \rho_s} \tag{11}$$

where ρ_a is the electric resistivity of the air (Ωm). As the electric resistivity of the air is very high, the air can be treated as an ideal isolator. Then it can be written that reflection coefficient is $k = 1$ [22].

The per-unit length mutual capacities, which characterize the capacitive interaction between *i*-th and *j*-th segments, can be determined from the coefficient P_{ij} given by the following integral equation [21]:

$$P_{ij} = \frac{1}{4\pi\varepsilon_0\varepsilon_{rs}l_j}\left(\int_{l_j}\int_{l_i}\frac{1}{D_{ij}}dldl + k_\varepsilon\int_{l_j}\int_{l_{i'}}\frac{1}{D'_{ij}}dldl\right) \tag{12}$$

where k_ε is the reflection coefficient defined by following equation:

$$k_{\varepsilon} = \frac{\varepsilon_s - \varepsilon_a}{\varepsilon_s + \varepsilon_a} \quad (13)$$

where ε_a is the relative permittivity of the air (F/m).

From equation (12) mutual per-unit length capacity can be determined using the following equation:

$$C_{ij} = \frac{1}{P_{ij}} \quad (14)$$

When calculating per-unit length mutual inductance, unlike the previous cases of mutual resistance and capacitance, calculation is done without taking into account the reflections. This is due to the fact that soil permeability is equal to air permeability, therefore reflection does not exist. Therefore, per-unit length mutual inductance between *i*-th and *j*-th segments can be calculated using the following equation [23]-[25]:

$$L_{ij} = \frac{\mu_0}{4\pi l_j} \int_{l_j} \int_{l_i} \frac{1}{D_{ij}} dl dl \quad (15)$$

Due to the nature of the magnetic field, there are no inductive interactions between the vertical segments [23]-[25].

1.2. Current source modelling

High frequency transient currents caused by lighting discharge can be modelled in several ways. Today, literature offers different expressions for the modelling the lightning current, such as double exponential function, Heidler function, CIGRE function and many others [26]. Within this paper, double exponential function was used for modelling of the lighting current. This function can mathematically be represented by the following equation [26], [27]:

$$i(t) = I_0\left(e^{-at} - e^{-bt}\right) \quad (16)$$

where:

I_0 – is peak value of the current wave (A),
a,b – are coefficients defining the slope of the front and tail of the current wave.

2. MODEL APPLICATION

In order to demonstrate application of the previously described model, calculation of the electromagnetic transients on two simple geometry grounding system was done. For the calculation of the grounding parameters, a developed computer application has been used and the EMTP software package was used to calculate transients on the grounding system.

2.1. Horizontal grounding simulation

Previously described model is verified through the example of a horizontal grounding conductor of radius r = 6 mm, which was buried in the soil at a depth of h = 0.6 m. Specific electrical resistances of grounding system conductor (copper) and soil are ρ_c = 1.78·10^{-8} Ωm and ρ_s = 65 Ωm, respectively. The relative dielectric constant and the relative permeability of the soil are ε_{rs} = 15 and μ_{rs} = 1 [7], [28]. The current wave is injected into one end of l = 15 m long horizontal grounding conductor. The shape of the current wave is given by the double exponential function, given by the equation (16), where the current wave peak value is I_0 = 36.5 A and coefficients a and b are 60000 s^{-1} and 6000000 s^{-1}, respectively. The rise time of the current wave is 0.8 μs, while the time of 50% of the current is 12.5 μs [29]. Below, Figure 3 shows the geometry of the considered grounding conductor, while Figure 4 shows the shape of the injected current wave. Considered grounding system is discretized on straight thin-wire elements of Δl = 0.5 m length.

Overvoltage waveform at test points T_1, T_2 and T_3 obtained by simulation are given in Figure 5.

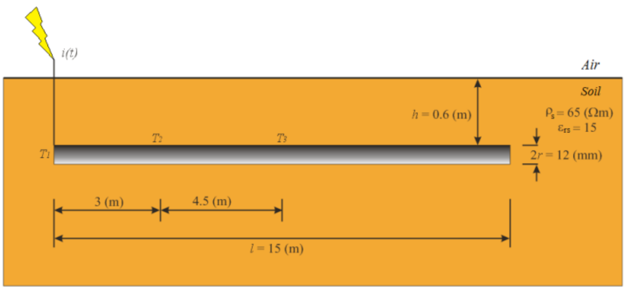

Figure 3: Geometry of analysed grounding [7]

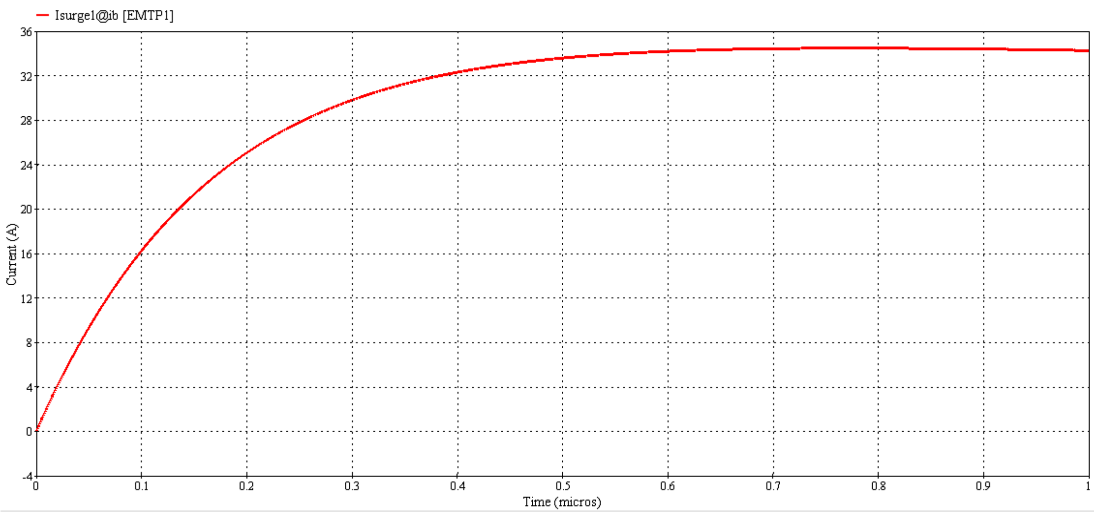

Figure 4: Form of injected current wave

From the results given in Figure 5 it can be noted that overvoltage peak values on the grounding system decrease with increase of distance from injection current point (T_1). Also, time delay increases with increase of distance from injection current point.

2.2. Grounding contour simulation

Second analysed example of the grounding system is made of copper conductors of r = 7 mm radius and a side length of l = 10 m. The specific electrical resistance of the soil in which the grounding is buried is ρ_s = 1000 Ωm. Relative dielectric constant and relative permeability of soil are ε_{rs} = 9 and μ_{rs} = 1, respectively. Depth of burial of grounding system contour is h = 0.5 m. The geometry of the analysed grounding conductor is given in Figure 6 [29].

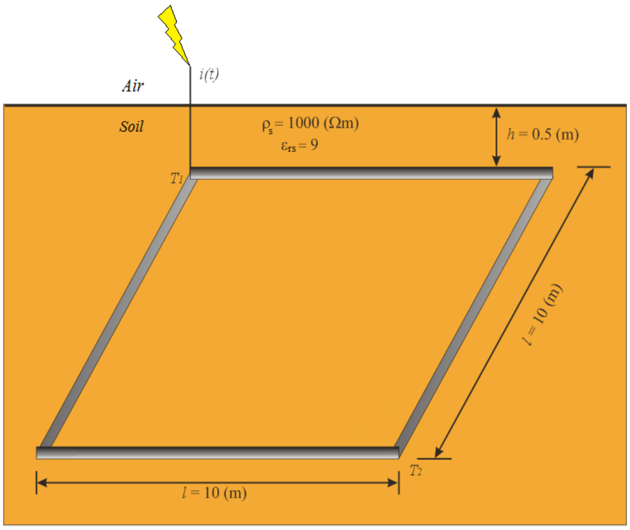

Figure 6: Analysed grounding contour [29]

The waveform of the current wave injected into the grounding system is described by a double exponential function whose amplitude is I_0 = 1 A. The parameters a and b of the injected current wave are 27000 s^{-1} and 5600000 s^{-1}, respectively. The front time of the current wave is 0.36 μs, while the time it takes for waves to reach 50% of the current value is 26.8 μs. The form of the injected current wave is shown in Figure 7 [29].

Overvoltage waveforms obtained by simulation in points T_1 and T_2 are shown in Figure 8.

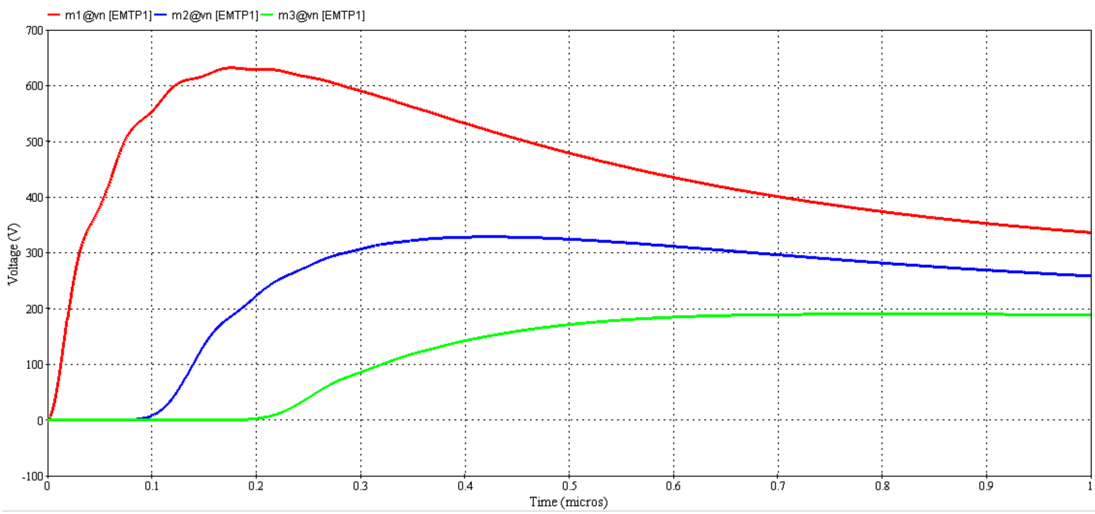

Figure 5: Forms of overvoltage at the measuring points obtained by simulation (— point T_1, — point T_2, — point T_3)

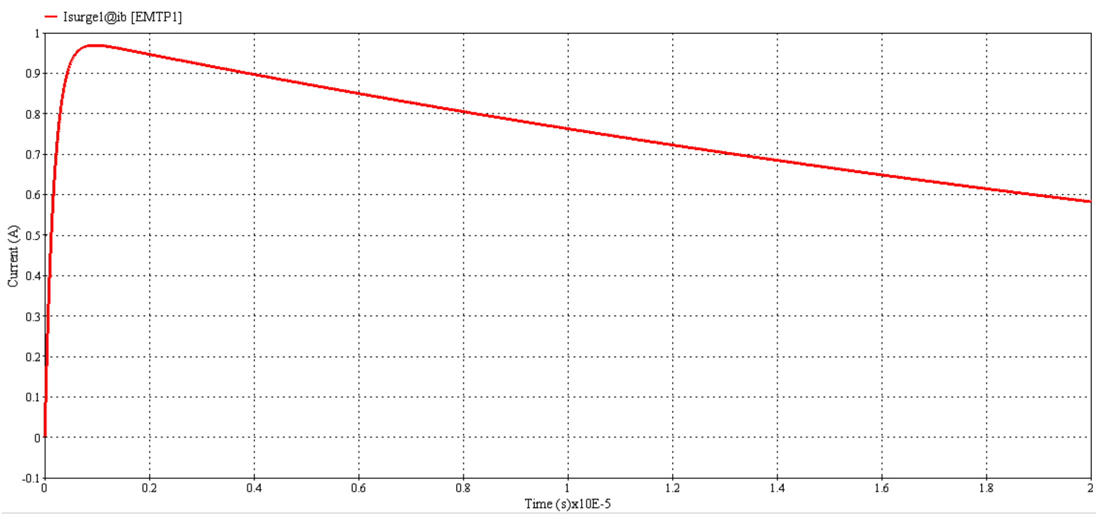

Figure 7: Form of the injected current wave

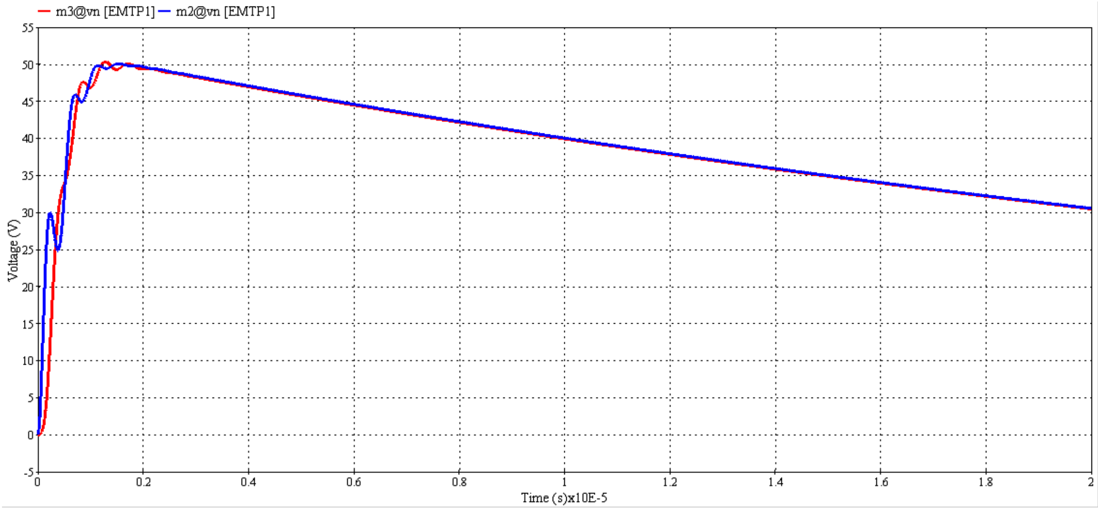

Figure 8: Overvoltage waveforms in points T_1 and T_2 (— point T_1, — point T_2)

The simulation results show a good match with the results of the simulations given in [29]. Therefore, following the previously presented analysis it can be concluded that the given model yields satisfactory results. It has also been demonstrated that the model is applicable not only to simple geometries, but also to complex geometries that are most commonly used in practice.

3. CONCLUSION

Knowing the transient characteristics of the grounding systems is of great importance for the analysis of the endangerment to power system facilities from lightning discharge and transitional phenomena caused by switching operations. Their determination presents a major problem due to the existence of a large number of influential parameters. The most important influence on the transient characteristics of the grounding system comes from the constructive characteristics of the grounding system, electrical characteristics of the soil, as well as the shape, amplitude and location of the current wave injection.

The paper gives an approach to modelling the grounding system parameters during the flow of transient currents. By the proposed approach the grounding system is divided into the appropriate number of straight thin-wire segments that are represented. Also, the previously presented mathematical model takes into account the mutual coupling between individual segments, which are represented by appropriate resistances, inductances and capacities.

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