TIME DOMAIN SOLUTION OF ELECTROMAGNETIC RADIATION MODEL OF THE GROUNDING SYSTEM EXCITED BY PULSE CURRENT

by

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This paper deals with an advanced electromagnetic radiation approach for analyzing the time-domain performance of grounding systems under pulse excitation currents. The model of the grounding systems presented within this paper is based on the homogeneous Pocklington integro-differential equation for the calculation of the current distribution on the grounding system and Lorentz gauge condition which is used for the grounding system transient voltage calculation. For the solution of the Pocklington integro-differential equation, the indirect boundary element method and marching on-in time method are used. Furthermore, the solution technique for the calculation of the grounding system transient voltage is presented. The numerical model for the calculation of the grounding system transients was verified by comparing it with onsite measurement results.

Key words: grounding system, transient current, transient voltage, Pocklington integro-differential equation, Lorentz gauge condition

INTRODUCTION

The purpose of the grounding system is to ensure working characteristics of the power system under normal operating conditions as well as to ensure the safety of personnel and power system equipment under fault conditions such as short circuits and lightning discharges [1]. The performance of the grounding system under low frequency current excitation is well covered in international standards [2]. On the other hand, the performance of the grounding system under transient currents such as lightning discharge currents is poorly covered by international standards [3]. Researchers have extensively analyzed the grounding system pulse characteristics trough the complex experimental as well as computational investigations. Excitation of the grounding system by transient currents is an important parameter for the analysis of the electromagnetic compatibility (EMC) studies as well as lightning protection (LP) efficiency study [4]. Grounding system impulse characteristics depend on many influencing factors such as grounding system parameters, surrounding soil characteristics and excitation current shape and magnitude [5]. Therefore, the analysis and modeling of the grounding system under pulse current excitation represent a challenging task.

To date, numerous models have been developed for the grounding system impulse characteristic calculations. These models can be classified as circuit theory models, transmission line models and full-wave models *i. e.* models based on antenna theory [6, 7]. Antenna theory model of grounding system considers both processes of wave propagation along the grounding system as well as electromagnetic field radiation [8] in surrounding soil. Therefore, grounding system models based on antenna theory are considered as most rigorous but mathematically and computationally most demanding. According to the antenna theory approach, current distribution on the grounding system conductors can be calculated by solving the Pocklington integro-differential equation. The solution to the grounding system's current distribution can be achieved by using analytical or numerical methods. For the grounding system, antenna theory model analytical solution exists for simple geometries such as buried horizontal wire [9, 10]. In most cases, real grounding systems are composed of multiple interconnected horizontal and/or vertical unisolated wires that way forming the complex geometries grounding systems such as grounding mesh with vertical rods used for high voltage substations, or multiple interconnected rectangular contours used for the distribution network substations or ring-type contour used for the wind turbines, *etc*. Therefore it is suitable to use the numerical methods since unlike analytical methods, numerical methods are geometrically independent.

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The solution of the transient current and voltage distribution along the grounding system can be obtained in frequency or time domain. The frequency-domain approach of grounding system impulse characteristics calculation by antenna theory approach is mostly used in the literature [11, 12]. By using this approach, inverse fast Fourier transformation (IFFT) must be applied to the obtained results in order to obtain calculation results in time-domain [12, 13]. On the other hand, a direct time-domain approach of grounding system impulse characteristic modeling provide better physical insight and easier implementation of nonlinear phenomenon such as soil ionization phenomenon [9, 14]. Time-domain modeling has some disadvantages in comparison to the frequency domain modeling such as the existence of the numerical oscillations due to the existence of a derivative operator within the Pocklington integro-differential equation [15] and high computational cost due to existence of the convolution integrals in the calculation model [16].

MATHEMATICAL MODEL

The mathematical model given within this paper is composed of two stages. The first stage is a solution of the Pocklington integro-differential equation with the purpose to calculate the current distribution on the grounding system conductors. The second stage is a solution of the integro-differential equation derived from the Lorentz gauge to calculate transient voltage on the grounding system. The solution of the second stage is based on the results obtained in the first stage *i. e*. on the solution of the current distribution on grounding system conductors.

The following assumptions and approximations have been used in the presented model:

– Thin wire approximation can be applied on the grounding system conductors.
– Soil can be treated as half-infinite lossy media.
– Soil – air boundary can be considered by the modified image theory reflection coefficient.
– The internal impedance of the grounding system conductor can be neglected. and
– Soil ionization phenomenon is not taken into account.

The first approximation is valid in most practical cases as the length of the grounding system conductor is much higher than the conductor´s diameter. By applying thin wire approximation, integral order in the model is reduced from surface integral to line integral. This further reduces both the complexity and computational time of the mathematical model.

Grounding systems are in most practical cases buried on depth on which influence of the boundary air-soil cannot be neglected. Therefore, surrounding soil must be treated as half-infinite lossy media. The influence of the boundary soil-air can be considered by Somerfield's integrals [17, 18] or by reflection coefficients [19]. Somerfield's integrals approach is considered more rigorous but it is mathematically more complex and computationally more time-consuming in comparison to the reflection coefficient approach. Furthermore, Somerfield's integrals do not have closed-form expression in time domain meaning that their use would require calculations in the frequency domain and the application of IFFT. On the other hand, the modified image theory reflection coefficient does have a closed-form expression in time-domain [9] and has the simple mathematical formulation.

Even though internal impedance of the grounding system conductor has an impact on the calculation results in most practical cases the surrounding soil has significantly higher resistivity compared to the grounding system material allowing to neglect the influence of the internal impedance. By neglecting the influence of the grounding conductor internal impedance, the Pocklington integro-differential equation has homogenous form. This further reduces the mathematical complexity of the model and computational time.

Generally, the electromagnetic field in surrounding soil is a non-ionization radiation field when the grounding system is excited by lower magnitude currents. The ionization process occurs when an electric field caused by pulse currents flow through grounding system conductors is higher than soil breakdown electric field strength [20]. Considering that in this paper low magnitude transient currents have been analyzed, this phenomenon is neglected.

Transient current distribution calculation model

Pocklington integro-differential equation can be derived from Maxwell´s equations. This procedure can be found elsewhere [21]. Within this paper, the Pocklington integro-differential equation is derived under the assumption that the excitation electric field along grounding system conductors does not exist [22]. Taking into account previously listed approximation, transient current distribution on the grounding system conductors can be calculated from the following homogenous Pocklington integro-differential eq. [21]

$$\frac{\partial^2}{\partial r^2} \quad \mu\sigma\frac{\partial}{\partial t} \quad \mu\varepsilon\frac{\partial^2}{\partial t^2}$$

$$\mu \int_0^L I \quad r ,t \quad \frac{R}{c} \quad g(r,r ,t)\,\mathrm{d}r$$

$$\mu \int_0^L \int_0^t \Gamma(\tau) I \quad r ,t \quad \frac{R}{c} \quad \tau \quad g(r,r \quad ,t)\,\mathrm{d}\tau\,\mathrm{d}r \qquad 0 \qquad (1)$$

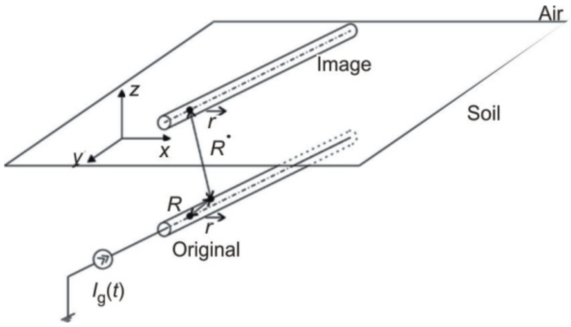

Figure 1. Grounding wire buried in lossy half infinite media

where R is the distance between source point r' and observation point r, R^* – the distance between the image of the source point r^* and observation point r, fig. 1, σ – the soil electric conductivity, ε – the soil permittivity μ – the soil permeability, c – the wave propagation speed in the soil, $I(r', t\text{-}R/c)$ is unknown current distribution, and $g(r, r', t)$ is Green function for lossy media defined by

$$g(r,r',t) = \frac{e^{-\frac{1}{\tau_g}\frac{R}{c}}}{4\pi R}\delta\left(t - t' - \frac{R}{c}\right) \qquad (2)$$

where δ is Dirac delta function and τ_g – the time constant of the media defined by

$$\tau_g = \frac{2\varepsilon}{\sigma} \qquad (3)$$

The impact of the boundary soil-air in this paper is treated by using a modified image theory reflection coefficient. The used reflection coefficient is defined by the following equation [9, 21, 22]

$$\Gamma_{\mathrm{ref}}(\tau) = \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\delta(\tau) + \frac{\sigma}{\varepsilon_0(\varepsilon_r + 1)}\left[1 - \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\right] e^{-\frac{\sigma\tau}{\varepsilon_0(\varepsilon_r + 1)}} \qquad (4)$$

where ε_r is the relative dielectric permittivity of the soil and ε_0 – the dielectric permittivity of free space.

By solving eq. (1) the transient current induced on the buried wire can be calculated. To obtain a unique solution, adequate initial and boundary conditions must be applied. As stated earlier, the boundary between soil and air has been treated by the modified image theory reflection coefficient. On current injected point, following boundary condition is introduced [21]

$$I(r_i, t) = I_g(t) \qquad (5)$$

where r_i is the current injection point on the grounding system and I_g – the current injected in the grounding system.

Transient potential distribution calculation model

In order to calculate the scalar electric potential on the surface of the buried grounding wire caused by the flow of the transient current, the Lorenz gauge condition can be used. Lorenz gauge condition is defined by [23]

$$\frac{\partial}{\partial r}\vec{A}(r,t) + \mu\varepsilon\frac{\partial}{\partial t}\varphi(r,t) + \mu\sigma\varphi(r,t) = 0 \qquad (6)$$

where $\varphi(r, t)$ is scalar electric potential and $\vec{A}(r,t)$ is a magnetic vector potential which is for analyzed case defined by [21]

$$\vec{A}(r,t) = \mu\int_0^L I\left(r', t - \frac{R}{c}\right) g(r,r',t)\,\mathrm{d}r' + \mu\int_0^L\int_0^t \Gamma(\tau) I\left(r', t - \frac{R^*}{c} - \tau\right) g(r,r^*,t)\,\mathrm{d}\tau\,\mathrm{d}r' \qquad (7)$$

By combining eqs. (6) and (7) the potential homogenous integro-differential equation can be obtained

$$\frac{\partial}{\partial r}\left[\mu\int_0^L I\left(r', t - \frac{R}{c}\right) g(r,r',t)\,\mathrm{d}r' + \mu\int_0^L\int_0^t \Gamma(\tau) I\left(r', t - \frac{R^*}{c} - \tau\right) g(r,r^*,t)\,\mathrm{d}\tau\,\mathrm{d}r'\right] + \mu\varepsilon\frac{\partial}{\partial t}\varphi(r,t) + \mu\sigma\varphi(r,t) = 0 \qquad (8)$$

Using Green's symmetric property the potential integro-differential equation takes the following form [23]

$$\mu\int_0^L \frac{\partial I\left(r', t - \frac{R}{c}\right)}{\partial r'} g(r,r',t)\,\mathrm{d}r' + \mu\int_0^L\int_0^t \Gamma(\tau)\frac{\partial I\left(r', t - \frac{R^*}{c} - \tau\right)}{\partial r'} g(r,r^*,t)\,\mathrm{d}\tau\,\mathrm{d}r' + \mu\varepsilon\frac{\partial}{\partial t}\varphi(r,t) + \mu\sigma\varphi(r,t) = 0 \qquad (9)$$

By solving eq. (9) transient potential on the grounding wires in the time domain can be obtained.

SOLUTION TECHNIQUE

In the previous section, integro-differential equations for the transient current and potential distribution are derived. In this section of the paper solution techniques of the eqs. (1) and (9) are presented. Transient current distribution and transient potential distribution are calculated separately. The solution of eq.

(9) is based on the solutions obtained by solving eq. (1).

Solution technique for transient current distribution

By solving homogeneous Pocklington integro-differential, eq. (1), transient current distribution along the grounding system conductor can be calculated. Within this paper, the marching-on-in time (MOT) numerical solution technique is used for calculation of the transient current distribution calculation. The first step in this procedure is space-time discretization. The space-time discretization is conducted according to Courant-Friedrichs-Lewy condition

$$\frac{c\Delta t}{\Delta l} \quad 1 \tag{10}$$

where t is a time step size and l is a space element length.

To solve eq. (1), after space-time discretization, it is necessary to approximate the current for each segment, by the following series

$$I \quad r, t \quad \frac{R}{c} \quad \sum_{i \ 1}^{Ns} \sum_{j \ 1}^{Nt} I_{i,j} N(r) T \quad t \quad \frac{R}{c} \quad j\Delta t \tag{11}$$

where $I_{i,j}$ are unknown coefficients, $N(r')$ – the space shape function, and $T[t \quad (R/c) \quad j\Delta t]$ – the time shape function. In this paper, linear basis function has been used for space shape functions and quadratic Lagrange functions for time shape functions.

Finally, by applying Galerkin-Bubnov procedure in space and point-marching procedure in time *i. e.* by choosing shape function as weight function for space and Dirac delta function as weight function in a time domain and integrating equations over both space and time [24], following differential matrix equation is obtained

$$[\mathrm{M}]\frac{\partial^2}{\partial t^2}\{I(t\ )\} \quad [\mathrm{C}]\frac{\partial}{\partial t}\{I(t\ )\} \quad [\mathrm{K}]\{I(t\ )\} \quad \{0\} \tag{12}$$

where $\{I(t')\}$ is vector matrix of unknown coefficients $I_{i,j}$ and [M], [C], and [K] are square coefficient matrix whose elements are calculated by the following equations

$$M_{i,k} \quad \mu\varepsilon \quad \underset{\Delta l_i \, \Delta l_k}{} \{N\}_i \{N\}_k^T g(r, r\ , t)\mathrm{d}l\mathrm{d}l$$
$$\underset{\Delta l_i \, \Delta l_k \quad n\Delta t}{\overset{(n\ \ 1)\Delta t}{}} \Gamma(\tau)\{N\}_t \{N\}_k^T \{T\} g(r, r^*, t)\mathrm{d}\tau\mathrm{d}l\mathrm{d}l^* \tag{13}$$

$$C_{i,k} \quad \sigma\mu \quad \underset{\Delta l_i \, \Delta l_k}{} \{N\}_i \{N\}_k^T g(r, r\ , t)\mathrm{d}l\mathrm{d}l$$
$$\underset{\Delta l_i \, \Delta l_k \quad n\Delta t}{\overset{(n\ \ 1)\Delta t}{}} \Gamma(\tau)\{N\}_t \{N\}_k^T \{T\} g(r, r^*, t)\mathrm{d}\tau\mathrm{d}l\mathrm{d}l^* \tag{14}$$

$$K_{i,k} \quad \underset{\Delta l_i \, \Delta l_k}{} \{D\}_i \{D\}_k^T g(r, r\ , t)\mathrm{d}l\mathrm{d}l$$
$$\underset{\Delta l_i \, \Delta l_k \quad n\Delta t}{\overset{(n\ \ 1)\Delta t}{}} \Gamma(\tau)\{D\}_i \{D\}_k^T \{T\} g(r, r^*, t)\mathrm{d}\tau\mathrm{d}l\mathrm{d}l^* \tag{15}$$

where D is a space derivative of the shape function, T – the matrix transpose operator and n – the time step sequence number.

Space part of integral eqs. (13)-(15) is solved by using Gauss-Legendre quadrature formulas and time parts are solved by applying Trapezoidal rule for each time step.

Finally, by applying the MOT procedure on differential matrix, eq. (12), takes the following form [25]

$$[[\mathrm{M}] \quad \gamma\Delta T[\mathrm{C}] \quad \beta\Delta t^2[\mathrm{K}]]\{I\}^k$$
$$2[\mathrm{M}] \quad (1 \quad 2\gamma)\Delta t[\mathrm{C}] \quad \frac{1}{2} \quad 2\beta \quad \gamma \quad \Delta t^2[\mathrm{K}] \ \{I\}^{k \ \ 1}$$
$$[\mathrm{M}] \quad (1 \quad \gamma)\Delta t[\mathrm{C}] \quad \frac{1}{2} \quad 2\beta \quad \gamma \quad \Delta t^2[\mathrm{K}] \ \{I\}^{k \ \ 2} \tag{16}$$

Parameters $\gamma = 1/2$ and $\beta = 1/4$ are selected. By solving matrix, eq. (16), the solution of the current distribution along grounding system conductors is achieved.

Solution technique for the transient potential equation

After the induced transient current is calculated for all analyzed time steps, the transient potential on the grounding wire conductor can be calculated by using eq. (9). By assuming that the scalar electric potential at remote soil is equal to zero, the scalar electric potential of grounding wire can be treated as transient grounding voltage. By applying Galerkin-Bubnov procedure in space and point-marching procedure in time on the eq. (9), following matrix equation can be written

$$[\mathrm{A}]\{I(t')\} \quad [\mathrm{B}]\{I(t')\}$$
$$[\mathrm{E}]\{\varphi(t')\} \quad [\mathrm{F}]\{\varphi(t')\} \quad \{0\} \tag{17}$$

where matrix [A], [B], [E], and [F] are square coefficient matrices, $\{I(t')\}$ – the vector matrix of coefficients $I_{i,j}$ calculated in previous stage, and $\{\varphi(t')\}$ – the vector matrix of unknown scalar electric potential coefficients $\varphi_{i,j}$.

After some mathematical manipulation matrix, eq. (17), takes the following form

$$\{\varphi(t')\} \quad ([\mathrm{E}] \quad [\mathrm{F}])^{\ 1}([\mathrm{B}] \quad [\mathrm{A}])\{I(t')\} \tag{18}$$

Elements of the coefficient matrix are calculated by the following eqs.

$$E_{i,j} \quad \begin{matrix} \mu\varepsilon\{N\}\{N\}^T \dfrac{\mathrm{d}T}{\mathrm{d}t}, & i \quad j \\ 0 & i \quad j \end{matrix} \tag{19}$$

$$F_{i,j} \quad \begin{matrix} \mu\sigma\{N\}\{N\}^T\{T\}, & i \quad j \\ 0 & i \quad j \end{matrix} \tag{20}$$

$$A_{i,j} \quad \mu \underset{\Delta l_i \Delta l_k}{} \{N\}_i \{D\}_k^T g(r, r, t)\mathrm{d}l\mathrm{d}l \quad B_{i,j} \tag{21}$$

$$= \mu \underset{\Delta l_i \Delta l_k}{} \underset{n\Delta t}{\overset{(n \quad 1)\Delta t}{}} r\,\Gamma(\tau)\{N\}_i \{D\}_k^T \{T\} g(r, r^*, t)\mathrm{d}\tau\mathrm{d}l\mathrm{d}l \tag{22}$$

If the same space-time discretization scheme is used, transient current and scalar electric potential distribution can be sequentially calculated at each time step.

CASE STUDY

In order to verify the previously presented mathematical model an experimental investigation on the spatially prepared vertical grounding electrode, fig. 2(a), has been conducted. The measurements have been conducted according to the electrical scheme given in fig. 2(b).

The vertical grounding electrode has been excited by four-stage 300 kV impulse generators. Transient current and voltage waveforms have been measured by a low-resistive shunt resistor and resistive voltage divider, respectively. The waveform of the current voltage has been registered by two digital storage oscilloscopes. The detailed specification of the used measuring equipment can be found in the literature [26, 27] as the same measuring equipment has been used for the experimental investigation.

Three experiments on vertical grounding electrode were performed with different transient current peak value and different front rise time. On all registered current and voltage waveforms, high frequency interferences were noted. Measured parameters' uncertainty can be caused by different low and high frequency interference sources [28-30]. It was assumed that the proximity between measuring equipment and impulse generator was the cause of the high-frequency interferences [26, 27]. To set-up an adequate injection current model and calculate the grounding system transient characteristics, it is necessary to remove

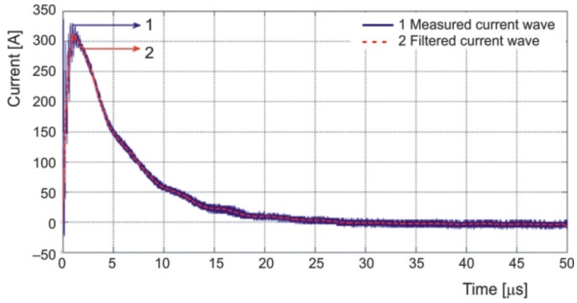

Figure 3. Comparison of the measured current waveform and filtered current waveform

these unwonted high frequency oscillations *i. e.* to filter the signals. Within this paper, for the removal of the high frequency oscillations discrete wavelet transformation (DWT) has been used, as suggested in [27]. In fig. 3 the comparison between measured and filtered current waveform is given.

In order to model the transient characteristics of the grounding system by the presented mathematical model, it is necessary to represent the injected current by appropriate mathematical function in the time domain. Within this paper the injected current has been modeled by two exponential terms as given by

$$i(t) \quad I_{01}\mathrm{e}^{\;\;\alpha t} \quad I_{02}\mathrm{e}^{\;\;\beta t} \tag{23}$$

where I_{01}, I_{02}, α, and β are model parameters and t – the time. For each analyzed case, filtered current data points have been used to evaluate the parameters of the injected current model. For the evaluation of the unknown current model parameters, the Levenberg-Marquardt non-linear regression has been used. The evaluated injected current parameters for all three cases are given in tab. 1.

In fig. 4 the comparison of the filtered current waveform and modeled current waveforms for all three analyzed cases are given.

Modeled injected currents have been further used to calculate the transient voltage at the injection

Table 1. Parameters of the injected current model

Case	I_{01}	α	I_{02}	β
1st case	428,4514	0.1989	415,2060	2.1262
2nd case	322,9921	0.1562	315,0524	2.4846
3rd case	184,4458	0.1017	175,7460	2.6569

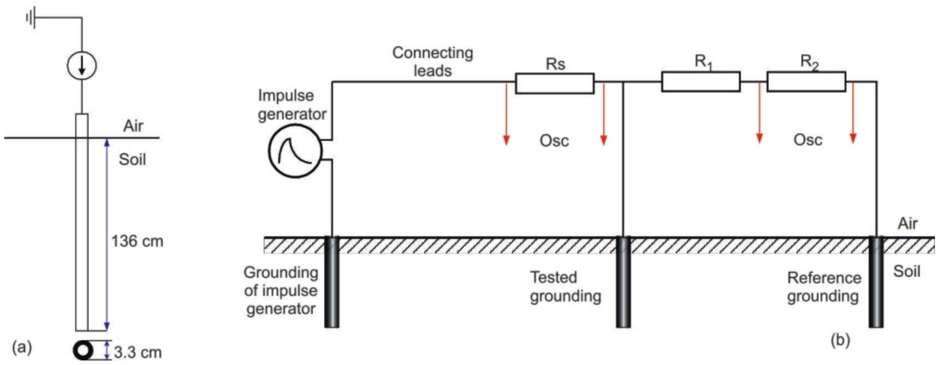

Figure 2. Tested vertical grounding electrode (a) geometry, (b) the electrical scheme of measuring circuit [26]

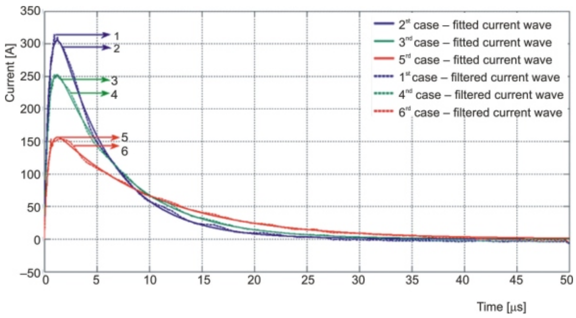

Figure 4. Waveforms of the filtered current and modeled current waveform

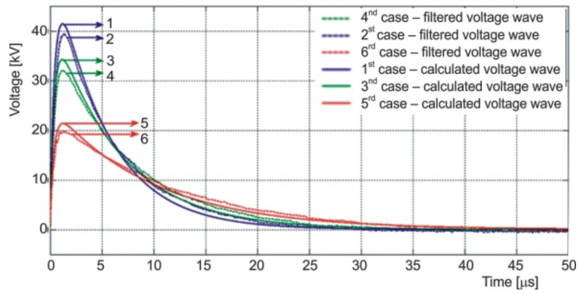

Figure 5. Comparison between measured (and filtered) and calculate voltage waveforms at the injection point

Table 2. Parameters of the injected current model

Case	U_{peak} [kV]		I_{peak} [A]		Z [ ]	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
1st case	39.55	41.11	314.18	305.11	125.60	135.83
2nd case	32.04	34.23	252.70	251.83	126.79	135.91
3rd case	19.91	21.38	154.19	156.01	129.13	136.97

point of the grounding system by the previously presented mathematical model. Soil resistivity was measured by Wenner four-probe method and it was established that mean soil resistivity is 274.85 m.

A comparison between measured (and filtered) results and calculated results is given in fig. 5. A good argument between measured and calculated voltage waveforms.

In tab. 2 peak values of the transient current, voltage, and impedance, based on measured and calculated value are given. As can be noted from the given results, the mathematical model presented within this paper gives satisfactory results.

CONCLUSIONS

This paper presents the advanced mathematical model for the calculation of the grounding system characteristics under pulse current excitation. Transient current distribution on the grounding system is based on the integro-differential equations of the Pocklington type. Due to the high complexity of the presented mathematical model, the solution is achieved by using the combination of the numerical procedures. The indirect boundary element method has been used for the solution of the space integral part of the equation, the trapezoidal rule has been used for the solution of the time integral part of the equation. The derivative part of the equation has been solved by using the MOT procedure. Grounding system transient voltage has been calculated based on a transient current distribution calculation results and Lorentz gauge condition. For the calculation of the grounding system transient voltage Galerkin - Bubnov procedure in space and point-marching procedure in time was used.

Finally, the presented mathematical model has been validated by comparing the calculation results with the experimental results conducted on a spatially prepared vertical grounding electrode.

AUTHORS' CONTRIBUTIONS

Both authors have contributed equally to the experimental investigation and measurement results processing and analysis. N. Dautbašić has developed a mathematical model for the grounding system characteristics calculations in the time domain. Both authors participated in writing, editing and revising of the manuscript.

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РЕШАВАЊЕ ЕЛЕКТРОМАГНЕТНОГ МОДЕЛА ЗРАЧЕЊА УЗЕМЉИВАЧКОГ СИСТЕМА ПОБУЂЕНОГ ИМПУЛСНОМ СТРУЈОМ У ВРЕМЕНСКОМ ДОМЕНУ

У раду је описан напредни приступ за анализу перформанси уземљивачких система при импулсним побудним струјама. Модел уземљивачког система презентиран унутар рада је базиран на хомогеној Поклингтоновој интегро-диференцијалној једначини за прорачун расподеле струје и Лоренцовом баждарном услову који је коришћен за прорачун транзијентног напона уземљивачког система. За решавање Поклингтонове интегро-диференцијалне једначине коришћена је индиректна метода граничних елемената и метода марширања у времену. Надаље, техника за прорачун транзијентног напона уземљивачког система је презентирана. Нумеричка метода за прорачун транзијентних карактеристика уземљивачких система је верификована поређењем са теренским мерењима.

Кључне речи: уземљивачки систем, транзијентна струја, транзијентни напон, Поклингтонова интегро-диференцијална једначина, Лоренцов баждарни услов