Grzegorz MASLOWSKI, Robert ZIEMBA

Rzeszow University of Technology

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Measurements and modeling of electromagnetic disturbances in the lightning protection system of the residential building

***Abstract**. The paper presents measurements and computational results of the impulse current distribution in lightning protection system (LPS) obtained based on a circuit approach and a frequency-domain full-wave approach. There is a good agreement between computed and measured currents at the test site using the mobile impulse current generator and small residential structure. Small differences in the current waveshapes result mainly from the adopted mathematical approximation which does not perfectly match the current waveshape injected from the generator.*

***Streszczenie**. W artykule zaprezentowano wyniki pomiarów i obliczeń rozpływu prądu udarowego w instalacji odgromowej budynku. Obliczenia wykonano dla modeli obwodowego i polowego. Otrzymano dobrą zgodność wyników obliczeniowymi z pomiarami. Małe różnice w kształtach prądów wynikają głównie z przyjętej do obliczeń matematycznej aproksymacji prądu udarowego, która nie odwzorowuje dokładnie prądu z generatora. (**Pomiary i modelowanie zaburzeń elektromagnetycznych w instalacji odgromowej budynku mieszkalnego**).*

Keywords: lightning protection system, surge current distribution, measurements and simulations.
Słowa kluczowe: ochrona odgromowa, rozpływ prądu udarowego, pomiary i symulacje.

Introduction

The experimental and theoretical studies of lightning current distribution in LPS were carried out at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida, operated by the University of Florida (UF) [1-4]. In cooperation with the UF lightning research group, the experimental investigations of impulse current distribution in a small-structure LPS was conducted at the Rzeszow University of Technology (RUT), Poland [5-10]. A main objective of the preliminary experiments conducted at the RUT was practically the same as in Florida, that is, to examine the current waveforms in different parts of the circuit and the distribution of the injected impulse current between the grounding system of the LPS, and electrical installation of the building. Tests with current impulse generator enable one to compare experimental results for different type of soils. Note that the ground resistivity of clay soil in Poland was almost two order of magnitude lower than for sandy soil at Camp Blanding (less than 100 Ωm for clay soil versus 4000 Ωm for sandy soil). Recent experimental results has been presented in detail in [11].

Test site

The entire test system has been installed at a test site which was built in Huta Poreby, Poland 50 km far from the Rzeszow University of Technology. The test site is dedicated for testing of lightning protection systems of small structures. An overall view of the area where tests are conducted is shown in Fig. 1 and the lightning protection system mounted on the test house with marked measurement points is presented in Fig. 2.

Fig.1. An overall view of the test site in Huta Poreby

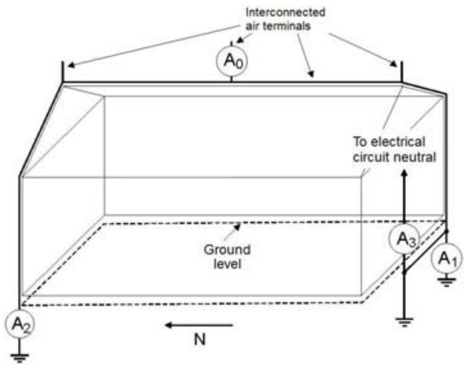

Fig.2. Lightning protection system mounted on the test house with marked measurement points

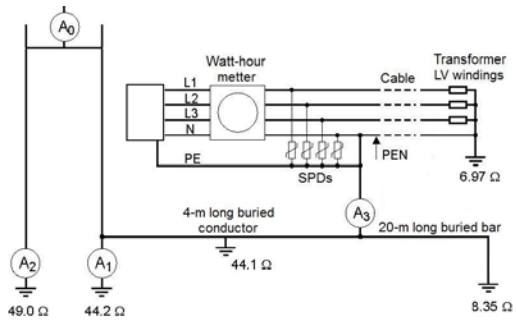

Fig.3. Lightning protection system mounted on the test house with marked measurement points

The measuring points are also shown in Fig. 3 together with the equivalent electrical diagrams of the test system. The detailed characteristics of the whole test site and test equipment used in the experimental investigations have been presented in [11].

Measurements and modelling

In order to compare measured currents injected into the LPS with theoretical predictions, a complex models of the system based on a circuit approach and a frequency-domain full-wave approach have been developed.

The first kind of model was implemented in the ATP-EMTP for computer simulation. The high-frequency representations of ground electrodes are the most important component of the model. Circuit models for vertical and horizontal ground electrodes are shown in Fig. 4.

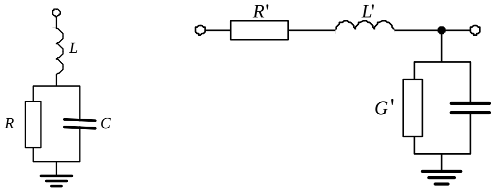

Fig.4. High-frequency models of (a) vertical and (b) horizontal ground electrodes

The entire circuit model in graphical representation used in ATP-EMTP is shown in Fig. 5. In the case of the vertical ground electrode (elements (4) in Fig. 5), a lumped model is adopted (Fig. 4a) with the following parameters [12]

(1) $$R = \frac{\rho_g}{2\pi\, l}\left(\ln\frac{8l}{d} - 1\right);\, \Omega$$

(2) $$L = \frac{\mu_0 l}{2\pi}\left(\ln\frac{8l}{d} - 1\right);\, \mu\text{H}$$

(3) $$C = 2\pi\, \varepsilon_g l\left(\ln\frac{8l}{d} - 1\right);\, \text{nF}$$

For the horizontal ground electrode (elements (5) and (6) in Fig. 5), one or more sections of length Δl are used (Fig. 4b) with parameters: $R = R'\Delta l$, $L = L'\Delta l$, $G = G'\Delta l$, $C = C'\Delta l$, where R', L', G', C' are parameters per unit length as follows [12]

(4) $$R' = \frac{\rho_\text{p}}{S_\text{p}};\, \Omega/\text{m}$$

(5) $$L' = \frac{\mu_0}{2\pi}\left(\ln\frac{2l}{\sqrt{dh}} - 1\right);\, \mu\text{H/m}$$

(6) $$G' = \frac{\pi}{\rho_\text{g}\left(\ln\frac{2l}{\sqrt{dh}} - 1\right)};\, \text{S/m}$$

(7) $$C' = \frac{\pi\varepsilon_g}{\left(\ln\frac{2l}{\sqrt{dh}} - 1\right)};\, \text{nF/m}$$

where: l - the electrode length; d - the diameter of the electrode; h - the burial depth of the horizontal electrode; S_p - the electrode cross-section, ρ_p - the electrode resistivity; ε_g - the resistivity of homogenous soil; ε_g - the soil permittivity (typical value $\varepsilon_\text{g} = 10\cdot\varepsilon_0$ where $\varepsilon_0 = 8.85\cdot10^{-12}$ F/m); μ_0 - the vacuum magnetic permeability ($\mu_0 = 4\pi\cdot10^{-7}$ H/m).

Note that the length Δl of a horizontal section have to satisfy the following condition

(8) $$\Delta l < \lambda/6 \qquad \lambda = 3160\sqrt{\rho_g / f_{\max}}$$

where λ is the wavelength in the soil, which corresponds to the highest spectrum frequency of the injected current.

The LPS are represented by lumped inductances estimated from geometrical dimensions of the air conductors and the underground cable 50 m long is modeled as a lossy transmission line. In case of computer simulation using ATP-EMTP a simple double-exponential approximation of the injected current is adopted as follows

(9) $$i(t) = I_\text{m}[\exp(-\alpha t) - \exp(-\beta t)]$$

where: α = 33700 s^{-1}; β = 116000 s^{-1}; I_m=2.8 kA.

The second kind of model was implemented in CDEGS software package and therefore the analysis of the issue takes into account the real parameters of lightning protection system wires as well as the effect of ground of finite conductivity. The computer calculations are based on the analysis of the studied system in the frequency domain. Wires are subdivided into segments in which the surface boundary condition must be satisfied for the axial electric field component

(10) $$\mathbf{t}\cdot(\mathbf{E}^i + \mathbf{E}^s) = I_l\, Z_w$$

where: $\mathbf{E}^s$ is scattered electric field generated by current in the analyzed segment due to existence of incident electric field $\mathbf{E}^i$, I_l is the current flowing in the segment, Z_w is the internal impedance of the wire, whereas $\mathbf{t}$ is a unitary vector tangential to segment surface.

From the Maxwell equations and Eq. 10 a relationship may be derived to bind the current flowing along wire axis with incident electrical field tangential to wire surface

(11) $$\mathbf{t}\cdot\mathbf{E}^i = I_l\, Z_w - \frac{\text{j}\omega\mu_1}{4\pi}\int_l I_l(\mathbf{r}')G(\mathbf{r},\mathbf{r}')dl$$

The Green's function, $G(\mathbf{r},\mathbf{r}')$ contains the Sommerfeld solution, which takes into account the effect of current dipoles immersed in a half-space conducting medium [13]. By using the method of moment [14], the integral Eq. 10 can be reduced to a set of linear equations from which currents in all defined segments may be calculated using standard numerical methods.

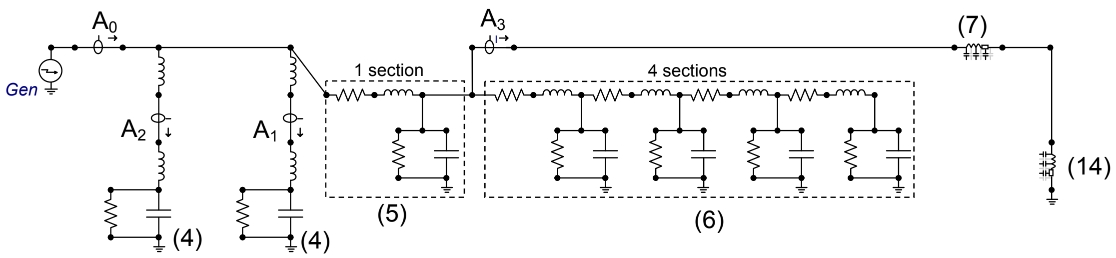

Fig.5. Lumped equivalent circuit of the analyzed system

The obtained propagation of currents takes into account the affects of each segment with the remaining ones, in the presence of lossy ground. In case of computer simulation in CDEGS accurate representation of the injected current is adopted. This input current is reproduced using point by point method.

The currents measured in the LPS and shown in Fig. 6 differ not only in peak value but also in waveshape.

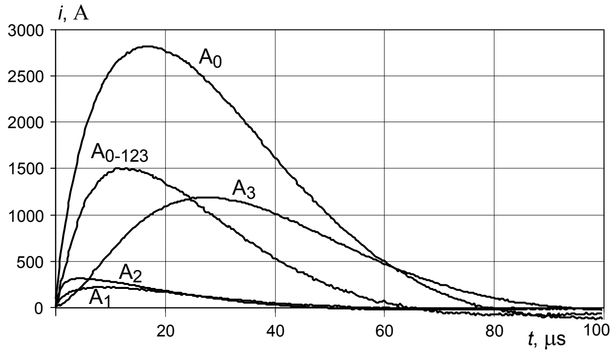

Fig. 6. Currents measured in test object; (A_0 - current injected from the generator to air terminal of LPS, A_1 and A_2 - currents flowing into the LPS vertical ground electrodes, A_3 - currents flowing into building electrical installation and cable neutral, $A_{0\text{-}123}$ - calculated current $A_{0\text{-}123} = A_0\text{-}A_1\text{-}A_2\text{-}A_3$ flowing into the ground from the horizontal 20-m long flat bar connecting LPS with the cable termination box).

This fact is important evidence of frequency dependent behavior of the system. LPS elements should be considered as a certain composition of resistance, inductance and capacitance.

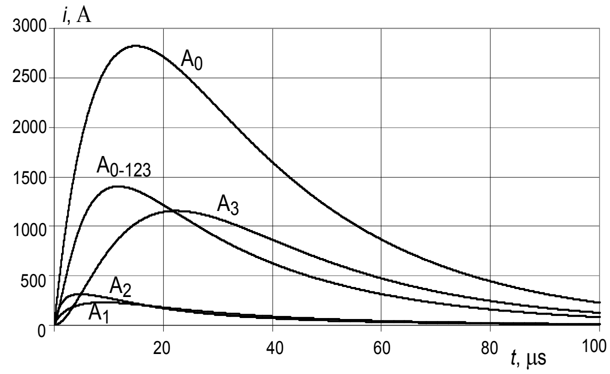

Fig. 7. The same currents as in Fig. 6 computed using a circuit approach implemented in ATP-EMTP. A simple double-exponential approximation of the injected current is adopted

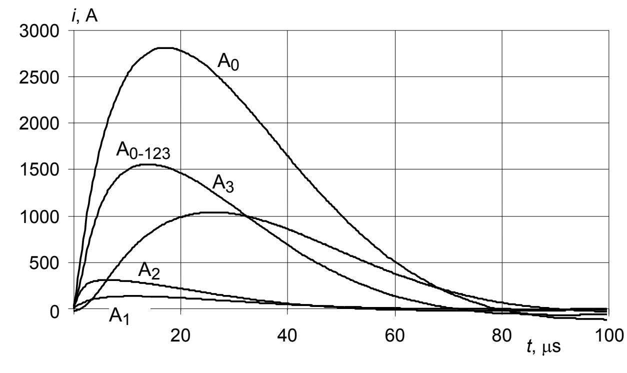

Fig. 8. The same currents as in Fig. 6 computed using a frequency-domain full-wave approach implemented in CDEGS. Accurate representation of the injected current created using point by point method is adopted.

The obtained computer results confirm such conclusions. Current waveforms obtained using the circuit approach (Fig. 7) and the full-wave approach (Fig. 8) are very similar to the measurements.

Small differences arise from the adopted simplifying assumptions in modeling process. In the case of the model implemented in the ATP-EMTP only rise time and a time to the half peak value on the tail is the same as measured injected current. The overall waveshape is not exactly the same and this is certainly the cause of slight discrepancies. Apart from, the circuit approach does not take into account the electromagnetic couplings between all elements of the system. For input current with shorter front time differences will by more visible.

On the other hand, the frequency-domain full-wave approach requires a very good mapping of the geometry of all system components. Differences in geometrical and physical parameters between complex real system and its model can also affect the minor differences between the measurements and the obtained results of computer simulations. For example, an impulse generator with return paths is represented by the ideal current source in the model. Despite these limitations, these two methods of modeling can be used to analyze the impulse current distribution in LPS and electrical installation.

Conclusion

The paper presents two different approaches to modeling of the impulse current distribution in LPS and electrical installation, that is, a circuit approach and a frequency-domain full-wave approach. Both methods have some limitations, but can be used to analyze the effectiveness of the LPS. There is a good agreement between measured and computed currents. A small differences in the current waveshapes result mainly from the adopted double-exponential mathematical approximation which does not perfectly match the current waveshape injected from the generator and some small differences in geometrical and physical parameters between complex real system and its model. Further studies are required in order to recognize the capabilities and limitations of different models, and finally, the nature of lightning currents propagating in the LPS and electrical installation.

***Authors**: dr hab. inż. Grzegorz Masłowski, Politechnika Rzeszowska, Katedra Elektrotechniki i Podstaw Informatyki, Al. Powstańców Warszawy 12, 35-959 Rzeszów, E-mail: maslowski@prz.edu.pl; dr inż. Robert Ziemba, Politechnika Rzeszowska, Katedra Elektrotechniki i Podstaw Informatyki, Al. Powstańców Warszawy 12, 35-959 Rzeszów, E-mail: ziemba@prz.edu.pl.*

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