http://dx.doi.org/10.5755/j01.eee.19.7.5160 ELEKTRONIKA IR ELEKTROTECHNIKA, ISSN 1392-1215, VOL. 19, NO. 7, 2013

Traveling Wave Phenomena in Modeling of Lightning Threat to Equipment during Direct Strike to the Tower of GSM Base Station

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***Abstract*–This paper deals with application of electromagnetic field theory and method of moments in analysis of lightning threat during direct strike to the tower of a GSM base station. The object is to elaborate analytical formulas and parameters for the waveforms of source current which would allow the natural traveling wave processes to be properly accounted for in the calculation results. These waveforms were estimated using numerical modeling. Based on these results, the computations, with the same numerical method, were performed in order to evaluate the level of lightning threat to the equipment of the GSM base station.**

***Index Terms*–GSM base stations, lightning strike, traveling wave phenomena lightning threat to equipment.**

I. INTRODUCTION

Application of circuit or electromagnetic field theory and moment method can presently be considered for analysis of lightning threat during direct strike to a complex wire structure [1], [2]. In these methods all electromagnetic couplings as well as both the aboveground and underground parts of a structure are naturally taken into account. A problem, however, arises with lightning current waves of short front times, travelling in electrically long wires or structures, for example in high telecommunication towers.

Proper representation of these phenomena in modeling of lightning return stroke using current or voltage source is not straightforward. This is due to reflections from the source, which do not correspond to reality, since the lack of a-priori knowledge on the characteristic impedance of a structure.

In this paper, the travelling wave phenomena in a typical rural GSM base station, with 60 m high radio-communication tower struck by lightning, are considered. The main object of the analysis was to develop analytical expressions and estimate parameters for the waveform of source current, which would allow the natural traveling wave processes to be properly represented in the current waveforms computed numerically.

The source current waveform and its parameters were estimated with numerical modeling in preliminary computation. Using the elaborated expressions, lightning threat to telecommunication equipment was estimated.

II. REPRESENTATION OF LIGHTNING RETURN STROKE

In the analysis, the incident wave of the return stroke current at the lightning channel base was characterized with the waveform recommended by the international standards on lightning protection [3] as follows

$$i(t) = \frac{I}{\eta} \cdot \frac{(t/\tau_1)^{10}}{1+(t/\tau_1)^{10}} \cdot e^{-t/\tau_2}, \quad (1)$$

where I = current peak value, η = correcting factor for the current peak value, τ_1, τ_2 = time constants of the front and the tail of the current impulse respectively, and t = time.

The values of the parameters in (1) were set according to the recommendations provided by the standard [3] for the III-rd protection level (Table I).

TABLE I. PARAMETERS USED IN EQUATION (1).

Parameter	Unit	First stroke	Subsequent stroke
I	kA	100	25
η	-	0.93	0.993
τ_1	μs	19	0.454
τ_2	μs	485	143

Hence, the incident waves of the lightning return stroke current were characterized as follows:

1) The first return stroke: 100 kA, 10/350 μs;
2) The subsequent return stroke: 25 kA, 0.25/100 μs.

III. REPRESENTATION OF THE GSM BASE STATION

The base station in concern includes a 60 m high radio-communication tower and a container with dimensions 3.8 m x 2.5 m x 3 m. The tower construction has a form of three supporting steel pillars set on a triangular basis and slanted bars linking the pillars along the tower.

For numerical modeling, the base station was represented as a network of cylindrical conductors. According to the requirements of the numerical method [2], the conductors were partitioned in short segments so that the thin wire approximation and a linear current distribution along a single segment could be assumed. Hence, the aboveground

Manuscript received December 29, 2012; accepted May 2, 2013.

structure was divided in segments of no more than 1.2 m long and the underground structure – no more than 0.3 m long (based on computed wavelengths and adopted soil parameters). Nearly all the segments were at least 10 times longer than their radii. The geometrical structure of the base station model is presented in Fig. 1.

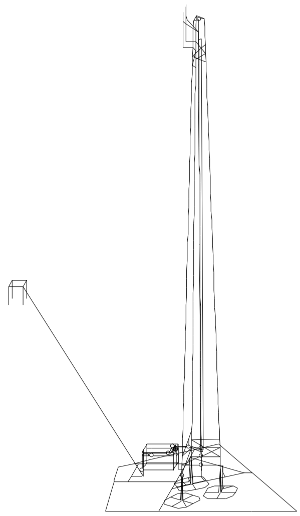


Fig. 1. Thin wire model of the GSM base station.

The model includes the following elements [4]:

1) Tower construction: three pillars (radius: 6.4 cm) and some slanted bars (radius 3.2 cm) linking the pillars at the top and base of the tower;
2) Cable support ladder along one of the tower flanks and between the tower and the container (radius 7.3 cm);
3) Reinforcement bars of the tower foundation footings (radius 0.8 cm);
4) Reinforcement bars of the container: vertical and horizontal conductors (radius 0.8 cm) forming the edges of a rectangular parallelepiped;
5) Base station grounding system: ring earth electrodes (1.1 cm) around the tower, the container and the whole station (buried at 0.6 m) and around particular tower foundation footings (buried at 3.2 m), all linked together;
6) Transformer station grounding system (66 m away from the GSM station): ring earth electrode (0.4 cm) buried at 0.6 m and four vertical electrodes (0.85 cm) 2.5 m long;
7) Air termination rods (1 cm) at the tower top;
8) Equipotential bonding networks outside and inside the container;
9) Selected elements of the cabling systems along the tower, between the tower and the container, inside the container and between the container and the transformer station.

The main details of the container cabling, equipment and equipotential bonding systems are presented in Fig. 2.

The following surges were adopted as a measure of lightning threat to equipment (Fig. 1 and Fig. 2):

1) Current that flows to the transformer station through the protective earth conductor;
2) Voltage at the terminals of the open-ended DC power cable supplying the Base Transceiver Station U_P;
3) Voltage at the 100 Ω termination of the signal cable U_S;
4) Potential difference between the main earthing terminal and the antenna cable earthing terminal.

The structure was assumed to be placed in a two-layer soil. The resistivity of the upper layer (30 m deep) was equal to 260 Ωm and of the bottom layer to 1060 Ωm.

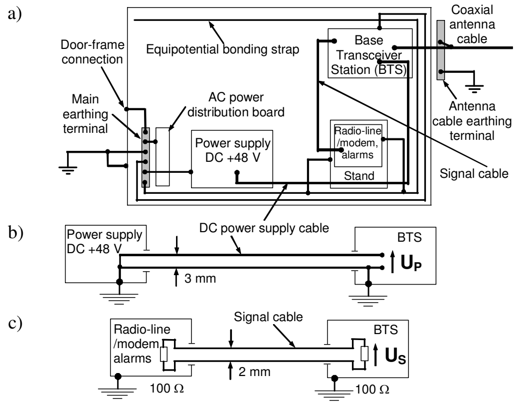


Fig. 2. Main details of the cabling and equipotential bonding systems inside the container ([4] extended by the details on the signal cable).

These parameters are typical for terrains in north-east Poland and Lithuania [5].

IV. ESTIMATION OF THE REFLECTION COEFFICIENTS

To represent direct lightning stroke to the tower top an ideal current source was adopted. In order to determine the total current waveform of the source, so that it could properly represent all the naturally reflected travelling wave components, the reflection coefficients at the tower top and base had to be calculated first. Due to tower height this was possible for the subsequent stroke only.

For this purpose a hypothetical structure representing the lowest part of lightning channel was attached to the tower top (Fig. 1). The structure was composed of 400 m vertical cylindrical wire of 1 cm radius and uniform resistivity of $4.54 \cdot 10^{-5}$ Ωm [6]. The lower end of the wire was attached directly to the tower top. The upper end was energized by the current source described according to (1) for subsequent return stroke of 0.25/100 μs 25 kA.

The analysis of current waveforms at various points along the 400 m wire and in the tower top revealed that the incident current wave injected to the wire is successively attenuated and, to a certain degree, distorted while traveling down. However these effects are much more significant in the upper parts of the wire (near the source) and can be neglected in the tower and at places located relatively low above the tower.

Taking these features into account, it was assumed that the total current waveforms in the tower and low above the tower can be expressed as for transmission line. Hence, the current waveforms at point K of the wire $i_K(t)$, at the tower top $i_T(t)$ and at the tower base $i_B(t)$ are as follows:

$$\begin{aligned} i_K(t) = {} & i_{K0}(t) + |\beta_1| \cdot i_{K0}(t - t_K) + \\ & + (1 + |\beta_1|) \cdot k \cdot i_{K0}(t - t_K - 0.4) + \\ & + (1 + |\beta_1|) \cdot k \cdot s \cdot i_{K0}(t - t_K - 0.8) + \ldots \end{aligned} \quad (2)$$

$$i_T(t) = \alpha_1 \cdot i_1(t) + k \cdot \alpha_1 \cdot i_1(t-0.4) + s \cdot k \cdot \alpha_1 \cdot i_1(t-0.8) + \\ + s^2 \cdot k \cdot \alpha_1 \cdot i_1(t-1.2) + s^3 \cdot k \cdot \alpha_1 \cdot i_1(t-1.6) + \\ + s^4 \cdot k \cdot \alpha_1 \cdot i_1(t-2) + s^5 \cdot k \cdot \alpha_1 \cdot i_1(t-2.4) + \ldots \quad (3)$$

$$i_B(t) = \alpha_1 \cdot \alpha_2 \cdot i_1(t-0.2) + s \cdot \alpha_1 \cdot \alpha_2 \cdot i_1(t-0.6) + \\ + s^2 \cdot \alpha_1 \cdot \alpha_2 \cdot i_1(t-1) + s^3 \cdot \alpha_1 \cdot \alpha_2 \cdot i_1(t-1.4) + \\ + s^4 \cdot \alpha_1 \cdot \alpha_2 \cdot i_1(t-1.8) + s^5 \cdot \alpha_1 \cdot \alpha_2 \cdot i_1(t-2.2) + \ldots \quad (4)$$

$$k = (1 - |\beta_1|) \cdot |\beta_2|, \quad (5)$$

$$s = -|\beta_1| \cdot |\beta_2|, \quad (6)$$

where β_1, β_2: reflection coefficients at the tower top and base respectively; $\alpha_1 = 1+\beta_1$, $\alpha_2 = 1+\beta_2$: refraction coefficients at the tower top and base respectively; $i_1(t)$: incident current wave at the 400 m wire base; α_1 $i_1(t)$: current wave transmitted to the tower top; $i_{K0}(t)$: incident current wave at point K of the wire.

The tower base reflection coefficient is generally dependent on the observation point (more than one element links the aboveground and underground parts). Here, β_2 is understood globally as related to the total current that flows to ground.

By identifying the first two or three components of (2) and (3) in the computed current waveforms at points K of the wire and at the tower top, the values of the reflection coefficients were estimated as: $\beta_1 = -0.38$ and $\beta_2 = 0.85$.

The estimated values of reflection coefficients at the GSM tower top and base, together with selected results based on experimental data recorded during natural strikes to different towers reported in the literature, are presented in Table II.

TABLE II. REFLECTION COEFFICIENTS ESTIMATED NUMERICALLY AND EXPERIMENTALLY FOR DIFFERENT TOWERS.

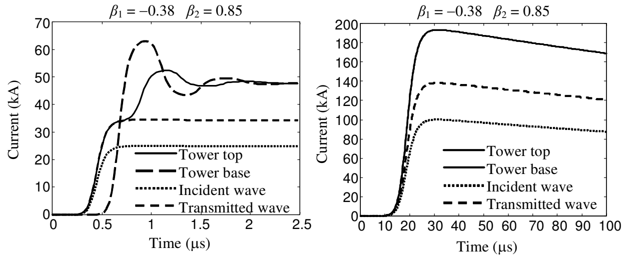
Tower	Tower top β_1	Tower base β_2
60 m GSM base station tower	–0.38	0.85
500 m CN tower in Toronto; Janischewskyj *e. al.* [7]	–0.27 ÷ –0.49	0.34 ÷ 0.43
200 m tower in Japan; Michishita *et al.* [8]	–0.6	0.4
160 m Peissenberg tower in Germany; Fuchs [9], [10]	–0.39 ÷ –0.68	0.64 ÷ 0.81
540 m Ostankino tower in Moscow; Rakov [10]	–	~1

The value of reflection coefficient at the base of the GSM tower is close to observed for Peissenberg and Ostankino towers.

V. Dependence of the Lightning Return Stroke Current Waveform on the Reflection Coefficients

Using expressions (3)–(6), the influence of the reflection coefficients on the total current waveforms observed at the tower top and base for the first and the subsequent return strokes was studied (Fig. 3 [4]). Generally, the higher the value of the reflection coefficient at the tower top or base is, the more significant is the difference between the current waveforms observed at the tower top and base.

For the first lightning return stroke, the traveling wave phenomena in the tower are not perceptible. The waveshapes as well as the peak values of the currents at the tower top and base are identical.



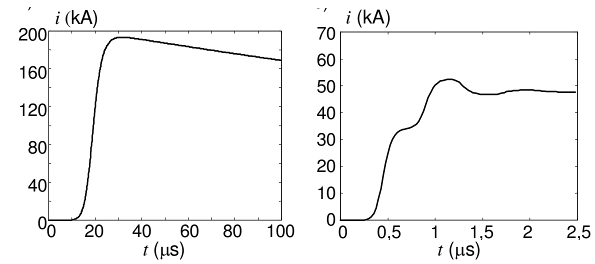
a) b)

Fig. 3. Return stroke current waveforms at the tower top and base according to (3) and (4) for calculated reflection coefficients: a – subsequent stroke; b – first stroke.

However, their peak value is significantly higher than the peak value of the incident wave.

Estimation of reflection coefficients for the first return stroke in this case is not possible, since the incident current wave front time is relatively long with respect to its travel time along the tower. Moreover, some research show that the frequency dependence of the reflection coefficients is rather weak. For example, in [11] it was estimated that in a range of 50 – 850 kHz the module of the reflection coefficient at the tower base is from 0.8 to 0.6 while the phase is negligibly small. Therefore, in further considerations it was assumed that the values of the reflection coefficients for the first return stroke are the same as for the subsequent one.

Under these assumptions and using the analytical expressions (3)-(6) with the parameters estimated in section IV, the final current waveforms for the ideal current source located at the tower top to represent the first and subsequent lightning return strokes was completed. These waveforms (Fig. 4) were used in further numerical computations.



a) b)

Fig. 4. Final current waveforms for the ideal current source located at the tower top to represent the first (a) and subsequent lightning strokes (b).

VI. Evaluation of Lightning Threat to Equipment during Direct Stroke to a GSM Base station Tower

The current waveforms from Fig. 4 were applied in numerical modeling of lightning stroke to the tower in order to estimate the level of threat to the telecommunication equipment (the ideal current source located at the tower top). The resultant waveforms of the currents flowing through the PE conductor to the transformer station grounding and of the potential differences between the container earthing terminals are shown in Fig. 5.

Fig. 6 presents the voltages computed at the open end of the DC power supply cable at the BTS terminal (Fig. 2b) for the first and subsequent lightning return strokes as well as currents in grounding conductors of BTS and DC power supply unit inside the container for the subsequent stroke.

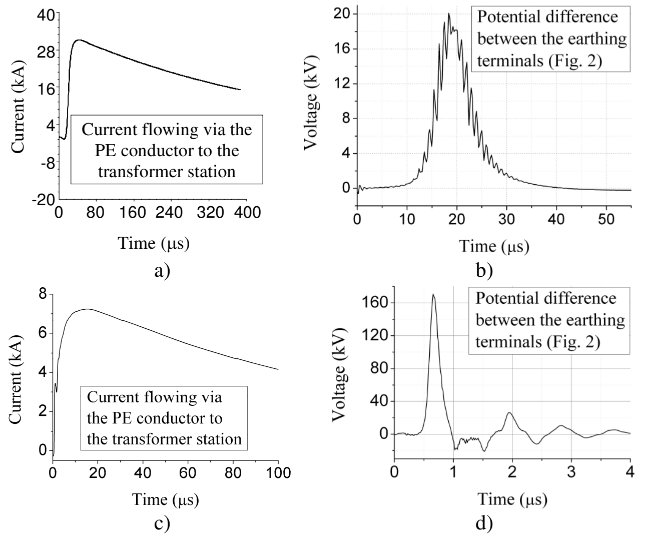


Fig. 5. Computed waveforms of the current that flows through the PE conductor to the transformer station and the potential difference between the container earthing terminals, a), b) first stroke, c), d) subsequent return stroke.

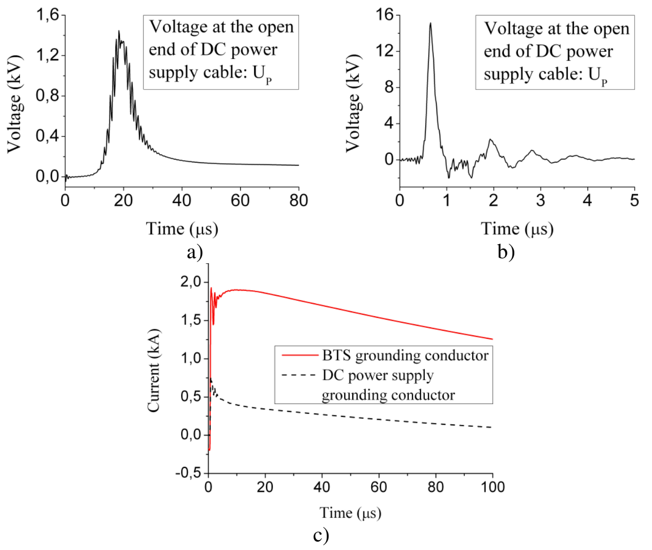


Fig. 6. Computed waveforms of surges: voltage at the open-ended DC power supply cable U_P (Fig. 2b): a – first stroke; b – subsequent stroke; c – lightning currents that flow in grounding conductors of BTS and DC power supply unit inside the container (Fig. 2a) for subsequent stroke.

The peak values of the voltages, which may result from the subsequent return stroke, are around ten times higher than that produced by the first stroke. The calculation results are summarized in Table III.

TABLE III. PEAK VALUES OF CURRENTS AND VOLTAGES CALCULATED FOR THE GSM BASE STATION.

Quantity	Unit	First stroke	Subsequent stroke
Current flowing via the PE conductor to the transformer station (Fig. 1)	kA	31.6	7.5
Potential difference between the container earthing terminals (Fig. 2a)	kV	18.7	171
Voltage at the open-ended DC power supply cable: U_P (Fig. 2b)	kV	1.3	15.2
Voltage at the 100 Ω termination of the signal cable: U_S (Fig. 2c)	V	0.54	4

VII. CONCLUSIONS

In the paper, analysis of traveling wave phenomena in a GSM tower struck by lightning has been presented. The analysis comprised computations using numerical modeling based on electromagnetic field theory and method of moments as well as simple analytical representation of lightning return stroke current. The analysis concerned currents and voltages in complex thin-wire model of rural GSM base station, in which both the aboveground and underground parts were taken into account.

Analytical expressions describing the total return stroke current in the tower, taking into account travelling wave phenomena, were developed and their parameters (e.g. the reflection coefficients at the tower top and base) estimated.

The elaborated expression for total lightning current at the tower top with the estimated reflection coefficients was then applied as the waveform of current source at the tower top in representation of lightning return stroke to the tower. Using these representation numerical computations of currents and voltages in the cable systems of the base station were performed and level of threat to equipment was estimated.

The estimation of the reflection coefficients is practically impossible in the case of electrically short objects. However, though the waveshape of the current at the channel base is undisturbed by the traveling wave phenomena, its peak value clearly depends on both the reflection coefficients.

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