ATP Analysis of Transient Process during Direct Lightning Strike to the Telecommunication Tower

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***Abstract*—For the wireless antenna industry, lightning protection has become even more necessary as a growing number of sophisticated electronic equipment is mounted on towers, which are more susceptible to direct strikes.**

A direct lightning strike to the telecomunication tower can cause dangerous overvoltages, which can result in malfunction of the sensitive equipment as well as dangerous step and touch voltages.

Over voltages and over currents arising in 60 m of telecommuni- cation tower during direct lightning strike on the top of the tower. The simulation of the electromagnetic transient process, caused from the lightning stroke on the upper most part of the telecommunication tower, has been carried out over the usage of the ATP Draw (Alternative Transient Program) software tool. ATP Draw [19], [18] is a graphical, mouse-driven preprocessor to the ATP version of the Electromagnetic Transients Program (EMTP) on the MS-Windows platform. The Alternative Transients Program (ATP)[19] is considered to be one of the most widely used universal program system for digital simulation of transient phenomena of electromagnetic as well as electromechanical nature in electric power systems. The key focus of the study has been the assessment of the tower behavior under the effect of the different lightning sources.

In consideration of the propagation phenomenon of lightning current, each conducting branch of the multi conductor system of the tower, is subdivided into a suitable number of segments. The length of each segment is assumed to be less than or equal to one-tenth of the minimum of wavelength corresponding to the maximum frequency likely to affect the system transient.

A distributed parameters line model is employed, with Heidler's type surge current source representing direct lightning strike to the telecommunication tower.

The mathematical model elaborated for the ATP Draw characterized by loss lines with distributed constant parameter, which is based on the single phase Clark's model. The inductance, capacitance and characteristic impedance of the segment model have been calculated using average potential method and programmed in Matlab code. The impact of the equivalent grounding resistance has been considered through the adoption of the model that implies constant resistance. The usage of three impulsive standard sources has been implemented, respectively: 1, 2/50[µs]; 8/20 [µs] and 10/350[µs].

***Index Terms*—ATP, capacitance, conductor, current source, capacitance segment, length, line model, loss lines modeling, lightning, lightning protection system, grounding, grounding resistance, surge current source, transient process, inductance**

I. INTRODUCTION

LIGHTINING performance of telecommunication tower has an important role for wireless antenna industry reliable operation. Lightning is the most important external transient phenomenon [1] that can cause dangerous over voltages equipment damages, terrible induced high voltages as well as electromagnetic compatibility EMC problems [10]-[12]. Following some peer review with the telecommunication tower infrastructure deployment teams, clear issues have been identified in the cases where the tower equipment rollout takes place in specific mountains where the grounding resistivity is very high following the specific rock electric resistance.

Counterpoise grid with vertical rods or grounding grids [5] are considered an effective solution for grounding system for all sites which must protected from lightning strokes[6] such as microwave towers [1], [4] petroleum fields, electric substation [1], plants and buildings. There is a very high research interest, on the study and the modeling, of the impacts caused from the transients processes introduced during the lightning strokes, from impulsive currents of the lightning. The calculation accuracy, time span of the calculation procedure, input and output variables setup, represent a complex and challenging assessment environment.

For the modeling of lightning over voltages and over currents of LPS (Lightning Protection System) of buildings and towers, power lines [1], very more accurate methods based on the electromagnetic field theory [1], [7], [10] usually employ the electric field integral equation in frequency or time domain for thin wire structures and the method of moment for solving the equation [1], [10]. The methods are suited for considering the overall electromagnetic environment around the towers. However large computing resources are required.

Among the different methods that are present for the electromagnetic transient processes we could mention the following: Integral equation solution over the moment method [7], [8] and the finite element method [1] coupled with the finite differences within the time and frequency domain [11], [12]. In our study we have adopted the analysis method over the distributed parameter circuits. [1], [2], [3].

This paper presents a transmission lines model [6] for the telecommunication tower lightning transient analysis, which is based on the use well know ATP_EMTP software package [18], [19]. Direct lightning strike to the top tower is modeled with the Heidler's type of surge current source [3]. The tower of iron structure of conductors by circular cross section conductors are approximated. In numerical model, conductors, are subdivided in to segments and Clark's model with distributed parameters is used. The number of the segments required for an accurate simulation depends on the highest frequency of the injected lightning impulse.

II. SEGMENT LENGTH CALCULATION

Segment length can be defined, depending upon maximum frequency, and the minimum length of electromagnetic wave

$$\Delta L < \frac{\lambda_{\min}}{10} \qquad (1)$$

So depending to the electromagnetic wavelength $\lambda_{\min}$, it is calculated the segment length ΔL, which will be represented with an equivalent electrical circuit. The minimum length of electromagnetic wave is being defined by this formula:

$$\lambda_{\min} = \frac{c}{f_{\max}} \qquad (2)$$

where: f_{max} is the maximum frequency of the lightning current wave spectrum and c is free space velocity;

$$\lambda_{\min} = \frac{300}{f_{\max}[MHz]} \text{ [m]} \qquad (3)$$

Hence, in external lightning protection systems, the segment length is calculated:

$$\Delta L < \frac{30}{f_{\max}[MHz]} \text{ [m]} \qquad (4)$$

Since we take the maximum frequency of injected lightning current on top tower equal to:

$$f_{\max} = 2[MHz] \qquad (5)$$

So the criterion to select segment length has the form:

$$\Delta L < \frac{30}{f_{\max}[MHz]} = 15 \text{ [m]} \qquad (6)$$

III. CAPACITANCE, INDUCTANCE AND CHARACTERSTIC IMPEDANCE CALCULATION [3]

Per unit capacitance of the segment, can computed as follows [3], [5]:

$$C = \frac{4\pi\varepsilon_0 \cdot \Delta L}{\int\limits_{\Gamma'}\int\limits_{\Gamma} \frac{\Delta L \cdot \Delta L'}{r} - \int\limits_{\Gamma_S}\int\limits_{\Gamma} \frac{\Delta L_S \cdot \Delta L}{r}} = \frac{4\pi\varepsilon_0 \cdot \Delta L}{I_{self} - I_{mutual}} \qquad (7)$$

where permittivity of free space

$$\varepsilon_0 = 8.854 \cdot 10^{-12} \text{ [F/m]}$$

I_{self} is a double integral that support the actual estimation of the self segment capacitance, independently of the geometric position of the segment, as opposed to the earth surface [3].

I_{mutual} is a double integral, through which, the assessment of the capacitance in between the real segment and the images segment, as opposed to the earth surface, is being carried out. The value of this integral depends on the geometric position of the segment. Provided the calculation of both the aforementioned double integrals has been performed, the unit capacitance of the segment is measured.

All integrals can be computed analytically [3]. Once the capacitance is computed, one can easily obtain the needed value of the segment's per unit inductance [3], [12], [13], [14] from the following relationship:

$$L = \frac{\varepsilon_0 \cdot \mu_0}{C} \text{ [H/m]} \qquad (8)$$

where permeability of free space

$$\mu_0 = 4 \cdot \pi \cdot 10^{-7} \text{ [H/m]}$$

Characteristic or surge impedance, can computed as follows:

$$Z_S = \sqrt{\frac{L}{C}} = \frac{\sqrt{\varepsilon_0 \mu_0}}{C} \text{ [}\Omega\text{]} \qquad (9)$$

Per unit resistance of tower segment can computed as follows:

$$R = \frac{1}{\sigma_{Fe} \cdot \pi \cdot r^2} \text{ [}\Omega\text{/m]} \qquad (10)$$

where r is radius of segment

$$\sigma_{Fe} = 1.03\text{e+07 [S/m] [10]} \qquad (11)$$

$$\sigma_{Cu} = 5.76\text{e+07 [S/m] [10]} \qquad (12)$$

Per unit resistance of segment, can computed [9], [10], [16] as follows:

$$R = \frac{1}{\sigma_{Fe} \cdot \pi \cdot (r^2 - (r-\delta)^2)} \qquad (13)$$

where δ is the penetration depth, calculated at maximum of frequency of the lightning spectrum, and is calculated:

$$\delta = \sqrt{\frac{2}{\sigma_{Fe} 2 \cdot \pi \cdot f_{\max}}} \qquad (14)$$

IV. ANALYTICAL SOLUTION OF SELF DOUBLE INTEGRAL, I_{self} [3]

Expression for distributed and lumped unit capacitance value of segment include two double integrals. The first of them is integral:

$$I_{self} = 2\cdot[\Delta L\cdot f_1 - f_2 + r_0] \tag{15}$$

$$f_1 = \ln\left(\frac{\sqrt{(\Delta L)^2 + r_0^2} + \Delta L}{r_0}\right) \tag{16}$$

$$f_2 = \sqrt{(\Delta L)^2 + r_0^2} \tag{17}$$

The first step of the double integration, implies the integration along the segment axis [3], [2] Γ' curve, Fig.1, meanwhile the second integration is performed along the surface of the segment, namely the Γ curve, Fig.1, that is actually in parallel with the segment axis.

The calculation of the I_{self} integral does not depend on the geometric position of the segment as opposed to the earth surface; hence for its calculation the required parameters are the radius r_o of the conductor and the length of the conductor ΔL.

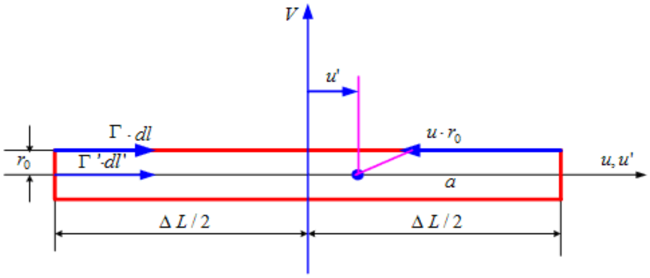

Fig.1. Geometry involved in computing self double integral, I_{self} [3]

V. ANALYTICAL SOLUTION OF MUTUAL DOUBLE INTEGRAL, I_{mutual} [3]

The estimation of the double integral has a dependency on the geometric position of the segment as opposed to the earth surface. Below you may find a set of cases where the calculation of this integral takes place.

First Case:

The segment is parallel with a height h from the earth surface and length l. In this case there is the presence of two segments, the real one and the images one. The double integral is calculated over the substitution indicated below

$$r_o = 2\cdot h \tag{18}$$

in the formulas (16) and (17). Thus the double reciprocal integral has the below form.

$$I_{mutual} = 2\cdot[\Delta L\cdot f_1 - f_2 + 2\cdot h] \tag{19}$$

Second case:

The segment is perpendicular with the height h_1 and h_2, from the earth surface and it has the conductor radius r_o.

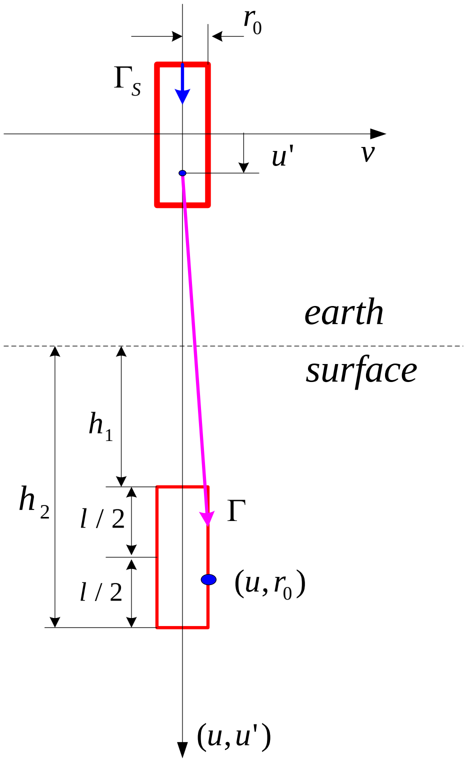

Fig.2. Geometry involved in computing mutual double integral for the perpendicular segment to earth surface [3]

The first integration is carried out along the axis of segment image, Γ_S curve in the Fig.2, while the second integration is carried out along the curve on segment surface, which is parallel to the segment axis, Γ curve in the Fig.2.
For this case:

$$I_{mutual} = f_3 - f_4 + f_5 - f_6 - f_7 + f_8 \tag{20}$$

$$f_3 = u_1\cdot arsh\frac{u_1}{r_0} \tag{21}$$

$$f_4 = \sqrt{u_1^2 + r_0^2} \tag{22}$$

$$f_5 = u_2\cdot arsh\frac{u_2}{r_0} \tag{23}$$

$$f_6 = \sqrt{u_2^2 + r_0^2} \qquad (24)$$

$$f_7 = 2 \cdot u_1 \cdot arsh\frac{u_3}{r_0} \qquad (25)$$

$$f_8 = \sqrt{u_3^2 + r_0^2} \qquad (26)$$

where

$$u_1 = h_1 + h_2 + l \qquad (27)$$

$$u_2 = h_1 + h_2 - l \qquad (28)$$

$$u_3 = h_1 + h_2 \qquad (29)$$

Third case:

The segment has an inclination with its extremities marked from the relevant coordinates , hights h_1, h_2 with regards to the earth surface and *d* represents orthogonal projection of the segment onto the earth surface

If segment is in inclined position to the earth surface, parameters signed in the Fig.3, can computed as follows:
Length of segment can computed as follow

$$l = \sqrt{d^2 + (h_2 - h_1)^2} \qquad (30)$$

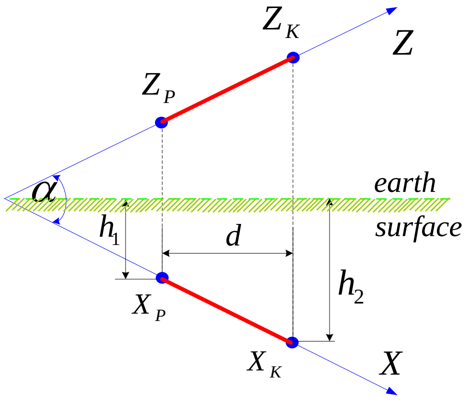

Fig.3 Geometry involved in computing mutual capacitance of the inclined segment to earth surface [3]

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$$x_p = z_p = \frac{\min\{h_1, h_2\}}{|h_2 - h_1|} \cdot l \qquad (31)$$

$$x_k = z_k = \frac{\min\{h_1, h_2\}}{|h_2 - h_1|} \cdot l \qquad (32)$$

$$\cos\alpha = \frac{2 \cdot d^2}{l^2} - 1 \qquad (33)$$

$$I_{mutual} = 2 \cdot [B(x_p, z_p) + B(x_k, z_k)]$$

$$+ 2 \cdot [-B(x_p, z_k) - B(x_k, z_p)] \qquad (34)$$

where for $r_0 << l$

$$B(x,z) = x \cdot \ln(z - f_9 + f_{10}) \qquad (35)$$

$$f_9 = x \cdot \cos\alpha \qquad (36)$$

$$f_{10} = \sqrt{x^2 + z^2 + r_0^2 - 2 \cdot x \cdot z \cdot \cos\alpha} \qquad (37)$$

VI. NUMERICAL APPLICATION

A typical Albanian-built of Telecommunication tower (TT) with quadratic base is considered here for practical application purpose. The dimensions of the TT are in meter. The 3D view of TT is show in Fig.4.

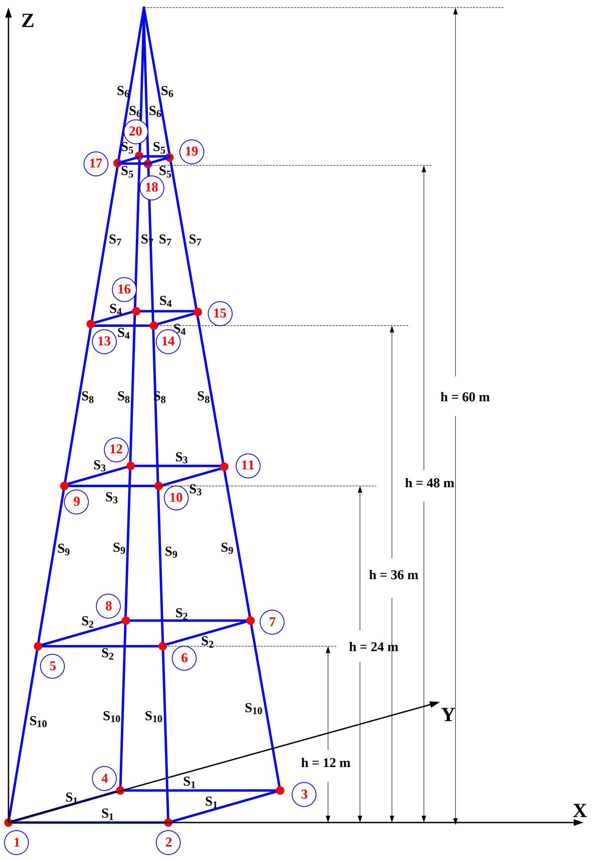

Fig.4. 3D view of telecommunication tower and its geometrical data

From the Fig.4, can see that we have only parallel and inclined segments. In Fig.5, is represented 2D view of TT with its segments names and length less than 15 [m], see equation (6). TT structure by circular cross section conductors are approximated.

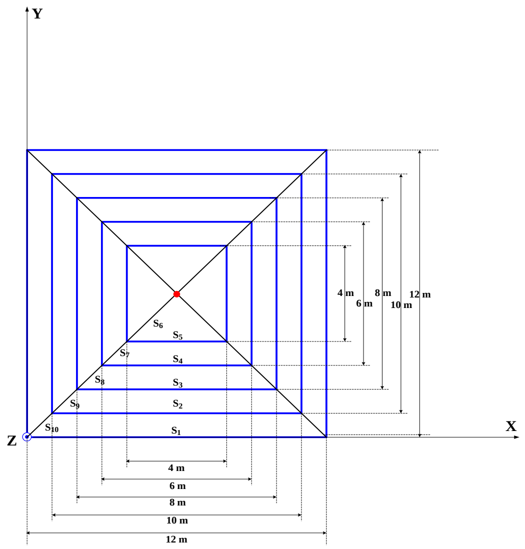

Fig.5. Top view(2D) of tower with its segments names and lengths

The inductance, capacitance and characteristic impedance of the segment model have been calculated using average potential method and programmed in Matlab code. In the Table I, are calculated the unit capacitance and characteristic impedance of parallel segments to earth surface as follows:

TABLE I
Calculated unit capacitance and characteristic impedance of parallel segments to earth surface, $r_0 = 3.2$ [cm]

Segments name	Length [m]	Hight [m]	Capacit. [pF/m]	Caract.Imped. Z[Ω]
S_1	12	0.5	8.5	392.2
S_2	10	12	11.01	302.9
S_3	8	24	13.78	242
S_4	6	36	17.95	185.8
S_5	4	48	27.49	121

In the Table II, are calculated the unit capacitance and characteristic impedance of inclined segments as follows:

TABLE II
Calculated unit capacitance and characteristic impedance of inclined segments, $r_0 = 6.4$ [cm]

Segment Name	Hight h_1 [m]	Hight h_2 [m]	Capacit. [pF/m]	Caract.Imped. Z[Ω]
S_6	48	60	7.74	430.46
S_7	36	48	7.76	429.49
S_8	24	36	7.79	427.75
S_9	12	24	7.82	423.58
S_{10}	0.5	12	8.4	396.93

The mathematical model elaborated for the ATP Draw characterized by loss lines with distributed constant parameter, which is based on the single phase Clark's model as show in Fig.6

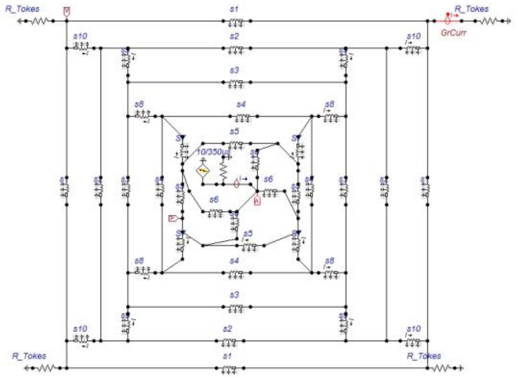

Fig.6. ATP Draw representation of the telecommunication tower with loss lines of a distributed constant parameters (Clark's Model), fed by standard lightning sources

Lightning surge model for the simulation on the Heidler's model of current source, which can be described with the following expression:

$$i(t) = \frac{I_p}{\eta} \cdot \frac{(\frac{t}{\tau_1})^n}{1+(\frac{t}{\tau_1})^n} \cdot e^{-\frac{t}{\tau}} \qquad (38)$$

where: I_p, η peak value of the lightning current and it's correction factor, respectively, n factor influencing the rate of rise of the function, τ the strike factor; is interval between start time and the point on the tail where the function amplitude has fallen to 50 % of its peak value τ_1 duration of the lightning surge front.

The lightning current is modeled as a current source and applied to the top node of the ATP circuit. The lightning path impedance is equal 1000 [Ω] as suggested from Disendorf [17] and are usually used in CIGRE, IEEE and IEC standard. The impedance value of real lightning path has not been clear, and requires further investigation. Grounding modeling of the TT is a critical aspect. A nonlinear frequency-dependent representation is required to obtain an accurate simulation. Since he information needed to derive such a model is not always available, a lumped circuit model is usually chosen for representing the footing impedance, although it is recognized that this model is not always adequate. A grounding design based on one or several vertically driven rods has t include soil ionization effect. In such case the grounding model[1] may be represented by mans of non linear resistance whose value is approximated as follows:

$$R_T = \frac{R_0}{\sqrt{1+\frac{I}{I_g}}} \qquad (39)$$

where R_0 is the footing resistance at low current and low frequency I is the stroke current through the resistance, and

I_g is the limiting current to initiate sufficient soil ionization, which given by:

$$I_g = \frac{E_0 \cdot \rho}{2 \cdot \pi \cdot R_0^2} \qquad (40)$$

being ρ [Ω m] the soil resistivity and E_0 the soil ionization gradient (about 400 [kV/m]). This tower grounding model can modeled in ATP Draw on the basis of the expression shown in equations (37) with the aid of MODELS.

It has been known in general that the footing impedance tends to be capacitive in the case of a high resistivity earth [1] and inductive in the low resistivity earth case. A problem of representation is:

The footing impedance can be resistive, inductive and capacitive depending on the season and the weather when a measurements is made, i.e the impedance is temperature-and soil moisture dependent. Therefore, it is not easy to select a model of the footing impedance and this is reason why we a constant resistance have been chosen.

VII. SIMULATION DATA

During the simulation the usage of 3 standard lightning waves as current sources has been carried out with the Clark Model, please see Fig. 7.

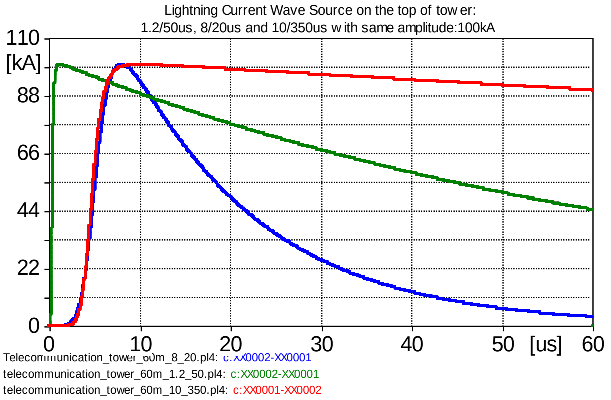

Fig. 7. Lightning Current waves on the top of tower for 3 standard lightning waves as current sources:1.2/50 [µs], 8/20 [µs] and 10/350 [µs] with same amplitude 100 [kA].

Meanwhile in Fig. 8, we have the representation of the voltages on top of the tower, for distinguished lightning current waves (for the above mentioned standard lightning waves), considering grounding constant resistance R_t= 5 [Ω].

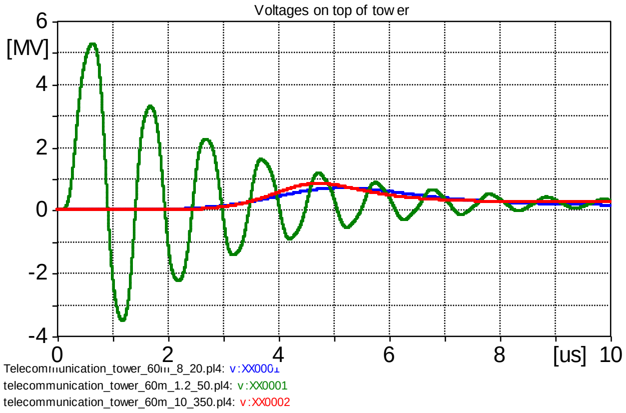

Fig. 8 Voltages on the top tower for distinguished lightning current waves: 1.2/50 [µs], 8/20 [µs] and 10/350 [µs] with same amplitude 100 [kA] and grounding constant resistance R_t =5[Ω].

Current waves on grounding resistance with R_t =5 [Ω] for standard wave 1.2/50 [µs] lightning current sources, with peak current 100 [kA] on top of the tower are shown in Fig. 9

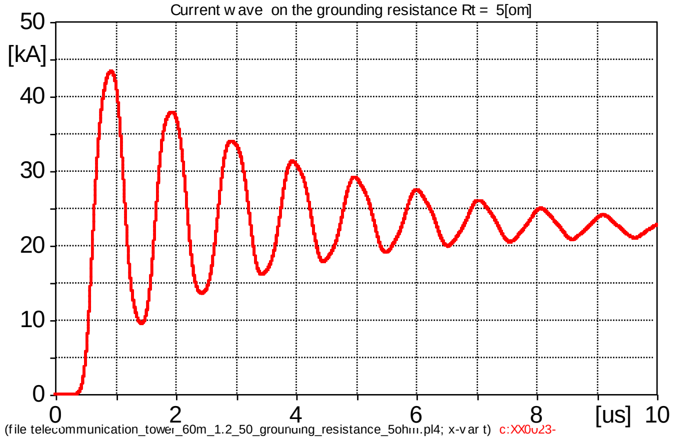

Fig. 9 Current waves on grounding resistance with R_t =5 [Ω] for standard wave 1.2/50 [µs] lightning current sources, with peak current 100 [kA] on top of the tower

In Fig.10 we have the representation of current waves on grounding resistance with R_t =5 [Ω] for standard wave 8/20 [µs] lightning current sources, with peak current 100 [kA] on top of the tower.

Fig. 10 Current waves on grounding resistance with R_t =5 [Ω] for standard wave 8/20 [µs] lightning current sources, with peak current 100 [kA] on top of the tower

In Fig.11 we have the representation of current waves on grounding resistance with R_t = 5 [Ω] for standard wave 10/350 [µs] lightning current sources, with peak current 100 [kA] on top of the tower.

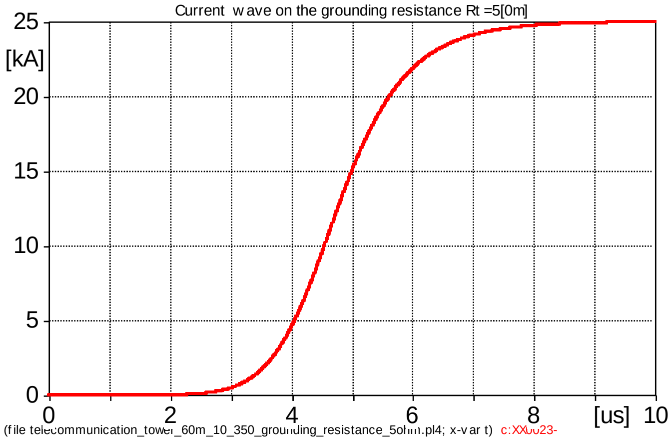

Fig. 11 Current waves on grounding resistance with R_t = 5 [Ω] for standard wave 10/350 [µs] lightning current sources, with peak current 100 [kA] on top of the tower

It is important to present the variation of the lightning current waves on the grounding resistance R_t=10 [Ω] and R_t = 5 [Ω] for the standard wave of the 1,2 /50 [μs] with an amplitude of 100 [kA] (see Fig.12)

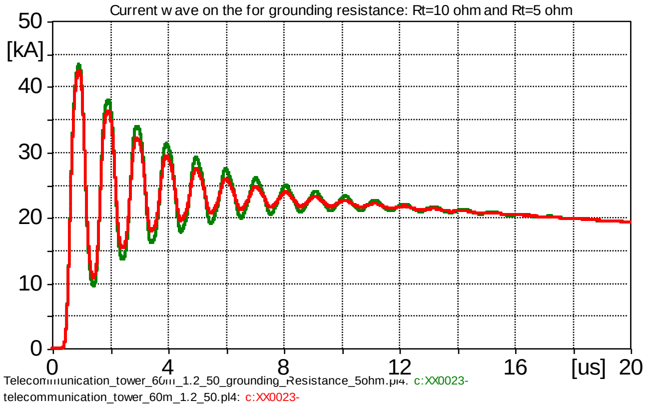

Fig.12 Lightning Current waves on the grounding resistance: R_t =10 [Ω] and R_t = 5 [Ω]

For the very same standard wave of the lightning current, in Fig.13 we have the presentation of the voltage waves on top of the tower for grounding resistances R_t =10 [Ω] and R_t= 5 [Ω].

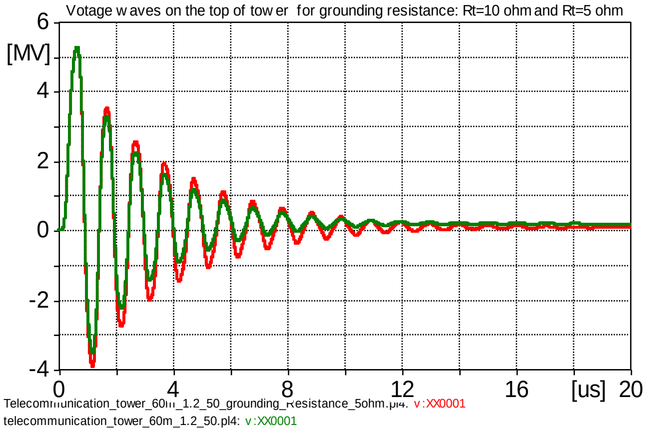

Fig.13 Voltage waves on the top of tower for grounding resistances: R_t= 10 [Ω] and R_t = 5 [Ω]

In Fig.14 we can clearly see the voltage wave on the grounding resistance with different resistance R_t = 10 [Ω] and R_t = 5 [Ω], with lightning current source 1.2/50 [µs], 100 kA.

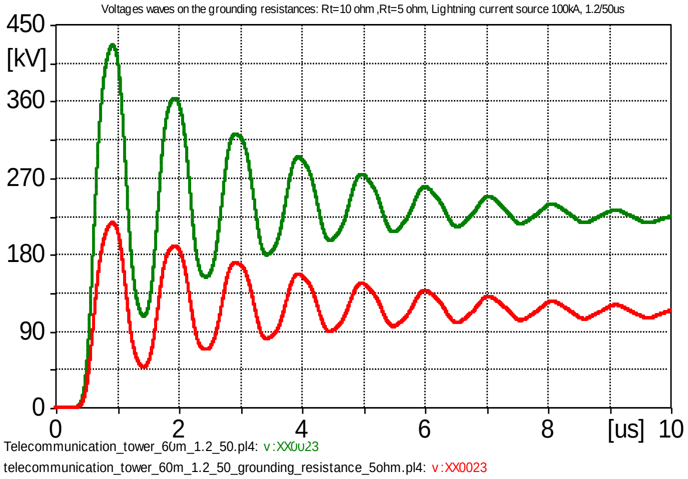

Fig.14 Voltage waves on the grounding resistance, with different resistance R_t = 10 [Ω] and R_t = 5 [Ω] with Lightning Current Source 1.2/50 [µs], 100 [kA]

VIII. CONCLUSION

1. The analysis of the lightning strikes transient processes, on the tower infrastructure, adopted in telecommunication, electric power systems and in the oil industry, is to be addressed as a critical task preventing negative impacts in the service availability, of the respective equipment. Based on the level of over-voltages, during a transient processes, through the tower construction elements coupled with the tower base connected to the grounding resistance, we can assess the insulation-co-ordination of the various elements located on the tower and the ones in its close proximity. Using the level of the wave of currents, in all segments of the towers, we can calculate the magnitude of induced magnetic field in the power cables along with the one in electronic control equipment. Issues and topics related to EMC can be addressed as well.

2. The grounding and grounding resistance simulation model, especially in mountain areas with cliffs, with high electric resistivity, i e 1000 to 2000 [Ωm] results of vital importance. Tower grounding system simulation model affects considerably the computed over voltages, which increase with tower grounding resistance.

3. Parameter that have the greatest influence on the transient performance of TT ground grid, counterpoise form, vertical rods, etc, subjected to lightning current waves are, soil resistivity, shape of the lightning current front, more specifically, the average steepness of current impulse, not only the short time rise, but the high steepness of the lightning current during part of the rise, induce higher voltages.

4. In the future we will extend the research studies related with earth impedance modelling considering the influence of soil ionisation, the influence of soil with very large specific electric resistance and its model in the simulation.

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