Variation of Tower Footing Resistance on the Lightning Surge Propagation through Overhead Power Distribution Lines

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***Abstract*—This paper deals with the analysis of the effects of electromagnetic transients generated by lightning on power distribution lines, considering the influence of tower footing resistance variation. Both types of lightning stroke, direct and induced, are considered. The model of a 20 kV three-phase overhead power distribution line is performed considering a simple line circuit with triangle canopy and 50/8 mm^2 Ol-Al conductors. The model of the power distribution line is done considering a Multistory tower model. New concepts regarding lightning assessment through Electromagnetic Transients program and Finite Element Method are implemented. The simulations are performed based on a time domain analysis, considering the lightning stroke as an electromagnetic perturbation within frequency range of 10-100 kHz. A contribution to value creation is the design of the Multistory tower model, used for electromagnetic transients analysis for medium voltage power distribution lines. Excepting previous research, current study was done by considering the variation of tower footing resistance of the tower, between 4-35 ohms. The novelty of the study is the analysis of the dependency determined by the variation of tower footing resistance on the lightning surge propagation through power distribution networks and subsequent consumers.**

***Index Terms*—electromagnetic transients, finite element methods, power distribution lines, surges, time domain analysis.**

I. INTRODUCTION

Actual researches [1-5] within power systems are directed through improvement of different methods and tools to counteract or decrease the effect of electromagnetic perturbations generated by lightnting or switching and also of the electromagnetic perturbations coupling mechanisms. Different strategies have been taken into account to achieve these objectives:

Enhance immunity of devices and installations exposed to conducted or radiated transient electromagnetic perturbations;

Identification of high frequency perturbation sources within power systems and the assesement of their magnitude and influence;

Measuring the electric and magnetic fields (at power frequency) within substations or near power distribution lines in order to identify the exposure risks.

Actual researches [6], [8-16] deal with the complex analysis of lightning phenomena by simulation and modeling on high voltage power systems, considering the multiconductor vertical line model including the bracings and cross-arms for the tower model of the overhead power line. Not many researches are directed through the assessment of lightning effects on medium voltage overhead power lines. Many studies are directed through the assessment of induced lightning performance of medium voltage distribution lines from statistical point of view using Monte Carlo simulation.

Related to lightning surge propagation through overhead power lines, most of the studies are performed considering, the influence of the ground conductivities and resistances, not many are taking into consideration the influence of the towers impedances.

According to current regulations [16], the electrical insulation system of the medium voltage power distribution lines includes surges arrestors or insulator strings. It is imperative to underline that the configuration of insulation design is not continuous, with respect to the line length. In this sense, an issue is to determine the influence of electromagnetic transients generated by lightning surges propagation where the line insulation is not continuous.

As shown in [19-20], the magnitude of the currents and voltages within direct lightning stroke is influenced by the tower geometry and shielding protection of the power distribution line. Current regulations [21-23] underline that the protection of power distribution lines even against lightning it’s completely realized both considering the existence of the ground wire and also designing a bound connection of the power line with the underground surrounding systems, obtaining in this way a grounding connection which is mandatory to be kept around 4-10 Ω. Based on this, further analyses are needed taking into account the following issues:

(1) Which should be the value of the tower footing resistance in order to obtain a perfect grounding connection of the power line?

(2) Is there and influence generated by the variation of tower footing resistance on the lightning surge propagation through power line or surrounding systems?

The aim of this research is to assess the effect of direct and induced lightning surge on an overhead power distribution line, taking into account the variation of tower footing resistance. In this sense, several simulations are done for two different real situations highly encountered in

This paper is supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), financed from the European Social Fund and by the Romanian Government under the project number POSDRU/159/1.5/S/134378.

Digital Object Identifier 10.4316/AECE.2016.01014

practice:

-Lightning stroke to the tower structure – direct stroke;

-Lightning stroke to phase wire – induced stroke;

Complex analysis and simulations were performed, using both numerical modeling method and finite element method, using Electromagnetic Transients program (EMTP) (Matlab package software) and Comsol Multiphysics.

Multiple simulations were performed based on time domain analysis, as follows:

(1) Using MATLAB, a numerical analysis was done in order to highlight the effect of electromagnetic transients generated by lightning on the power distribution line;

(2) Using Comsol Multiphysics, the finite element method was applied in order to assess the electric potential near power distribution line and surrounding constructions / power networks.

Considering that the towers of overhead power lines have the charge to dissipate the lightning surge, it is imperative to study the role of their impedance within strike. In these sense, for simulation purposes, the footing resistance of the tower was varied between 4 – 35 Ω, as for a medium voltage power line tower model.

The novelty of the study is the analysis of the dependency determined by the variation of tower footing resistance on the lightning surge propagation through power distribution networks and subsequent consumers. Considering the existing researches, current work is directed through the study of medium voltage overhead power line circuits affected by direct / indirect lightning surge by Matlab and Comsol simulations, considering the Multistory model for the tower design.

II. System Description

In the case when an overhead power line is subjected to a direct lightning stroke, the surge it's taken over by the upper phase wire of the power line. In this case, according to [21] the phenomena can be described as in Fig. 1.

The lightning propagates through a lightning channel with impedance Z_T of about 400 Ω. The lightning current (1), flows through the phase wire of the power line to the grounding connection of the tower, generating an electric potential (2) through the other phase wires of the power line. It is obvious that the generated electric potential *(P)* is strongly dependent by the tower footing resistance (*R*) of the power line. The following issue arises: what value should have the tower footing resistance in order to reduce the value of the generated potential.

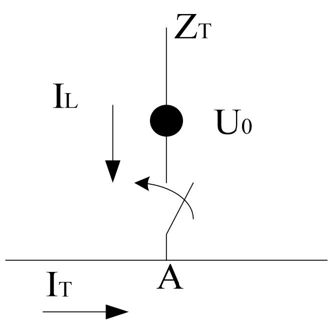


Figure 1. Direct lightning surge through phase wire

The obtained surge can be estimated, with the relations:

$$
\begin{aligned}
I_L &= \frac{U_0}{Z_T} \\
I_T &= 2 \cdot I_L \\
U_{ins} &= 100 \cdot I_T
\end{aligned}
\quad (1)
$$

where Z_T is the impedance of the lightning current before the surge, I_L is the lightning current after surge, U0 is the AC voltage source, I_T is the current that flows through the phase conductor after lightning, U_{ins} is the overvoltage that is stressing the phase insulation [21].

$$P = I_T \cdot R \quad (2)$$

Based on this issue, it was done the research, considering the following procedure: a three-phase medium voltage overhead power distribution line of 20 kV, with simple circuit, triangle canopy, with Ol-Al conductors of 50/ 8 mm^2 cross section is considered.

The corresponding electrical parameters of the line (Table I) have been established according to [17], and the line design was performed according to the model proposed in [11] and [18].

TABLE I. Electrical Parameters of the Medium Voltage Overhead Power Line

Item	Type	S [mm^2]	Structure	D_o [mm]	R_l [Ω/km]	I_{max} [A]
Phase conductor	50/ 8	56.3	6 wires of Al Ø3.20mm + 1 wire of Ol Ø3.20mm	9.6	0.5946	302

Two real situations encountered in practice are analyzed: lightning surge to the tower construction and to the phase wire, both cases taking into account the protection of the distribution power line through insulator strings.

The tower model of the overhead power distribution line and the phase wires are shown in Fig. 2, where, R, S, T` are the OL-Al phase conductors, IS are the insulator strings and the geometrical dimensions are: x_1=1.4m, x_2=2.2m, x_3=1.4, h_1=12m, h_2=9m, h_3=6m, h_4=9m.

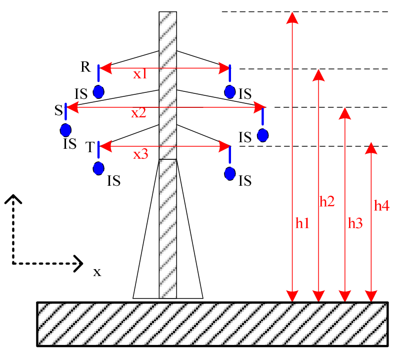


Figure 2. Model of the tower and phase conductors

For the case of lightning surge through the tower construction, the simulations were performed using the Electromagnetic Transients program (Matlab-Simulink) and the other one was performed based on Finite Element Method, according to the sketch illustrated in Fig. 4, in which: 1-Ground; 2-Multiphase matching impedance; 3-AC Source; 4-Overhead power distribution line; 5-Tower; 6-Norton Circuit-Lightning current source.

In this case, the lightning phenomenon was considered an electromagnetic perturbation with frequency range between 10-100 kHz.

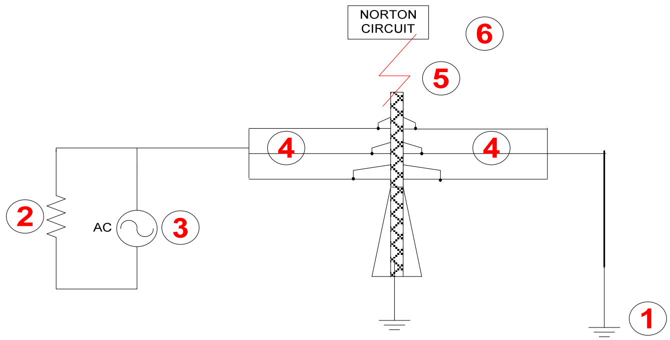


Figure 3. Simplified overhead 20 kV power distribution line model with single tower

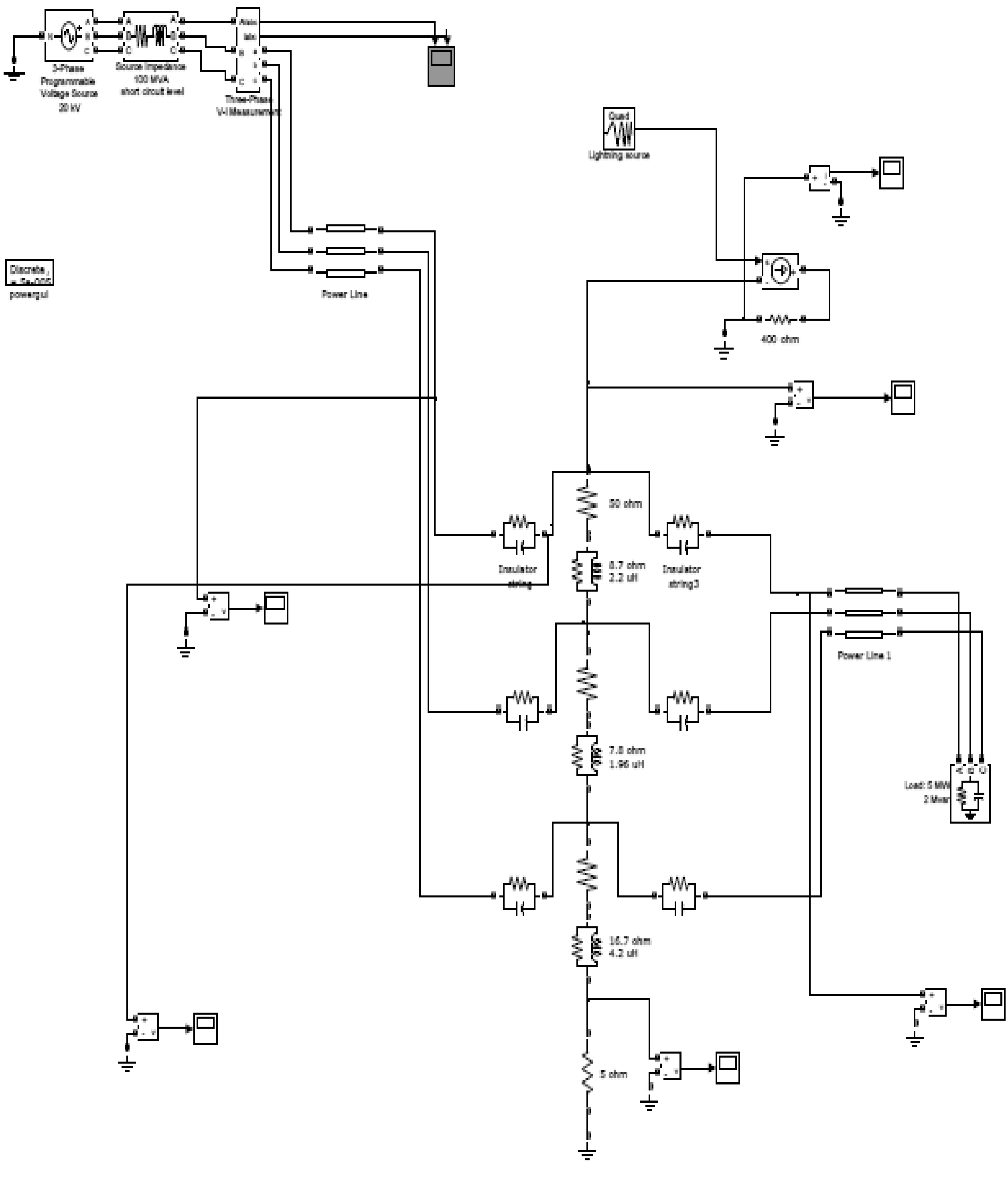


Figure 4. Model system for the Matlab simulation of the lightning to the tower construction

III. SIMULATIONS BASED ON ELECTROMAGNETIC TRANSIENT PROGRAM

A. Model description

Considering the model from Fig.4, the simulations were done using the Electromagnetic Transients program (EMTP) - Matlab Simulink and the Multistory model of the tower.

The simulation model was adapted from typical studies performed by Kuczek, Rakov, Martinez and others described in [8-15]. They all studied the lightning surge phenomena on high voltage power lines considering the tower model with constant footing resistance.

Within current analysis, two assumptions were considered:

(1) Lightning surge propagates towards an overhead power distribution line, after a direct lightning stroke hits the tower construction of the power line.

(2) Tower model has variable footing resistance;

The three-phase power distribution line has the following parameters: l=20 km, R=0.0514 Ω/km, L=0.757 mH/km, C=9.26 µF/km, and supplies a grounded load of about 5 MW, supplied with a rated voltage of 20 kV.

A 20 kV AC voltage source is connected at the end of the power distribution line, in order to quantify the effect of lightning surge on the steady state voltage. The impedance of the voltage source is designed based on the parameters of an ideal RL circuit who can describe matching impedance: R=0.181 Ω, L=7.53 mH.

The lightning current is generated by a DC current source in parallel with an impedance of 400 Ω, according to [20].

The time domain analysis based on Matlab simulations has been performed based on an assumption of transverse electromagnetic propagation of the lightning surge [20-21].

The circuit model of the tower was designed taking into account the values of the following impedances:

-Tower top to the upper phase arm: Z_t=250 Ω;

-Tower top to tower bottom: Z_{t1} =100 Ω.

In order to represent the travelling surge wave attenuation and distortion during lightning, RL parallel circuits were added. The electrical parameters of the line and the geometrical design for the tower are established as follows:

$$
\begin{aligned}
&R_i = \Delta R_i \cdot x_i \\
&\Delta R_1 = \Delta R_2 = \Delta R_3 = 2 \cdot Z_t \cdot \frac{\ln\left(\frac{1}{\alpha_1}\right)}{(h - x_4)} \\
&\Delta R_4 = 2 \cdot Z_{t1} \cdot \frac{\ln\left(\frac{1}{\alpha_4}\right)}{h} \\
&\tau = \frac{h}{c_0} \\
&L_i = 2 \cdot \tau \cdot R_i
\end{aligned}
\tag{3}
$$

where,

R_i and L_i are the values for resistance and inductance of each $(RL)_i$ circuit of the tower, τ is the time of the travelling lightning wave along the tower height expressed in µs, h=12 m is the tower height, x_i is the distance between power distribution line phases (according to Fig. 1, c_0=300 m/µs is the light speed in free space, $\alpha_1 = \alpha_4$=0,89 is the attenuation coefficients along the tower.

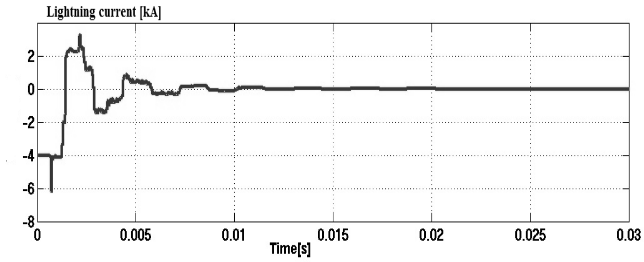
The tower footing resistance was modeled according to [22-23] as a simple linear resistance, whose value varies between 4 – 35 Ω.

The time domain analysis was done considering the lightning duration of about 45 µs within frequency ranges between 10 – 100 kHz.

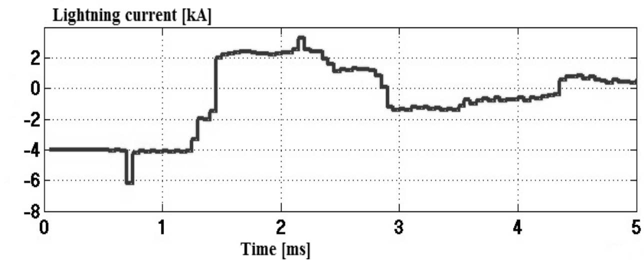
Because the considered distribution power line has each phase protected by insulator strings, in order to design each element, it was considered for each item an RC parallel block, where R=1000 MΩ and C=1 nF [20].

B. Matlab Simulations Results

Considering the assumption related to the lightning duration, it was observed that the lightning activity is more intense within a time frame of 10 ms and based on this the lightning current variation was modeled for two different time intervals: 30 ms and 5 ms (Fig. 4) in order to highlight the peaks recorded during electromagnetic transients states.



a)



b)

Figure 5. Lightning current variation: a) time interval 30 ms; b) time interval 5 ms

In addition, within each simulation case (obtained by varying the tower footing resistance) it was found that the voltage peak of the lightning surge varies as follows:

-Near the point of the stroke (pointing to the left side of the tower) remains constant during each particular case (Table II);

-From the stroke point through the structure of the tower to earth it increases according to Fig. 6, according to the variation of tower footing resistance;

-From the stroke point towards the load it varies according to Table III;

TABLE II. LIGHTNING SURGE VARIATION TOWARDS POWER DISTRIBUTION LINE

Tower footing resistance [Ω]	Lightning surge [MV]
4	4.00
5	4.00
6	4.00
8	4.00
10	4.00
20	5.00
25	5.5
35	5.5

TABLE III. LIGHTNING SURGE VARIATION TOWARDS LOAD

Tower footing resistance [Ω]	Lightning surge [MV]
4	0.02
5	0.02
6	0.02
8	0.02
10	0.02
20	3.00
25	3.2
35	3.4

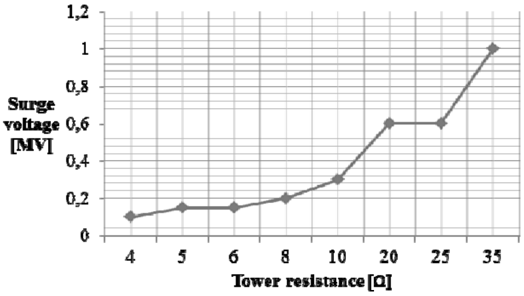
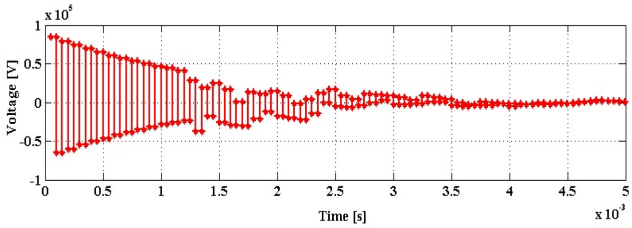


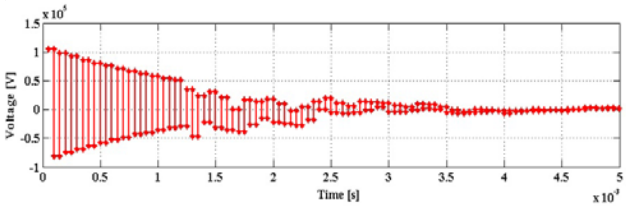
Figure 6. Voltage surge dependency on tower footing resistance

Based on the results it was found that: by varying the tower resistance one can increase or decrease after lightning, the level of the electrical potential of each phase wire of the power line, which is clearly different from the rated value..

Within Fig. 7 a) h) are shown the plots describing the voltage surge variation obtained for each particular simulation case, when the tower footing resistance varies from 4 – 35 Ω. For each case, the lightning current is applied to the tower structure.



a)



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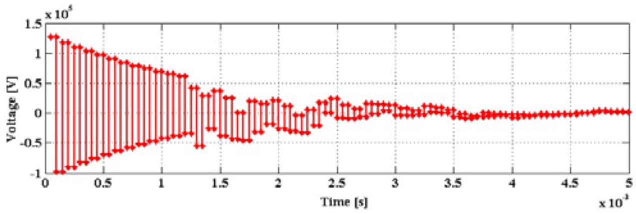
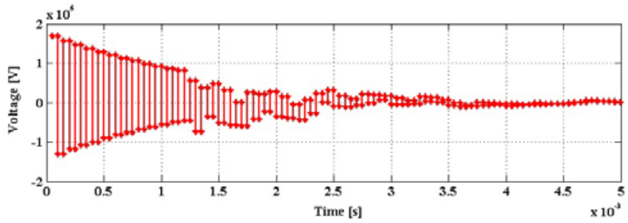
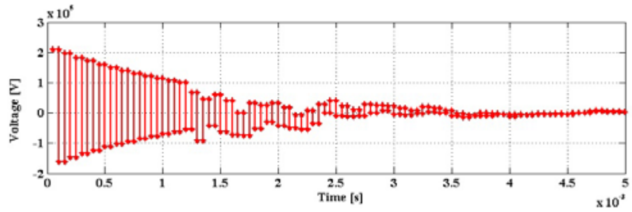


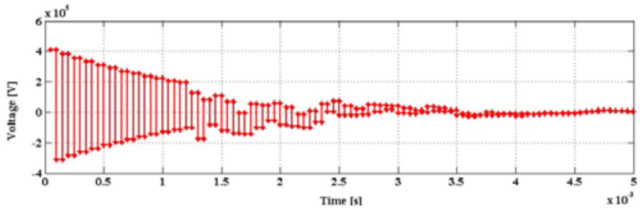
c)



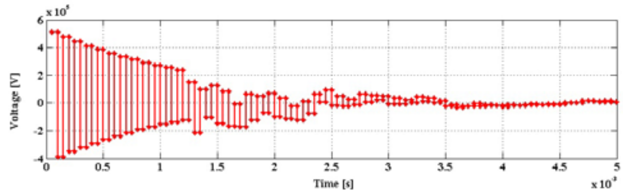
d)



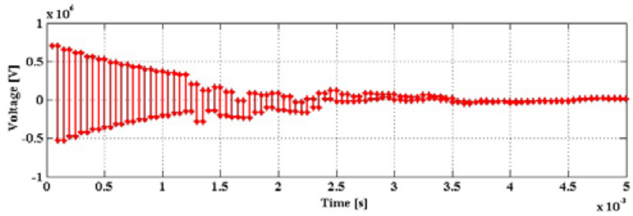
e)



f)



g)



h)

Figure 7. Voltage surge waveform through tower structure: a)4Ω; b)5 Ω ; c)6 Ω; d)8 Ω; e) 10Ω; f) 25 Ω; g) 25Ω; h) 35

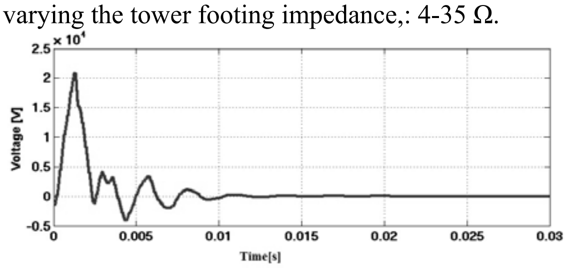
Based on the generated plots, the trend line of the voltage surge to the tower footing impedance was established (4), where V is the voltage surge and x is the tower foot resistance, according to a polynomial function:

$$V(x) = 0{,}022 \cdot x^2 - 0{,}0792 \cdot x + 0{,}1821 \quad (4)$$

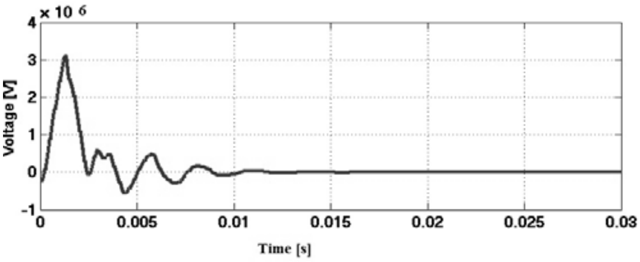
By analyzing the waveforms that describe the surge propagation after lightning surge (Fig. 7 a)-h)) one can observe that for tower footing resistance from 7 Ω to 35 Ω, allows the growth of the voltage surge level through the power line/ load. One should consider time t=0, the starting moment of the lighting activity and also the surges will be observable within 10 ms. This is the reason why each time frame of the generated plots was established at about 30 ms.

Based on this, the design of the overhead medium voltage power distribution line insulation system can be optimized, by applying both rules: tower structure with a footing resistance of max.6 Ω and insulators strings for the line protection against overvoltages.

The above plots, (Fig. 8) describe the surge wave towards the load, considering each simulation case, obtained by varying the tower footing impedance,: 4-35 Ω.



a) 4 - 10Ω

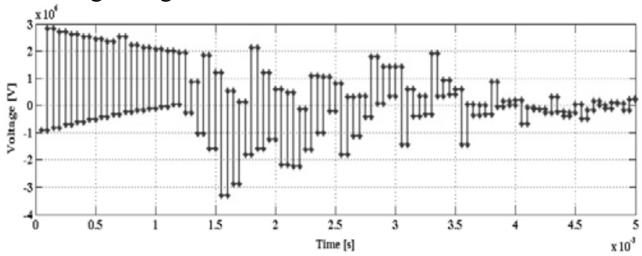


b) 20-35 Ω

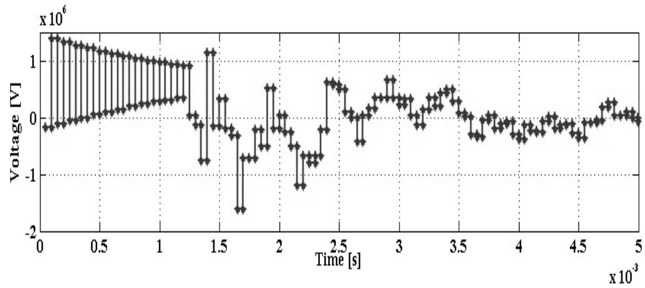
Figure 8. Voltage surge waveform towards load

During simulation, it was noticed that when the tower footing resistance is increasing from 4 – 35Ω, the magnitude of the voltage surge through the tower structure is growing, especially when the resistance exceeds 6 Ω. This could mean that the proper design for the tower footing resistance of a power distribution line should be maintained between 5-6 Ω, in order to avoid the electrical stresses both to the power line insulation and to surrounding structures.

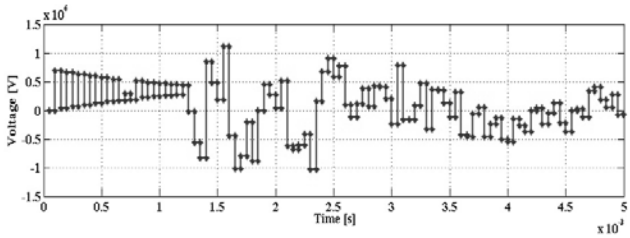
In order to have an assessment of the voltage surge variation towards power distribution line, in the case when the tower footing impedance is about 4 Ω, the voltage waveforms were generated for each phase of the power line, according to Fig. 9.



a) phase R



b) phase S



c)phase T

Figure 9. Surge variation towards power distribution line phases

IV. Simulations Based on Finite Element Method

A. Simulation scenarios and model description

The Finite Element Method was applied, to simulate a non-transverse electromagnetic propagation, considering the model of the tower and phase conductors (Fig. 10), and using the Comsol Multiphysics platform. It was applied the AC/DC Module, for a the time domain (time interval in seconds: 0, 0.001, 0.02) analysis, performed according to the following scenarios: S1. Lightning stroke on tower structure; S2. Lightning stroke on power distribution phase wire. It was assumed that each phase of the power distribution line is supplied by a 20 kV AC voltage.

A finite channel of about 100 m, simulates the lightning current. The lightning channel has a resistance of about R=0.33889 Ω, equivalent to a copper wire with cross section S=5.0868 mm^2 and the outer diameter of d=1.8 mm. The lightning current waveform is described according to the Heidler function [25-26]:

$$i_{surge}(t) = k_i \cdot \left[\frac{I_p}{k_{surge}} \cdot \frac{\left(\frac{t}{\tau_1}\right)^{\eta_{surge}}}{1+\left(\frac{t}{\tau_1}\right)^{\eta_{surge}}} \cdot e^{\frac{-t}{\tau_2}} \right] \tag{5}$$

where, k_i, k_v are current correction coefficients, τ_1, τ_2 are rise and fall time of the pulse, η_{surge}, k_{surge} (according to (5)) are wave shape correction coefficients, and I_p is the peak value of the surge current, of about 40 kA.

$$k_{surge} = e^{-\frac{\tau_1}{\tau_2}\cdot\left(\frac{\eta_{surge}\cdot\tau_2}{\tau_1}\right)^{\frac{1}{\eta_{surge}}}} \tag{6}$$

According to [26], the parameters of the 8/20 µs surge current wave shape were established: k_i =1, η_{surge} =2,741m, τ_1=47,52 µs and τ_2=4,296 µs.

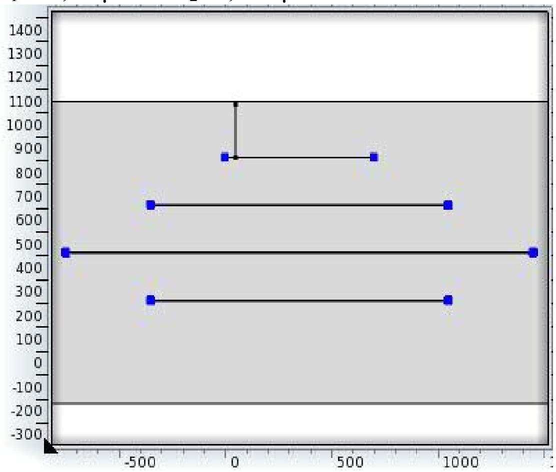


Figure 10. 2D Geometry model - Direct lightning surge - Top view

The boundary conditions were established as for the Electrostatic laws, according to the AC/DC model. A triangular mesh was applied, based on two reasons: firstly, it subdivides the CAD geometry being modeled into smaller triangular pieces over which the Maxwell equations have been applied and it is used to represent the field solution to the physics being solved.

B. Comsol Simulations Results

In Fig. 11 – Fig. 13 are shown the plots obtained for the electric potential distribution corresponding to each particular scenario simulated in Comsol.

For the considered case studies, it was obtained that:

-The electrical potential calculated for scenario S1 is bigger than for the scenarios S2;

-Induced lightning leads to an increase of the tower's potential which is essentially determined by the tower footing resistance;

-A high potential near tower implies backward flashovers across the insulators and overvoltage with high rates of change can be recorded.

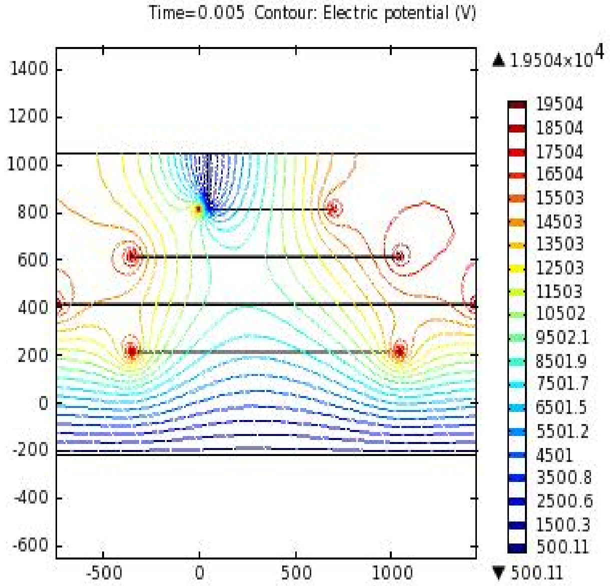


Figure 11. Distribution of electric potential - Scenario S1

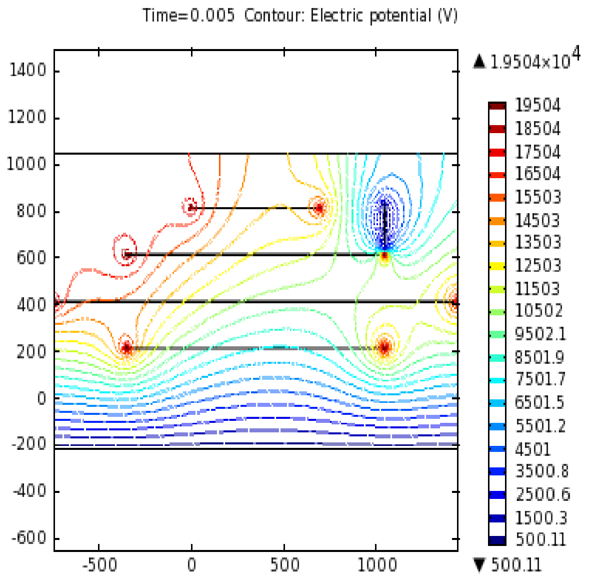


Figure 12. Distribution of electric potential - Scenario S2

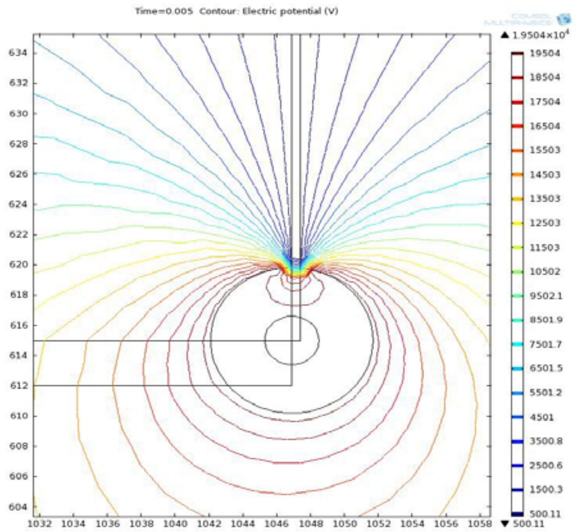


Figure 13. Electric potential distribution around phase conductor - Scenario S2

For a comprehensive evaluation of the influence of each scenario of the lightning propagation within the power distribution line, with the criterion of electric field intensity, a comparative analysis is done (Fig. 15).

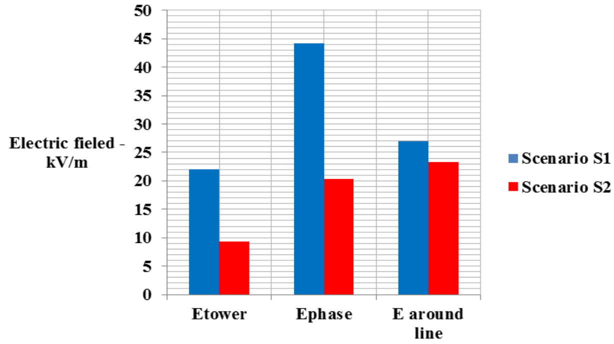


Figure 14. Lightning surge evaluation – comparative analysis on electric field distrbution

According to Fig. 14, the electric field intensity near the phase conductor of the power distribution line it's high and it can causes the insulation breakdown, considering that this could happen for an electric field intensity of about 18-20 MV/m. It is obvious that both scenarios, of the induced lightning through the phase conductor and through the tower generates effects through the medium voltage distribution power line/ load. The effects of the lighning surge are influenced by the tower footing resistance and also by the grounding coonection of the power distribution line. In both cases the voltage surge is propagated through the phase conductors of the line or through the tower structure, to the ground electrode and in this mode an increase of the electric field distribution near underground power distribution lines or pipelines is observed.

Another effect of the lightning phenomena near power distribution lines is determined by the propagation of the voltage surges as travelling waves through the power line phases to the substations busbars generating insulation flashovers to differenet power equipments. These effects may lead to shortcircuits and line to ground faults. Based on this, further reserach are neded in order to increase the performances of power equipments from substations during lighnting.

The assessment of lightning propagation through residential low voltage networks and near substations, is needed, considering that those issues implies the evaluation of electromagnetic intereefereces between overhead and underground power lines.

V. Conclusions

Direct and induced lightning stroke, lead to an increase of the tower's potential which is essentially determined by his footing resistance. A high potential near tower implies backward flashovers across power line insulators and also to surrounding networks.

The protection of the overhead medium voltage power line in case of transients generated by lightning can be optimized, by using towers with a structure designed having a footing resistance of about 5-6 Ω plus insulator strings to take over the flashovers that may appear. Also, it was noticed that when the tower footing resistance is increasing from 7 to 35 Ω, the magnitude both of the voltage surge (after lightning surge) through the load and the power line's electric potential is growing, so the proper design for the tower resistance of a medium voltage power distribution line should be maintained as previous stated. In this manner future electrical stresses to the insulation/ phase conductors are limited.

Different behaviors were depicted, including that direct lightning lead to an increase of the tower's and phase wire's potential, also that a high potential implies backward flashovers across the insulators. Based on this can be concluded that direct lightning stroke is the case most unfavorable to happen. The design of the towers for distribution power lines should consider that way, the values of the footing resistances as it resulted from simulations. The attention is directed to medium voltage overhead power lines considering that their insulation system consist on insulators strings and they are more common subjected to direct lightning stroke.

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