LIGHTNING SURGE ANALYSIS ON GROUNDING MODELS OF A TRANSMISSION LINES

[1]G. RADHIKA, [2]Dr. M. SURYA KALAVATHI

[1]Sr. Asst. Professor (E.E.E) VNR VJIET Hyderabad, INDIA
[2]Prof and Head (E.E.E) J. N. T. University Hyderabad, INDIA
Email: [1]radlalitha.g@gmail.com, [2]munagala_12@yahoo.co.in

ABSTRACT

Lightning has been one of the important problems for insulation design of power systems and it is still the main cause of outages of transmission and distribution lines. The lightning return-stroke current and the charge delivered by the stroke are the most important parameters to assess the severity of lightning strokes to power lines and apparatus. In order to calculate lightning surge analysis in power systems, appropriate models and parameters describing the components of systems should be required. It is also necessary to clarify how much those models would influence results of simulation. In other words, it is important to confirm how much probability of back flashover accidents would occur in changing grounding model or its input parameters. In this paper we compare some models for components in transmission tower and will show the influence to the back flashover results, especially focusing on grounding impedance model.

KEYWORDS: *Lightning Surge, Back flashover, Transmission Lines, Grounding Impedance, PSCAD/EMTDC*

I. INTRODUCTION

Lightning strokes hitting towers, conductors or any object in the neighboring of a transmission line can produce abnormal current/voltage waves along conductors (phase and /or shield wires) as well as along steel towers, Due to these phenomenon, over voltages are produced and electric arcs (between two or more conductors as well as between phase conductors and the tower structure) may appear, if insulation breakdown voltage is reached. A direct lightning strike to the tower of an overhead power line produces a transient voltage across the insulation from which the phase conductors are suspended. An insulator will flash over if the transient voltage exceeds its withstand voltage level. This is called the back flashover. As far as grounding impedance model is concerned in lightning surge analysis, we often face such a problem that model or the parameter might be inaccurate on the present conditions such that the soil resistively ρ, soil permeability μ, capacitive or inductive element in soil C (or L), critical soil potential gradient E_0, these parameters are unpredictable unless they are measured in practice and, unfortunately in almost cases, it is impossible or very difficult to measure them in advance.

The goal of this study is, thus the sensitivity analysis to show how the results of a simulation will changes when a model or a parameter is changed. That is, we will examine how the number of failures due to back flashover will be changed when ρ, C, E_0 will be changed in several grounding models. Modern computed simulations including *PSCAD/EMTDC* have been developed with the progress of various models of components. A problem with these models or parameters caused by that it is very difficult to compare with experimental result and confirm the accuracy of models. The reason seems to be that (i) the mechanism of ionization and discharge phenomena in soil still remains to be unsolved and must await more detailed study, (ii) the soil in practice is not a homogenous medium due to the variation of water content and the variation in grain size, therefore, an ideal model does not always agree with the practical result, (iii) the cost for the experiment using a full-size tower footing on an extensive site would be very expensive, and so on.

II. LIGHTINING CURRENT AND NETWORK COMPONENTS

A lightning stroke hitting a phase conductor, a shield wire or even a tower, corresponds to the injection of a current wave in the point of impact. This current will propagate along conducting paths (electrical network or the tower's structure) and will produce instantaneous potential variations in the conducting paths [1]. Real lightning current wave shapes are characterized by its polarity, maximum instantaneous value, steepness, and equivalent front/tail times. Due to its non-regular shapes (see fig. 1), lightning current is not easy to describe by mathematical functions, even if complex functions are used. Due to high frequency associated with lightning transients, a PI model should not be used to represent transmission lines.

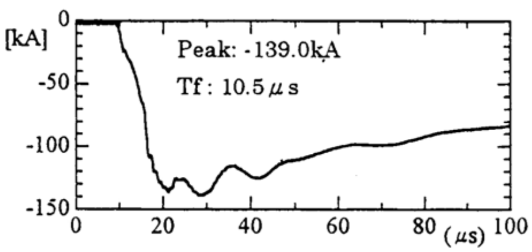


Fig. 1. Example of a lightning current wave shape [3]

A lightning flash generally consists of several strokes that lower charges, negative or positive, from the cloud to the ground. The first stroke is most often more severe than the subsequent strokes. Low current continues to flow between two strokes, thus increasing the total energy injected to the struck object. The transient voltage from the lightning is generated by: (i) direct stroke and (ii) indirect stroke. For direct strike, it can strike an apparatus in that case; the apparatus will be permanently damaged. Most often, lightning strikes the phase conductor of the power line in that case, a traveling voltage wave is generated on the line; it travels along the line and is impressed across the terminals of an apparatus or most often the insulator between the phase conductor and the cross-arm of the tower at the end of the span. If the voltage is high enough, the insulator flashes over causing a short circuit of the system. Many overhead power lines are equipped with shield wires to shield the phase conductors [4]. Even then, shielding failures occurs when lightning bypasses the shield wires and strikes a phase conductor. When lightning strikes a tower, a traveling voltage exceeds it's withstand level (back flash) even if lightning strikes a shield wire. The generated traveling voltage wave will travel to the nearest tower, produce multiple reflections along the tower, causing back flash across an insulator.

When lightning hits the ground several hundred meters away from the line (indirect stroke), the electric and magnetic fields of the lightning channel can induce high voltage on the line for the insulators of the low-voltage distribution lines to spark over causing a short circuit of the system. Thus, assuming the lightning channel to be a current source, the transient voltages across the insulator of a phase conductor are generated in three ways: (i) lightning striking the phase conductor (shielding failure), (ii) lightning striking the tower or the shield wire (back flash), and (iii) lightning striking the nearby ground (indirect stroke). The severity of these three types of transient voltages is influenced by different lightning parameters.

III. GROUNDING IMPEDANCE MODELS:

One of the critical parameters in the lightning performance of transmission lines is the impulse impedance of the tower footings. Here we will prepare various grounding impedance models to calculate lightning surge analysis.

i.) Constant resistance model: A constant resistance model for a tower is simply given as a lumped constant resistance R_o whose value is determined by a formula for a hemisphere electrode.

$$R_o = \frac{\rho \times 1}{2\pi r \; n}$$

Where ρ is the resistively of the surrounding soil, r is the radius of the electrode (or equivalent radius of the tower footing), and n is the number of footings per a tower (normally n=4). The value of r is assumed to be 2.26 m through the present analysis because this size is for typical tower footing for 400 KV transmission lines in West Godavari district, India. Here constant resistance model has been widely used for *PSCAD/EMTDC* lightning surge analysis and various calculations for lightning protection because of its simplicity and convenience.

ii.) Nonlinear impedance model: In general the resistance of an earth electrode or a tower footing decreases with the applied current due to ionization of the soil. We proposed the appropriate model after the results using a 400 KV tower footing. That is

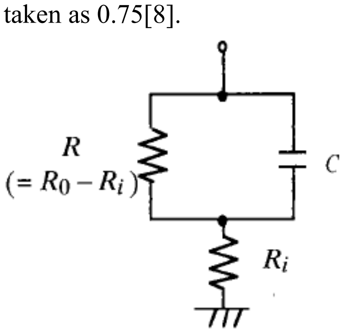
$$R = \begin{cases} R_0 & (I < I_c) \\ \dfrac{R_0}{\sqrt{\dfrac{I}{I_c}}} & (I \geq I_c), \end{cases}$$

Where I_c is a critical current for soil ionization and depends upon ionization gradient of the soil E_c, which is a particular constant for the surrounding soil and very important value whether soil breakdown would occur or not. The relationship between both the values is given as

$$E_c = \frac{\rho I_c}{2\pi r^2 n}\ .$$

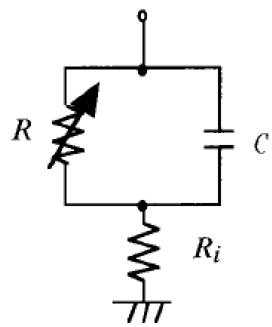
As on whole, there are several recommended values for E_c ranging from 300 to 1000 kv/m. With this it is easily understood that the result of lightning surge analysis would be significantly influenced by this value [6]. In this paper we will make the sensitivity analysis of the ionization gradient E_c in the grounding impedance model and we also examine how the back flashover accident would be influenced by the value of E_c.

iii.) Capacitive impedance model: With several reports, it is clear that capacitive characteristics are often measured in the grounding impedance on high– receptivity soil. Fig 2(a) shows commonly used grounding model with capacitive component and the value of capacitive element would have a significant influence on the back flashover accidents due to lag of current crest. In further units we will calculate the lightning surge analysis changing the capacitance ranging from 10^{-12} to 10^{-3} F. Here there is one uncertain parameter, which the ratio of R_i and R, where R_i is an initial resistance and R is given R_0 minus R_i and in most of the cases the ratio is taken as 0.75[8].



(a)

iv.) Combined Model: This model is the combined model with the nonlinear impedance model and the capacitive impedance model as shown in fig 2 (b). In this model, the grounding impedance has the characteristic curve with slow slow transient and temporary reduction. We obtain this type in experimental results and it is also important to examine which element and how does it affect the back flashover phenomena.



(b)

IV. PSCAD/EMTDC ANALYSIS FOR OTHER COMPONENTS

i.) Tower Model: Here we described a typical 400 KV transmission tower with 82m height in India and proposed the equivalent impedance model. This model includes three elements, main legs Z_T, branching Z_I, and cross arms Z_A. Thus, in this paper we employ this model in common for the comparison of various grounding models.

ii.) **Flashover model**: The overhead ground wires or shield wires have been located so as to minimize the number of lightning strokes that terminate on the phase conductor. The remaining and vast majority of strokes and flashed now terminate on the overhead ground wires. A stroke that forces current to flow down the tower and out on the ground wires. Thus voltage is built up across the line insulation. If these voltages equal or exceed the line CFO, flashover occurs [10]. This event is called a back flashover. So back flashover phenomenon at an arcing horn is regarded as one of the most important parameter on the lightning surge analysis. Fig 3 (a) shows the surge voltages at the tower and across the insulation.

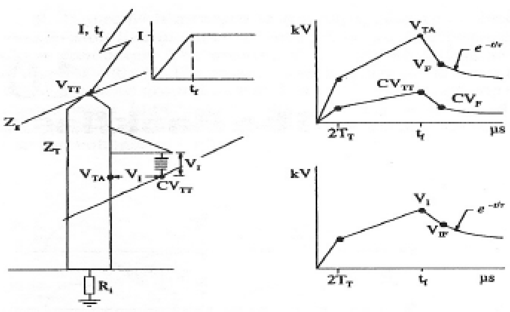


Fig 3(a)

iii.) Line model and other elements. : The line system model has eleven towers placed on the level, in a straight line and at even interval of 450m. Each of tower is assumed as the standard impedance model given in III.(i) and grounding model. The grounding impedance models described in II.(i) – II(iv) are adapted to the middle three towers, that is, the tower struck by the lightning and the neighboring towers. Here we assumed that the lightning to hit the cross arm edge holding overhead grounding wire on the middle tower [15]. The lightning is simulated by a current source with a 1/70μs ramp wave as shown in Fig 1(a) and a lightning path impedance of 400Ω.The maximum value of injected current I_{max} is assumed as 150 and 200KA as shown in Table 1.

Table 1 Examining models and parameters

	changing parameter	examining range	measured value [6]	result of analysis
Constant Model				§4.1
Nonlinear Model	E_0 [kV/m]	300 - 1000	600	
	ρ [Ωm]	2000, 4000		§4.2
	I_{max} [kA]	150, 200		
Capacitive Model	C [F]	10^{-12} - 10^{-3}	320×10^{-9}	§4.3
	R_i / R_0	0.75, 0.5	0.75	
Combined Model	combination of above			§4.4

V. SENSITIVITY ANALYSIS ON GROUNDING MODELS

Here we provide sensitivity analyses on the various grounding models and parameters where we discussed in chapter II.

Expectation of failed phases due to back flashover is used to evaluate the situation of back flashover accidents. Here expectation is defined as the average number of failed phases in case of lightning strike on all electric angles. Table2 has shown an example of the result of *PSCAD/EMTDC* surge analyses. This table has twelve rows, each of which corresponds each analysis under the condition of electric angle of upper phase (phase A) on line #1 on the moment of lightning strike. The symbol 'l" in the table denotes an arcing horn failure caused by back flashover at the corresponding phase on the corresponding angle [16]. Thus this table clarifies the situation of back flashover accident. Summing the number of "√" and dividing by twelve, the expectation of failed phases due to back flashover is obtained. In table 2, the expectation of failed phases is calculated to be 58% at a lightning strike [20].

Table 2 An example of a situation of back flashover accident
(with constant model, I_{max} = 200 kA, ρ = 2000 Ωm)

base angle on 1A	Line #1			Line #2		
	Upper (A)	Middle (C)	Lower (B)	Upper (B)	Middle (C)	Lower (A)
0			✓	✓		
30			✓	✓		
60		✓	✓	✓	✓	
90		✓	✓	✓	✓	
120		✓	✓	✓	✓	
150		✓			✓	
180		✓			✓	
210	✓	✓			✓	✓
240	✓	✓			✓	✓
270	✓					✓
300	✓		✓	✓		✓
330	✓		✓	✓		✓

" ✓ " denotes a failed phase due to back flashover

iv) Comparison between different grounding impedance models

The total number of failed phases by back flashover was reduced, because the impedance-decreasing characteristics caused the reduction of voltage on the arcing horn in each phase incase of nonlinear grounding model (where E_o = 600Kv/m), whereas in constant model the estimated failed phases be too much [18]. It is also important to examine the sensitivity analysis with respect to critical soil ionization gradient E_o whose value varying from 300 to 1000Kv/m. It was examined that the smaller the value of E_o causes the higher effect of the decrease of impedance and therefore results in the lower expectation of failed phases. It is noteworthy that, that there is no flashover failure in any case of E_o = 300Kv/m.

The sensitivity analysis under the condition of C ranging from 10^{-12} to 10^{-3}F is examined and expresses the result of *PSCAD/EMTDC* analysis that indicates the relationship between the value of capacitive element and expectation of failed phases. Results say that the influence due to capacitance clearly occurs on the condition of C of over 100nF in each case.

The ratio of R_i/R_o in capacitive grounding model is approximately 0.75 with references [22], there is no guarantee that the ratio will be accurate in any soil, Results say that the initial resistance R_i makes huge influences to the back flashover accident.

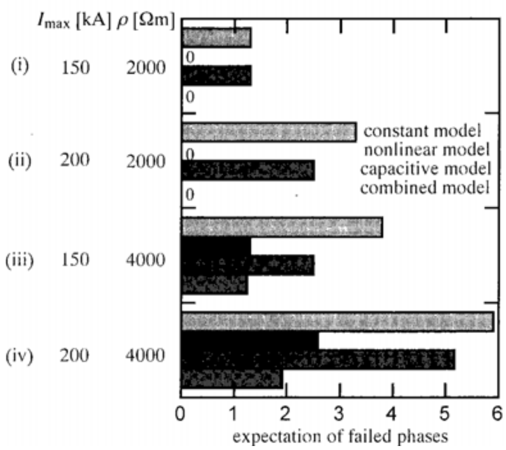


Fig 4(a) Comparison among various models for grounding impedance
(E_o = 600Kv/m, C=320nf, R_i/R_o=0.75)

The result of *PSCAD/EMTDC* analysis using each models are arranged in Fig 4(a) wherein we have chosen a value of 320nf for C and 600Kv/m for E_o. It is easy to understand that the capacitive model has less influence. Thus, in analyzing the lightning surge, care must be taken in choosing the grounding model and parameters according to simulating situation and circumstances.

VI. CONCLUSION:

Unfortunately, there is no universal agreement on the soil ionization mechanism hence lightning surge analysis on power electric systems requires special attention to the grounding conditions with the knowledge of the properties of grounding models and surrounding soil. This is the reason we examined the sensitivity analysis on various models.

Changing the grounding models including the constant model, the nonlinear model, the capacitive model and the combined model various analyses was tested which results in accurate methodology to employ the grounding model according to the desired conditions. For example;

Under the condition of higher resistively and injected current, the nonlinear model is more accurate than the constant model.

- The capacitive model gives less influence to back flashover analysis unless the value of capacitance is higher than several microfarads.
- The critical soil ionization gradient E_o is very important parameter, which gives significant influence to the result of the back flashover analysis
- The initial resistance value in the capacitive model is sensitive and gives much influence to the back flashover analysis.
- Whether nonlinear, capacitive model, or combined model the value of capacitive element plays very important role.

Hence, with the results, we had better accurate model and parameters to examine the actual circumstances of the tower and we suggest a methodology of reasonable design of lightning protection.

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[29] **Akihiro Ametani:** (M'71, SM'84, F'92) B.S. and M.S. degrees from Doshisha University in 1966 and 1968. Ph.D. from UMIST in 1973. Currently a Professor at Doshisha University and a Vice President of IEE Japan.

[30] **Naoto Nagaoka:** (A'87) B.S. and M.S. and D.Eng. from Doshisha Univ. in 1980, 1982 and 1993. Currently a Professor at Doshisha Univ. **Toshihisa Funabashi:** (M'90, SM'96) B.S. from Nagoya University in 1975 and D.Eng. from Doshisha Univ. in 2000. Currently he is a Manager of Power System Analysis Sec. of Meidensha.

[31] **Nagahiro Inoue:** received B.S. and M.S. degrees from Doshisha Univ. in 2001 and 2003. He has been with Fujitec Co. since April. 2003

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