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The effect of wide band modeling of tower-footing grounding system on the lightning performance of transmission lines: A probabilistic evaluation

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ABSTRACT

This paper presents a probabilistic evaluation, based on Monte-Carlo method, to estimate back flashover rate (BFR) and shielding failure flashover rate (SFFOR) of overhead transmission lines (TLs). In the proposed approach, as opposed to the conventional methods, a wide band model of the tower-footing grounding system is adopted assuming the soil electrical parameters to be either constant or frequency dependent. The statistical parameters affecting the TLs' outage rate are taken into account in the probabilistic studies. Simulations are done for a typical 400-kV transmission line which is modeled in EMTP.RV. From the simulation results, it is found that the BFR of transmission lines is markedly affected by the tower footing grounding system model. This effect is more pronounced when the soil electrical parameters are frequency dependent. It is also found that the SFFOR of the transmission lines is not significantly affected by the wide-band model of the tower-footing grounding system.

1. Introduction

Lightning is one of the main reasons of insulation breakdown in transmission and distribution lines. This can make the operators and customers incur expenses due to the increase in maintenance services, the need to replacement of damaged equipment and the cut of electricity due to line outages [1]. Generally, surge arresters and shield wires are used for the protection of transmission lines (TLs) against lightning generated overvoltages. These measures are not however enough as there is still a probability of insulation failure following back-flashover (BF) on the regions with high ground resistance. Furthermore, there is a probability of shielding failure (SF) which can result in flashover across the line insulators causing insulation breakdown [2].

So far, extensive studies have been carried on the lightning performance of TLs in order to improve the lightning protection of transmission lines [3–7]. However, the previous works have not taken into account the exact wide band model of tower footing-grounding system and use a simple linear or nonlinear resistor [2–5] to model the grounding system. Recently, a systematic approach has been presented in [8,9] which allows the inclusion of wide band model of grounding systems into the EMTP-like tools. This adequately helps with the exact calculation of lightning generated overvoltages within the electrical networks. With this regard, the effect of wide-band model of grounding system on the lightning performance of a typical transmission line has been evaluated in [9]. However, in [9] the statistical nature of lightning return stroke current parameters has not been taken into account.

Within this context, this papers adopts the same approach presented in [9] for the probabilistic evaluation of lightning performance of a typical transmission line. As a complementary attempt to [9], in this paper, the statistical parameters affecting the TLs' outage rate are taken into account. The BFR and SFFOR of a typical 400 kV transmission line are obtained by establishing a link between Matlab and EMTP.RV. In this study, the tower-footing grounding system is modeled in three different ways namely: (1) static-model, (2) wideband model assuming constant electrical parameters for the soil, and (3) wide-band model assuming frequency-dependent electrical parameters for the soil. The Mont-Carlo method is used for carrying out the required probabilistic studies.

The paper is organized as follows: In Section 2, the lightning parameters are explained. Section 3 discusses the modeling of

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various transmission line (TL) components in EMTP-RV. In Section 4, the governing electric field integral equations for modeling the grounding systems and its MoM solution is revisited, while the state-space representation of the grounding system is briefly described. In Section 5, the Monte-Carlo simulation approach to calculate the BFR and SFFOR is explained. Simulation results are presented in Section 6. The conclusion remarks are given in Section 7.

2. Lightning parameters

The main parameters of the lightning waveform are the peak value (I_p), rise time (t_f) and time to half value (t_h). From the field data on lightning strokes, the probability density function of each lightning parameter is determined by the following equation [10]:

$$p(x) = \frac{1}{\sigma_{\ln x}\sqrt{2\pi}\,x}\exp\left\{-\frac{1}{2}\left(\frac{\ln x - \ln \bar{x}}{\sigma_{\ln x}}\right)^2\right\} \quad (1)$$

where $\sigma_{\ln x}$ and $\bar{x}$ are the standard deviation and median of x, respectively. Assuming dependence of the peak current magnitude and rise time, the joint probability density function of I_p and t_f reads:

$$p(I_p, t_f) = \frac{\exp[-(f_1 - f_2 + f_3)/(2(1-\rho_c^2))]}{2\pi\sqrt{1-\rho_c^2}.\sigma_{\ln I_p}\sigma_{\ln t_f}.I_p.t_f} \quad (2)$$

$$f_1 = \left(\frac{\ln I_p - \ln I_\mu}{\sigma_{\ln I_p}}\right)^2 \quad (3)$$

$$f_2 = 2\rho_c\left(\frac{\ln I_p - \ln I_\mu}{\sigma_{\ln I_p}}\right)\left(\frac{\ln t_f - \ln t_{f\mu}}{\sigma_{\ln t_f}}\right) \quad (4)$$

$$f_3 = \left(\frac{\ln t_f - \ln t_{f\mu}}{\sigma_{\ln t_f}}\right)^2 \quad (5)$$

where I_μ, $\sigma_{\ln Ip}$, $t_{f\mu}$, $\sigma_{\ln tf}$ are the median value and standard deviation of current amplitude and front time, respectively; and ρ_c is the coefficient of correlation of I_p and t_f. The log-normal characteristics of the lightning negative-polarity of first and subsequent return stroke currents are shown in Table 1. The number of subsequent strokes in a flash is also selected based on the known statistical distribution given in [10].

Having obtained the lightning parameters, a Heidler function can be used to represent the current waveform [11]:

$$i(t) = \frac{I_p}{\eta}\frac{k^n}{1+k^n}e^{-t/\tau_2} \quad (6)$$

where I_p, n and η are the peak current, the current steepness factor and the peak current correction factor, respectively; and $k = t/\tau_1$; τ_1 and τ_2 are time constants that determine the rise time and decay time of the lightning waveform, respectively.

Table 1
Statistical parameters of the lightning negative-polarity first and subsequent strokes [10].

Parameters	First stroke		Subsequent stroke	
	Median	$\sigma_{\ln x}$	Median	$\sigma_{\ln x}$
I_p (kA)	31.1	0.48	13	0.6447
t_f (μs)	3.83	0.55	0.32	0.6677
t_h (μs)	75	0.58	20	0.69
ρ_c (I_p, t_f)	0.47		0	

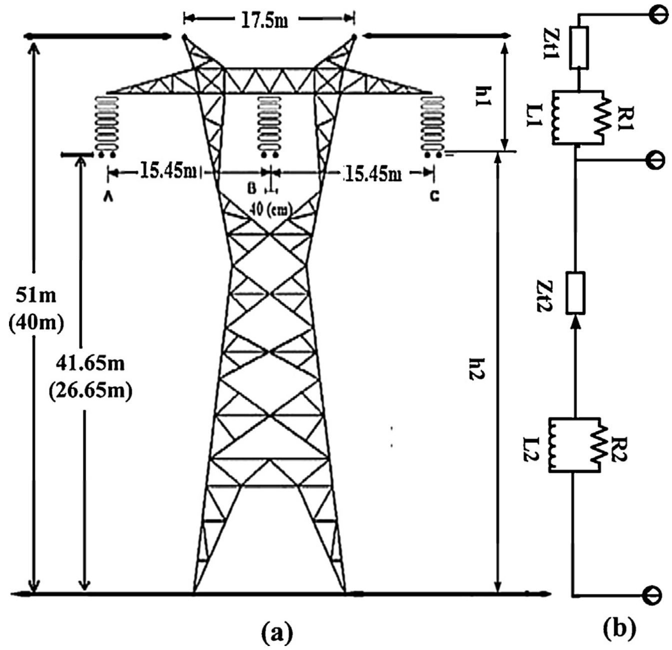

Fig. 1. (a) Tower configuration (values in brackets are midspan heights), and (b) multistory model of transmission tower.

3. Transmission line modeling

3.1. Transmission tower

A transmission tower can be represented by a multistory model, Fig. 1, consisting of two distributed-parameter lines, where Z_{t1} (=200 Ω) is the tower top to the phase arm and Z_{t2} (=150 Ω) is the phase arm to the tower bottom [12]. As shown in Fig. 1, an *RL* parallel circuit is added to each part to represent traveling-wave attenuation and distortion. The value of the *R* and *L* of each part is given by [12]:

$$R_i = \Delta R_i.h_i \quad (\Omega), \quad L_i = 2\tau R_i\,(\mu\text{H})$$
$$\Delta R_1 = \frac{2Z_{t1}}{h - h_2}\ln\left(\frac{1}{\alpha_1}\right) \quad (7)$$
$$\Delta R_2 = \frac{2Z_{t2}}{h}\ln\left(\frac{1}{\alpha_2}\right)$$

where h (m) is tower height, $c = 300$ m/μs is the light velocity in free space, $\alpha_1 = \alpha_2 = 0.89$ attenuation along the tower and $\tau = h/c$ is traveling time along the tower.

3.2. Insulator string

The model of insulator string used in the calculation can affect both BFR and SFFOR analysis. The insulator string of the *TL* can be modeled as a parallel capacitor connected to a voltage controlled switch [13] as shown in Fig. 2. If the peak value of the lightning current exceeds the so-called critical current, the line insulator experiences the flashover that leads to closing of the switch in parallel with the capacitor.

In this paper, the integration method or equal-area criterion is used for evaluating the effects of non-standard lightning overvoltages. The integration method can be used for determination of the performance of gaseous, liquid and solid insulation under non-standard fast-front overvoltages based on experimental results obtained under standard lightning impulses. In the integration method, V_0 is the minimum voltage beyond which any breakdown process occurs; and the breakdown time is a function of