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Original

The effect of grounding system modeling on lightning-related studies of transmission lines

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Abstract

Un-accurate modeling of power system may cause to under or over-design the insulation, which in turn, leads to increase in the investment and/or maintenance cost of the network protection against lightning overvoltages. The grounding system is an effective parameter on the magnitude of the lightning overvoltages and insulation coordination of high voltage transmission lines (*TLs*). This paper presents a comprehensive evaluation of the effect of grounding electrode impedance on the estimation of overvoltages caused by lightning strokes, in which both the vertical and non-vertical strokes are considered. In the presented study, static and wide-band model of the tower-footing grounding system is adopted assuming the soil electrical parameters to be either constant or frequency dependent. Also, the effect of modeling type of grounding system is considered on the *TLs*' reliability indices. The study was performed on a typical 400-kV transmission line which is modeled in EMTP-RV. From the simulation results, it is found that the outage rate of *TLs* is markedly affected by the model of the tower footing grounding system. This effect is more pronounced when the soil electrical parameters are frequency dependent. It is also concluded that, in addition to the lightning overvoltages, the unavailability of the *TLs* is significantly affected by wide-band model of grounding system, non-vertical lightning strokes and soil resistivity.

Keywords: Lightning overvoltage; Transmission lines; Grounding system; Non-vertical strokes; Reliability indices

1. Introduction

Lightning is one of the main factors causing the insulation failure and line outage and then imposes high costs to power utilities for the maintenance and replacement of damaged equipment. Surge arresters and shield wires are the main protective devices against lightning surges. In the case of shield wire installation, there is still the probability of Back-Flashover (*BF*) and Shielding Failure Flashover (*SFFOR*) which can result in insulation failure (Hileman, 1999). Consequently, using arresters is an efficient solution to improve the lightning performance and reliability of power networks.

The back flashover rate (BFR) is considered as one of the main factors in designing the lightning protection of *TLs* and high voltage (*HV*) substations. The analytical methods, in the design of lightning protection schemes, have been utilized in many researches (Araújo, Flauzino, Altafim, Batista, & Moraes, 2015; Christodoulou, Ekonomou, Papanikolaou, & Gonos, 2014; Ekonomou, Gonos, & Stathopulos, 2003; Shariatinasab, Safar, & Falaghi, 2014).

The main lightning parameters affecting on the resultant overvoltages are the peak current magnitude, and the front and tail time of the current waveform. Besides, the tower footing grounding impedance is effective on the lightning related overvoltages. The higher tower footing resistance, the severe lightning overvoltage is produced. So, it is important to perform the accurate modeling of grounding system for calculation the lightning performance of *TLs*. Usually, a simple linear or nonlinear resistance is conventional for modeling of tower footing resistance (Araújo et al., 2015; Banjanin, Savić, & Stojković, 2015; Mamiş, Keleş, Arkan, & Kaya, 2016; Shariatinasab et al., 2014; Tossani et al., 2015). In conventional modeling, the magnitude of tower footing resistance is only varied with the lightning current magnitude flowing through the tower footing into the ground. However, the electrical parameters of the soil, i.e. permittivity (ε) and

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resistivity (ρ) are frequency dependence. This means that not only the current magnitude, but also the frequency range associated with each lightning waveform must be taken into account for accurate estimation of lightning overvoltage.

In Ekonomou et al. (2003) the Wenner method has been used for measurement of the soil resistivity of the ground and the distance between two sequential electrodes was continuously varied in order to record the lack of homogeneity of the ground. The calculation of the parameters of grounding structure is considered as an optimization problem and tower footing resistance is calculated considering soil resistivity and the geometric characteristics of the grounding system. Recently, the effect of frequency dependence modeling of soil resistivity and permittivity on the response of grounding electrodes due to lightning surges has been analyzed (Alipio & Visacro, 2014; Shariatinasab, Gholinezhad, Sheshyekani, & Alemi, 2016)

This paper presents a comprehensive study to accurate modeling of the grounding systems and analyzing the lightning performance of *TLs*. In this study both the vertical and non-vertical lightning stroke have been considered and the effect of different modeling of grounding system on outage rate of *TL* is investigated. Also, as transmission lines transfer a large amount of energy, a reliability assessment is vital and can be used as a reference to design the proper lightning protection scheme. Therefore, the effect of wide-band modeling of grounding system on the reliability indices of *TLs* has been introduced. In order to go through this, a probabilistic evaluation on outage rates and reliability indices of a 400 kV transmission line is introduced by establishing a link between MATLAB environment and EMTP-RV software. The results are analyzed for different grounding system models and various soil resistivity.

2. Lightning overvoltages

2.1. Lightning parameters

From the field data on lightning strokes, the probability of occurrence of each lightning parameter x can be obtained by a log-normal probability density function as below (Chowdhuri et al., 2005):

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

where $\sigma_{\ln x}$ and $\bar{x}$ are the standard deviation and average of variable x, respectively. The parameters of log-normal distribution of the lightning negative-polarity are presented in Table 1.

Having parameters of the lightning surge, a Heidler function can be used to represent the lightning current waveform (Heidler, Cvetic, & Stanic, 1999):

$$i(t) = \frac{I_p}{\eta}\frac{k^n}{1+k^n}e^{-t/\tau_2} \quad (2)$$

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 rise and decay time of the lightning are determined based on, respectively.

Table 1
Statistical parameters of the lightning negative-polarity strokes (Chowdhuri et al., 2005).

Parameters	First stroke		Subsequent stroke	
	Median	σ_{lnx}	Median	σ_{lnx}
Peak current I_p (kA)	31.1	0.48	13	0.6447
Rise time t_f (μs)	3.83	0.55	0.32	0.6677
Time to half value t_h (μs)	75	0.58	20	0.69
Correlation coefficient ρ_c (I_p, t_f)	0.47		0	

2.2. Determination of termination point of stroke

The termination point of the lightning stroke (i.e. the phase conductor, shield wire or ground) is determined with the aid of electro geometric model (EGM), in which is established based on IEEE Std. 1243. The striking distances were calculated by:

$$R_C = 10\, I^{0.65} \quad (3)$$

$$R_g = \beta\, I^{0.65} \quad (4)$$

where R_C and R_g are the striking distances to the conductor and the ground, respectively, and I is lightning current amplitude and $\beta = 0.8615$. The EGM for the test tower is shown in Fig. 1 (Shafaei, Gholami, & Shariatinasab, 2012).

The number of direct lightning strokes to the *TL* is related to distribution of coordination of lightning strokes on the so-called struck area and the lightning parameters that are generated by means of Monte Carlo simulation. The convergence of Monte Carlo method is obtained after 30,000 runs.

3. Transmission line modeling

3.1. Transmission tower

Fig. 2(a) and (b) shows a typical 400 kV transmission line and its resultant multistory model consisting of two lines with distributed-parameters. The value of the R and L of each part showing traveling-wave attenuation and distortions are given by (Ametani & Kawamura, 2005):

$$R_i = \Delta R_i . h_i(\Omega), \quad L_i = 2\tau R_i(\mu\text{H})$$
$$\Delta R_1 = \frac{2Z_{t1}}{(h-h_2)}\ln\left(\frac{1}{\alpha_1}\right) \quad (5)$$
$$\Delta R_2 = \frac{2Z_{t2}}{h}\ln\left(\frac{1}{\alpha_2}\right)$$

where $c = 300$ m/μs is the light velocity in free space, h (m) is tower height, $\alpha_1 = \alpha_2 = 0.89$ attenuation along the tower and $\tau = h/c$ is traveling time along the tower. In this paper, the tower top to the phase arm impedance Z_{t1} is assumed 200 Ω and the phase arm to the tower bottom impedance Z_{t2} = is equal to 150 Ω.