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Shielding failure rate calculation by means of downward and upward lightning leader movement models: Effect of environmental conditions

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ABSTRACT

In this paper the effects of environmental conditions on shielding failure rate (SFR) of transmission lines are investigated. The study utilizes a previously published work in which leader progression model for lightning upward and downward leaders are used to calculate the SFR. Taking into account the effects of reduced air density and humidity on the parameters of upward leader model and wind pressure on the movement of lightning leaders and wires, SFR and maximum lightning stroke current causing shielding failure are computed. The electric field in all simulations is calculated by means of charge simulation method. The results of simulation show that the effects of relative air density and height of installation are quite higher than that of the wind pressure and humidity while the humidity has the lowest impact on the SFR of investigated transmission line.

1. Introduction

The well-known Electro-Geometrical Model (EGM) has long played the role of a simple and effective method for lightning performance analysis of transmission lines [1–3]. More complicated methods of leader progression models which consider the details of lightning leader movement from cloud to line and upward leader inception criteria have been proposed by investigators [4,5]. The procedure of shielding failure rate calculation in three dimensional configuration for modeling the sag, tower and wires with maximum possible details are also introduced [5]. The lightning performance of overhead transmission lines is usually expressed by a factor called shielding failure rate (SFR). It is important to know the effect of environmental conditions on SFR factor of transmission lines. Due to the fact that testing the environmental conditions for a real transmission line is not an easy job, simulation tools would be quite helpful to create insight into the problem. Actually, the upward lightning leader parameters (which influence the inception condition) are sensitive to environmental conditions. Different laboratory tests and theoretical modeling were performed to investigate the breakdown characteristics for large air gaps and also the influence of humidity and reduced air density on the parameters of discharge [6–10]. The most important effect of humidity is that it decreases the charge per-unit length of the lightning upward leader necessary to achieve thermal transition from diffuse glow to leader channel [6]. Also it will increase the streamer zone electric field intensity which is kept constant during propagation in the upward model [7,11]. Wind pressure changes the route of lightning upward and downward leaders and tilts the phase and ground wires and consequently it changes shielding conditions along the span [12].

In this paper, based on previous work of three dimensional leader movement model, the effects of humidity, reduced air density and wind on the shielding performance of overhead lines are investigated. The effects of humidity and air density are modeled by tuning the parameters of positive upward connecting leader. Shield and phase wires movement is also modeled in simplified conditions to estimate SFR changes due to conductor movement under wind pressure.

The rest of this paper is organized as follows. In Section 2, the leader movement model for shielding failure analysis is reviewed. The principle of modeling and effects of humidity, reduced air density and wind are described in Sections 3, 4 and 5 respectively. Section 6 is also dedicated to some discussions and conclusions.

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2. Leader movement model for shielding failure rate calculation

The leader movement model calculates the SFR of transmission lines based on dynamic simulation of downward lightning leader movement toward earth and checking the stable upward leader inception from towers, wires and ground [5]. Using the configuration of one span (two towers, conductors and a perfectly-conducting ground), the space above the span is divided into meshes, see Fig. 1. The width of area in Y direction, where the simulation should be performed, is selected so that out of this area no flash to wires and towers occurs. Owing the symmetry which exists in the problem, it is enough to perform the simulation for 1/2 of the span length. The downward lightning leader will start from each mesh, descends toward the ground in continuous steps until a stable upward leader is incepted from test points on towers, wires or ground.

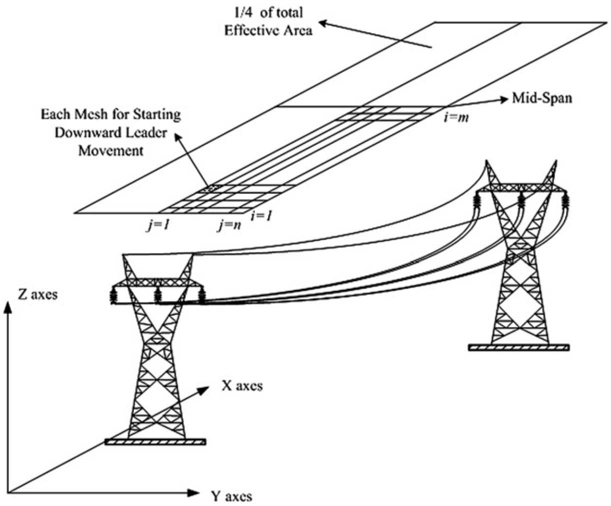

Fig. 1. The meshes for downward lightning leader movement toward ground and structure of a span.

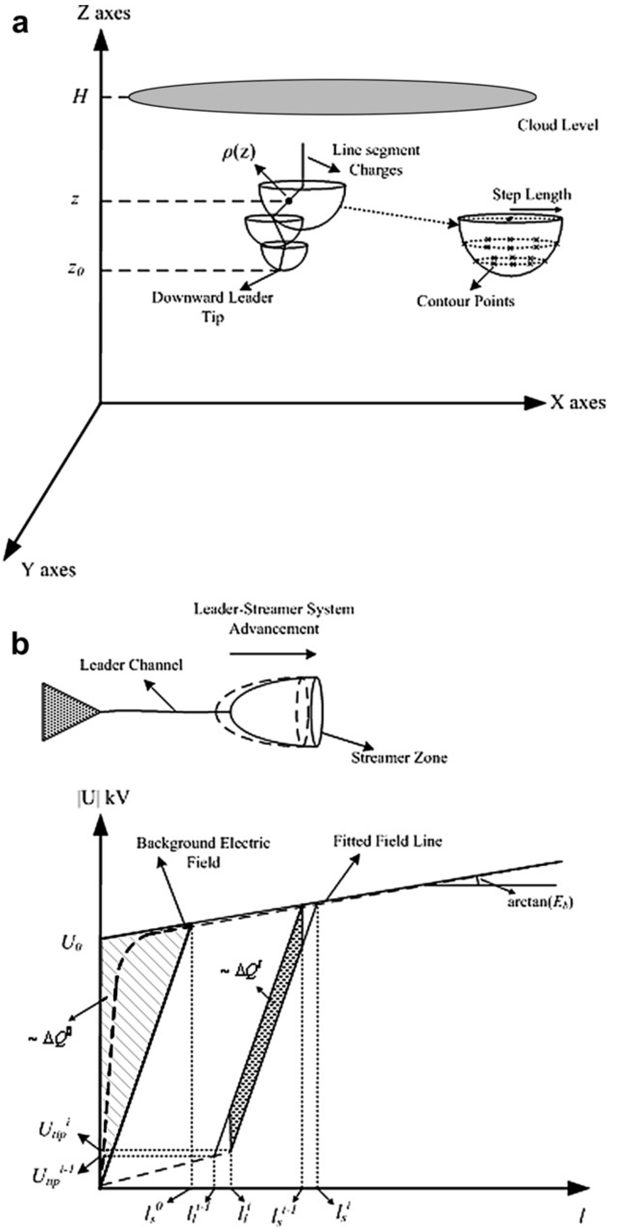

Fig. 2. Lightning leader movements models, (a) downward leader, (b) upward leader.

The field observations of negative downward lightning leaders revealed that these leaders approach the earth from cloud in consecutive steps [13]. The downward leader propagation is represented by the steps with a length of $1/k$ of the leader tip distance from ground, where k is the initial altitude of downward leader divided by 100 m. This model ensures the step length of downward lightning leader become always lower than 100 m in accordance with field observations [13]. Similarly, if the downward leader approaches near the earth and the model results in a step length lower than 10 m, the step length is set to 10 m. To find the next jump point of the downward leader, a hemisphere is drawn with a radius of step length around the tip of the downward leader. Because the potential is always negative (assuming negative downward leaders), next jump point of the leader is a point on the hemisphere where the absolute value of potential is the lowest (i.e. the voltage gradient along the line connecting the leader tip to the target point become maximum), see Fig. 2. The steps of downward leader are modeled by horizontal and vertical line charges. The charge density of downward leader (which is a function of lightning peak return stroke current) is computed by use of following equation based on electrostatic considerations of measured waveform of return stroke current [11]:

$$\rho(z) = I_p\left\{m_0\left(1-\frac{z-z_0}{H-z_0}\right)\left(1-\frac{z_0}{H}\right) + \frac{m_1+m_2(z-z_0)}{1+m_3(z-z_0)+m_4(z-z_0)^2}\times\left[0.3e^{\frac{10-z_0}{75}}+0.7\left(1-\frac{z_0}{H}\right)\right]\right\} \qquad (1)$$

where $m_0 = 1.476\times10^{-5}$, $m_1 = 4.857\times10^{-5}$, $m_2 = 3.9097\times10^{-6}$, $m_3 = 0.522$, $m_4 = 3.73\times10^{-3}$, z_0 is the height of the downward leader tip from earth in m. H is the cloud height in m, I_p is the return stroke peak current in kA, ρ is the downward leader charge density in C/m and z is the variable height of the point on the leader where charge density is to be calculated, see Fig. 2(a).

According to extensive field observation and measurements, some probability distribution functions are introduced for lightning peak current [14]. In this paper, we will use a range of 3–35 kA to scan the lightning current range causing shielding failure.

For shielding failure analysis of transmission lines, a lightning stroke with very low peak current does not create high enough overvoltage to be dangerous, even if they end directly to the phase