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Modeling of lightning impulse behavior of long air gaps and insulators including predischarge current: Implications on insulation coordination of overhead transmission lines and substations

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ABSTRACT

Evaluation of the dielectric strength of transmission line insulation subjected to fast-front overvoltages is of major importance for the insulation coordination of overhead lines and connected substations. Among models proposed in literature for the prediction of the dielectric behavior of long air gaps and insulators under lightning overvoltages, leader development models (also called leader progression models) have a greater physical significance. These models consider the predischarge current flowing in the gap during the leader propagation phase preceding breakdown. However, this current is often disregarded for simplicity in fast-front overvoltage simulations. In this study the effects of simulating predischarge current on voltage–time characteristics of long air gaps and insulators, critical currents of overhead transmission lines as well as fast-front overvoltages arising at substations are investigated with the aid of ATP–EMTP. Including predischarge current in simulations, affecting the flashover characteristics of air gaps and insulators, results in slightly higher estimates of the minimum backflashover current of overhead transmission lines. However, it does not affect the estimated minimum shielding failure flashover current of overhead lines. In addition, simulating predischarge current may affect the overvoltages arising at substations due to shielding failure of the connected overhead lines depending on withstand or flashover of line insulation. In the case of backflashover the wavefront steepness and amplitude of the overvoltages are lower. Thus, predischarge current effects should be considered in insulation coordination of overhead transmission lines and substations.

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1. Introduction

Insulation coordination of overhead transmission lines and of the connected substations necessitates the estimation of the arising fast-front overvoltages caused by lightning strokes. This task can be accomplished through analytical calculations [1,2] or computer simulations [3–6] typically using EMTP-type programs. For both approaches, the assessment of the dielectric strength of transmission line insulation stressed by lightning overvoltages is of crucial importance. The flashover characteristics of line insulation, that is, flashover voltage and time, can be estimated by utilizing different methods: voltage-dependent switches, volt–time curves [7–9], the integration method [10–12] or leader development models [13–18]. The former two methods are simplified and may introduce errors in the computed flashover characteristics, depending on the waveshape and amplitude of the overvoltage stressing line insulation. The integration method was introduced in 1950 as an empirical method [10,11]; a theoretical ground was provided many years later [12]. Generally, the applicability of the integration method may be limited since selection of its parameters is based on tests under a specific overvoltage waveform. Leader development models, allowing for the different phases of discharge process to be considered, namely corona inception, streamer propagation and leader propagation, may yield satisfactory predictions of breakdown characteristics. A more detailed account on the methods for evaluating flashover of line insulation has been given in [19].

As regards the implementation of the methods for the prediction of the lightning impulse behavior of line insulation in EMTP-type programs, the voltage-dependent switches, volt–time curves and integration method can be modeled by simply using a switch and the control logic that generates a flashover signal. On the contrary, leader development models should be represented by circuit elements so as to consider the predischarge current flowing in the gap during the leader propagation phase preceding breakdown.

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Table 1
Parameter values for streamer criterion (2).

Model	Polarity	Rod–rod		Cap and pin insulator		Composite insulator	
		K_1 (kV/m)	K_2 (kV)	K_1 (kV/m)	K_2 (kV)	K_1 (kV/m)	K_2 (kV)
Motoyama [17]	+	400	50	–	–	–	–
	–	460	150	–	–	–	–
Wang et al. [18]	+	–	–	430	190	360	290
	–	–	–	490	90	500	140

However, this current is most often disregarded in fast-front overvoltage simulations [3–5,19–25]; its modeling is a difficult task and may affect the assessment of line insulation flashover.

This work presents an investigation on the effects of considering the current flowing during leader propagation on the prediction of lightning impulse behavior of long air gaps and insulators with the aid of ATP–EMTP [26,27]. Simulations were performed by using a model developed in MODELS simulation language [28,29] of ATP–EMTP, as introduced in [30], that implements several leader development models. It is shown that simulating predischarge current, affecting the flashover characteristics of air gaps and insulators, influences the minimum backflashover current of overhead transmission lines as well as the fast-front overvoltages arising at substations due lightning strokes to the connected overhead lines.

2. Leader development models

Leader development models, also called leader progression models, were developed by considering the breakdown mechanism of long air gaps and insulators. With respect to lightning impulse voltages, the first leader development model was introduced by Akopian et al. [31] in 1954 on the basis of experimental results on long positive rod–plane gaps. In the same study, a model for a 1.25 m rod–rod gap was also developed but it was not generalized to other gap lengths. Since then, several leader development models were derived for rod–plane and rod–rod gaps as well as for insulators stressed by standard and non-standard lightning impulses of both polarities [13–18,32]. Generally, all leader development models assume three distinct phases in the breakdown process of long air gaps, namely corona inception, streamer propagation and leader propagation. Hence, the time to breakdown, t_c, is estimated as

$$t_c = t_i + t_s + t_l \tag{1}$$

where t_i is the corona inception time, t_s is the streamer propagation time and t_l is the leader propagation time.

2.1. Corona inception phase

The corona inception time is typically neglected in leader development models. This is because initial corona occurs early during the fast rising front of the lightning overvoltage stressing the gap and is associated with an inception voltage relatively low compared to breakdown voltage [14–16]. In fact, however, the corona inception time is included, in an indirect way, in the streamer propagation phase [16].

2.2. Streamer propagation phase

The streamer propagation phase is assumed to be completed when streamers bridge the gap. This is considered to occur when the average gradient in the gap becomes equal to a critical value [13,15,16,33,34], commonly called critical electric field strength, E_0. The latter varies with electrode configuration and voltage polarity; for the Pigini et al. [16] model E_0 is also assumed dependent upon gap length.

An alternative criterion for the completion of streamer phase, as proposed by Motoyama [17] and adopted by Wang et al. [18], uses integration of the voltage across insulation

$$\frac{1}{t}\int_0^t V\mathrm{d}t > K_1 \cdot D + K_2 \tag{2}$$

where V (kV) is the instantaneous voltage across the insulator or air gap, t (s) is the time, D (m) is the insulator or gap length and K_1 (kV/m) and K_2 (kV) are empirical constants (Table 1).

Other criteria proposed in literature are

$$t_s = \frac{A}{\left(V_{\max}/D\right) - B}\,[14] \tag{3}$$

$$\frac{1}{t_s} = 1.25\frac{E_{\max}}{E_{50}} - 0.95\,[16] \tag{4}$$

where A (MV•μs/m) and B (MV/m) are constants given in Table 2 of [14] for different gap configurations and polarities, $V_{\max}$ (MV) is the maximum value of the applied impulse voltage reached before breakdown, E_{50} (kV/m) is the average gradient in the gap at U_{50} and $E_{\max}$ (kV/m) is the maximum average gradient ($V_{\max}/D$) reached before breakdown. It is important, however, that both criteria (3) and (4) requiring prior knowledge of $V_{\max}$ and $E_{\max}$ cannot actually be used for the prediction of streamer propagation time. Furthermore, expression (4), proposed in [16] and suggested in [3–5] for fast-front overvoltage simulations, was derived based on experimental results referring solely to standard lightning impulse voltages (1.2/50 μs); thus, application to non-standard impulse voltage waveshapes is certainly not justified.

2.3. Leader propagation phase

After streamers have bridged the gap, leader starts to propagate from one or both electrodes, depending on gap configuration and voltage polarity. Breakdown occurs at the time instant when the leader bridges the gap or the two leaders meet at the center of the gap. The development of the leader stops if the average gradient in the unbridged part of the gap by the leader becomes less than E_0; in this case breakdown does not occur. The leader propagation phase is described by using experimentally derived leader velocity expressions, which are functions of the voltage stressing the gap and of the length of the unbridged gap by the leader. Table 2 summarizes several leader velocity expressions from literature with parameter values listed in Table 3; leader development models [31,32] are not included in these Tables, as they refer solely to rod–plane air gaps. It is noteworthy that leader development models [13,15,16] assume an equivalent leader propagating from one electrode only, whereas models [14,17,18] consider one or two leaders depending on gap configuration.

During the leader propagation phase a significant current, commonly called predischarge current, flows into the gap. According to (5), the predischarge current, i, can be considered as proportional to leader velocity, the coefficient of proportionality being the average charge per unit length of the leader, q. Although the latter is difficult to be derived experimentally [15,16], expression (5) is

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