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Analysis of different procedures for the application of the Disruptive Effect Model to distribution insulators subject to short tail lightning impulses

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ABSTRACT

The performance of electric power systems is usually greatly affected by lightning surges, whose characteristics may vary widely and differ significantly from the standard 1.2/50 μs waveshape. One of the most commonly used methods for predicting the strength of insulation subject to lightning impulses of non-standard waveshapes is the Disruptive Effect Model, for which different procedures exist for the estimation of the parameters required for its application. This paper aims at analyzing the main methods for the determination of such parameters. The investigation is based on the comparison of the measured and calculated volt–time characteristics of a 15 kV pin-type porcelain insulator considering two short tail impulse waveshapes (1.2/4 μs and 1.2/10 μs), as well as the standard lightning impulse voltage waveshape. The results relative to the positive and negative polarities of the three voltage waveshapes are presented and discussed. It is shown that, from an engineering point of view, all the presented procedures for determination of the Disruptive Effect Model parameters yield satisfactory results for the impulse waveshapes considered.

1. Introduction

Overhead distribution lines are often exposed to lightning overvoltages, whose waveshapes vary widely and can differ substantially from the standard impulse voltage waveshape used to test electric equipment insulation against lightning surges (1.2/50 μs waveshape) [1–7].

If a line protected with a shield wire is hit by a lightning flash, not only the peak of the overvoltage will be reduced – in comparison with the case of an unshielded line – but also the tail of the waveshape will be shorter, due to reflections from adjacent poles.

Nearby strokes also have an important impact on the lightning performance of distribution lines. Both the magnitudes and waveshapes of induced voltages depend on many lightning parameters and are greatly affected by the network configuration. However, independently of the combination of the relevant parameters, the wavetails of these voltage surges are usually much shorter than that of the standard waveshape.

It is well known that the voltage withstand capability of insulation depends not only on the amplitude but also on the voltage waveshape. Different models have been proposed for predicting the strength of insulation subjected to impulses of non-standard waveshapes. One of the most commonly used is the Disruptive Effect Model [8,9]. There are, however, different methods of applying this model, that is, different ways of estimating the parameters needed for its application [10–12].

This paper aims at evaluating the main methods for predicting the breakdown characteristics of distribution insulators subjected to short tail lightning impulses. For the analysis, tests were performed on a 15 kV pin-type porcelain insulator considering the 1.2/4 μs and 1.2/10 μs, as well as the standard lightning impulse voltage waveshape. The evaluation of the methods for determining the parameters of the Disruptive Effect Model was based on comparisons between the volt–time curves obtained experimentally and those predicted by each method, for the positive and negative polarities of each of the impulse voltages considered.

2. The Disruptive Effect Model

As it is impractical to test equipment insulations under all possible lightning overvoltage waveforms to which they can be subject

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over their useful life, some models have been proposed to assess the withstand capability under non-standard lightning impulses.

The first attempt was made by Witzke and Bliss [9], who carried out a study on the effects of non-standard impulse voltage waveshapes on oil-insulated transformers and presented for the first time the term "disruptive effect" (*DE*), defined as:

$$DE = \int_{t_0}^{t} [V(t) - V_0]^K \ dt, \quad (1)$$

where $V(t)$ is the applied voltage as a function of time t and t_0 is the instant when the voltage $V(t)$ reaches the level V_0, with the parameters V_0 and K fixed by the standard transformer test voltages. As mentioned in [9], this relationship has been established assuming that the transformer insulation could withstand the voltage V_0 for a certain period of time (a few hundred microseconds) without damage. It was also assumed that the disruptive effect associated with a surge is a function of both voltage amplitude and time, but that these factors do not have the same importance. The exponent K allows varying the relative weight given to these two quantities.

The main procedures for calculating the parameters V_0 and K are briefly described in this section.

The Disruptive Effect Model was evaluated by Caldwell and Darveniza [13], who determined the flashover characteristics of typical line insulation using standard and non-standard impulse waveforms. Later, in the analysis carried out in [10], Darveniza and Vlastos obtained the best match between calculated and experimental volt–time data adopting $K = 1$ and $V_0 \approx 90\%$ of the critical impulse flashover voltage V_{50} (i.e., the crest value of the standard lightning impulse wave that yields flashover in 50% of the applications). This procedure will be referred to as Ref. [10] in the next sections.

The volt–time characteristics of 5 cm long rod–plane and rod–rod air gaps were experimentally determined by Chowdhuri et al. in [11] with five different impulse waveshapes. The parameter V_0 was defined as the voltage of a specified waveshape which a particular air gap will withstand under repeated applications with very low probability of breakdown, and is given by:

$$V_0 = V'_{50} - ks, \quad (2)$$

where V'_{50} is the crest value of the specified impulse wave that causes flashover in about 50% of the applications and s is the standard deviation. The parameter k depends on the number of observations (n) of the normal distribution and on the population P greater than V_0 (assumed to be 0.999 with confidence $\gamma = 0.95$), and can be obtained from statistical tables [14].

The exponent K is given by:

$$K = \alpha \frac{V(t)}{V_0}, \quad (3)$$

where α is a constant to be determined experimentally. This procedure will be referred to as Ref. [11] in the next sections.

The breakdown characteristics of air gaps and medium-voltage (MV) insulators stressed by short tail lightning impulses have been studied by Ancajima et al. [12,15–17], who investigated two different methods of calculating V_0.

In the first procedure, based on the Kind model [8], K is assumed to be constant and equal to 1 and V_0 corresponds to the voltage that a particular air gap will withstand under the standard lightning impulse with very low probability of breakdown, and is calculated according to:

$$V_0 \le V_{50} - k(P, \gamma, \nu)\sigma^*, \quad (4)$$

where k is a tabulated statistical value as a function of P, γ, and ν; ν is the number of degrees of freedom of the n recorded points of the flashover voltage cumulative probability normal distribution; and $\sigma^* = \sigma(n/\nu)^{1/2}$ is the standard deviation corrected to take into account the ν degrees of freedom. The values assumed for P, γ, and ν are 0.999, 0.95, and $(n - 2)$, respectively. This procedure will be referred to as Ref. [12]a in the next sections.

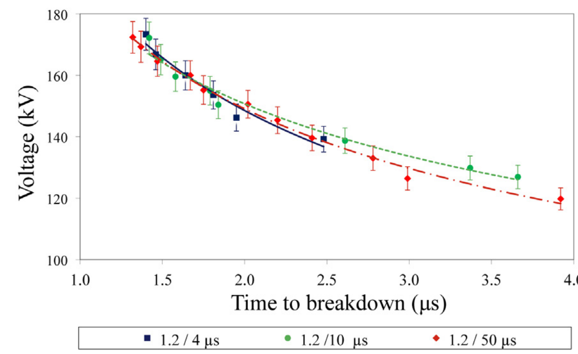

Fig. 1. Experimental volt–time curves of the three impulse voltages, of positive polarity, with indication of the measuring uncertainty for the 1.2/10 μs and 1.2/50 μs waveshapes.

The second method considered in [12] is based on the Chowdhuri et al. proposal [11]. The parameter V_0 is estimated according to (4), but with V_{50} replaced with V'_{50}, so that V_0 depends on the impulse waveshape. However, if the instantaneous value of the applied voltage falls below the value selected for V_0, a situation which may occur for short tail lightning impulses, Ancajima et al. propose that

$$V_0 \le v(t_{bM}), \quad (5)$$

where $v(t_{bM})$ is the voltage value at the longest recorded time to breakdown.

The value of K is the same as that used by Chowdhuri in [11], obtained from (3). This procedure will be referred to as Ref. [12]b in the next sections.

3. Test procedure

A 15 kV pin-type porcelain insulator with dry arc distance of 14 cm was mounted on a supporting structure so that the height of its base was 1.05 m above ground [18]. Besides the standard lightning impulse voltage, tests were also performed with two short tail impulse waveshapes (1.2/4 μs and 1.2/10 μs) of both polarities.

The multiple level method [19] was adopted for the determination of the lightning impulse flashover voltages V_{50} and V'_{50}. For each impulse waveshape and polarity a voltage level causing one or two disruptive discharges out of ten applications was selected as the first of the five levels ($n = 5$) used for the determination of the lightning impulse flashover voltages.

The volt–time curves were obtained by applying five impulses at each of the prospective voltage peak values. The number of voltage levels varied from 7 to 11, depending on the impulse waveform and polarity. As slight variations may occur between the applied voltages at each level, each point on the curve corresponds to the mean of the maximum values reached before flashover; analogously, the time corresponds to the mean time to breakdown.

4. Results and analysis

Figs. 1 and 2 present, respectively, the volt-time curves that best fit the experimental data obtained for positive and negative polarities of the 1.2/4 μs, 1.2/10 μs, and 1.2/50 μs impulse voltage waveshapes. It can readily be seen in Fig. 1 that the differences between the results are, in practically all the cases, within the measuring uncertainty (±3%).