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Estimation of the minimum shielding failure flashover current for first and subsequent lightning strokes to overhead transmission lines

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ABSTRACT

ATP-EMTP simulations are performed to estimate the minimum shielding failure current causing flashover in overhead transmission lines with operating voltage in the range of 66 kV up to 735 kV. This critical current, affecting shielding failure flashover rate, is of great importance for assessing the insulation coordination of overhead transmission lines and the connected substations. The minimum shielding failure current causing flashover of line insulation is highly dependent upon insulator string flashover modelling and, also, markedly higher than that calculated according to the relevant IEEE Std 1243-1997 simplified expression. A modification of the latter is suggested by using multiplication factors of 1.5 and 1.65 for first and subsequent lightning strokes, respectively, so as to account for the increased dielectric strength of line insulator strings under non-standard lightning overvoltage surges. Alternatively, the critical currents can be respectively estimated by using average negative breakdown gradients per unit length of insulator string of 680 kV/m and 750 kV/m. The shielding failure flashover rate of the overhead transmission lines, being greatly influenced by insulator string flashover modelling, is lower than that obtained based on the critical current according to IEEE Std 1243-1997.

1. Introduction

Shielding of overhead transmission lines against direct lightning strokes to phase conductors is provided by shield wires, which intercept the descending lightning leader through a connecting upward discharge. However, some of the less intense strokes may not be intercepted and strike to phase conductors; this causes flashover of line insulation when the arising overvoltages are higher than the insulation level of the line. Thus, shielding failure, that is, direct lightning strokes to phase conductors of overhead transmission lines is one of the main causes of line outages. Therefore also, the minimum shielding failure current causing flashover of line insulation, hereafter called critical current, is an important parameter for evaluating the lightning performance of overhead transmission lines.

According to the relevant IEEE Std 1243 [1], the critical current can be calculated by a simplified method, which considers the Critical Flashover Voltage (*CFO*) of line insulation under standard lightning impulses (1.2/50 μs) and the surge impedance of the phase conductor under corona. However, the overvoltages stressing line insulation due to shielding failure may differ significantly from the standard lightning impulse voltage in respect of overvoltage waveshape, mainly as a result of the stochastic nature of lightning stroke current parameters. Alternatively to the simplified method, the critical current causing flashover of line insulation can be estimated through computer simulations [2], which allow for the behaviour of line insulation under fast-front overvoltage surges to be considered in a more detailed way.

In this work the critical current of overhead transmission lines with operating voltage in the range of 66 kV up to 735 kV is estimated for first and subsequent lightning strokes through ATP-EMTP [3,4] simulations. Several insulator string flashover models were employed in simulations so as to demonstrate their effects on the critical current. Simulation results are discussed and compared with that obtained from the simplified method of the IEEE Std [1]. It is shown that the estimated critical current of the investigated lines, varying significantly among insulator string flashover models, is markedly higher than that estimated according to the IEEE Std [1]; this affects the estimated shielding failure flashover rate of the overhead transmission lines. A simple modification in the IEEE Std [1] expression estimating critical current is proposed so as to account for the increased dielectric strength of line insulation under non-standard lightning overvoltage surges due to first and subsequent strokes.

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2. Insulator string flashover modelling

For fast-front transient studies, transmission line insulator strings are usually represented by flashover switches in parallel with capacitors, which simulate the coupling effects of conductors to the tower [5]. The dielectric strength of insulator strings, that is the flashover voltage and time, is estimated by employing in electromagnetic transient simulations voltage-dependent switches, volt–time curves [6–8], the integration method [9–11] or leader development models [12–16].

2.1. Voltage-dependent flashover switches

The simplest approach for modelling insulator string flashover is the use of a voltage-dependent switch, closing when the voltage across the insulator string exceeds a specific value, most commonly the *CFO*. This simple model, however, disregards the voltage–time characteristic of the insulator string under lightning overvoltage surges. Thus, when insulation is overstressed the estimated flashover voltages corresponding to short times to flashover are erroneous as the *CFO* is related to the flat part of the voltage–time characteristic, where flashover occurs mainly on the tail of the fast-front overvoltage. Furthermore, as the *CFO* is normally determined under standard lightning impulse voltages, this model is not suitable for the prediction of the line insulation behaviour under fast-front overvoltages of non-standard waveshapes.

2.2. Volt–time curves

The volt–time curve of self-restoring insulation is defined as the curve associating the maximum value of the applied impulse voltage reached before flashover with the time to flashover. It corresponds strictly to a particular insulation configuration and to a specific impulse voltage waveshape and polarity. Most commonly, volt–time curves of insulator strings, with and without arcing horns, are obtained by applying standard lightning impulses. Several typical volt–time curves corresponding to different transmission line insulator types and configurations can be found in the literature [14,17–24].

Using volt–time curves in simulations, flashover occurs when the voltage across the insulator string becomes equal to or higher than the instantaneous flashover voltage, V_{FO}. A valid expression for the latter is given in [6–8]

$$V_{\mathrm{FO}} = \left(400 + \frac{710}{t_{\mathrm{c}}^{0.75}}\right) D \tag{1}$$

where V_{FO} is in kV, t_{c} (μs) is the time to flashover and D (m) is the insulator string length. This experimentally derived expression, often called CIGRE volt–time curve, is also valid for times to flashover shorter than 1 μs after extrapolation [6]. Alternatively, V_{FO} may be given as a function of *CFO* for times to flashover ranging from 2 to 11 μs [25] as follows

$$V_{\mathrm{FO}} = \left(0.58 + \frac{1.39}{t_{\mathrm{c}}^{0.5}}\right) CFO. \tag{2}$$

It is important to emphasize that volt–time curves are usually experimentally obtained by employing the standard lightning impulse voltage (1.2/50 μs), therefore, generally, they do not describe accurately the insulation behaviour under non-standard fast-front overvoltages. However, this is less important for short times to flashover, where the volt–time curves obtained for non-standard lightning impulses may not differ significantly from those obtained for standard lightning impulses [7,13]. Also, the volt–time curves, by definition [26], utilize the maximum value of the applied impulse voltage reached before flashover, which may differ from the instantaneous flashover voltage. More specifically, for flashovers occurring during the wavefront of the applied impulse voltage, the voltage value to be used in the construction of the volt–time curve is that corresponding to the time to flashover. However, for flashovers occurring during the wavetail, corresponding to lower flashover probabilities, the volt–time curves relate the crest voltage with time to flashover, that is, voltage and time values that do not refer to the same time instant. This introduces further inaccuracies in the estimation of the flashover voltage and especially time.

2.3. Integration method

The integration method, also called severity index or disruptive effect method, was originally proposed by Witzke and Bliss [9,10] as an empirical method for evaluating the effects of non-standard lightning overvoltages on transformers. It was later evaluated experimentally by Jones [27] mainly for rod–rod air gaps. In general, the integration method can be employed for the prediction of the performance of gaseous, liquid and solid insulation under non-standard fast-front overvoltages based on experimental results obtained under standard lightning impulses. The breakdown process of the insulation starts after a minimum voltage, U_0, has been exceeded and depends upon both the amplitude of the applied voltage and time during which the latter is higher than U_0. The general expression of the integration method is given as

$$DE = \int_{t_0}^{t} (U(t) - U_0)^k dt \tag{3}$$

where DE (kV$^{\mathrm{k}}$ μs) is the disruptive effect of the applied impulse voltage U (kV), t_0 (μs) is the instant when the applied voltage exceeds the minimum voltage U_0 (kV), t (μs) is the elapsed time after the impulse voltage application. k is a factor accounting for the effects of the applied voltage amplitude and time on DE [9,10]. According to the integration method, breakdown occurs when the integral (DE) becomes equal to or higher than the critical disruptive effect DE^*. Usually, for a given insulation configuration, appropriate values for DE^*, U_0 and k are considered those providing the best possible fit between the experimental and computed voltage–time characteristics under standard lightning impulses.

One of the main disadvantages of the integration method is the difficulty in the determination of the optimum values for the parameters in (3), normally requiring a trial and error procedure. For that reason simplified approaches have been proposed in [10,27] and [21] setting respectively U_0, thus also t_0, equal to zero and k equal to unity. Furthermore, the integration method, being essentially an empirical one, is not directly related to the physical processes involved in electrical breakdown. Despite the theoretical basis that was provided in [11], the integration method parameters still lack physical significance; utilizing a varying, rather than constant, U_0 [11,21] and/or k [28] during the entire breakdown process seems more appropriate. It must be noted that for uniform and quasi-uniform air gaps Kind's [29] equal or formative area criterion for breakdown can be applied, which, based on a more physical ground, employs an expression similar to (3) neglecting however k and assuming U_0 equal to the static breakdown voltage.

Nevertheless, many authors [11,21,27,30–32] have provided evidence that the integration method can be used for the prediction of the insulation behaviour under non-standard lightning impulse voltages with reasonable accuracy. However, according to Chowdhuri et al. [28] the parameters of the integration method depend on the impulse voltage waveshape. Certainly, there is a need for a thorough evaluation of the accuracy of the integration method in