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Introducing novel risk-based indicator for determining transmission line tower's backflashover performance

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ABSTRACT

Transmission line (TL) backflashover (BF) performance has been traditionally ascertained using a single number, the so-called backflashover rate, which is measured in number of BF events per 100 km-years. This paper aims at presenting a novel indicator for assessing performance of high-voltage TL tower's ability for tolerating direct lightning strikes without provoking BF events. This indicator is also defined as a single number, which can be computed for any TL tower (by means of EMTP simulations) and measures, in a novel way, its tolerance against BF events. It is given in terms of the risk of the BF occurrence, which means it is statistical in nature and depends on the total sum of conditions governing the BF events. The BF risk, as an indicator, is obtained from the probability density function of the shield wire(s) incident lightning currents and the cumulative distribution function of the BF currents statistical distribution. Hence, it merges complete probabilities of obtaining lightning currents striking a tower with probabilities of those currents provoking BF events on that tower. This novel risk-based indicator can be related to the price of that risk and the associated investment costs, enabling the cost-effective optimisation solutions to the problems of TL arrester applications and station insulation coordination design. This seems appropriate, considering the fact that the investment in surge arresters and related protective measures is commonly perceived as buying insurance.

1. Introduction

High voltage (HV) transmission lines are exposed to lightning strikes, where only direct lightning strikes (to shield wire(s), phase conductors and tower tops) are of engineering concern. Transmission line (TL) performance in relation to direct lightning strikes is of paramount importance, for several different reasons [1,2]: (i) determining line's yearly outage rate for reliability purposes, (ii) line insulation coordination, (iii) surge arresters (TLA) application on the line, (iv) incident transformer station (or switchyard) insulation coordination design, (v) optimising TL insulators archorn gaps, (vi) optimising tower geometry for lightning shielding of the line. Of particular importance, for several of the above-mentioned instances, is the TL backflashover (BF) performance, emanating from the direct lightning strikes to the tower tops and shield wire(s) [1–5]. Transmission line BF performance is traditionally ascertained using the backflashover rate (BFOR), which is a single number representing an entire line, expressed as the number of expected BF events per 100 km-years [5]. The backflashover probability, as a feature of the BFOR, is usually obtained from the repeated numerical simulations (i.e. Monte-Carlo method), e.g., [6–11] using the ElectroMagnetic Transients Program (EMTP) [12,13], or by other means (i.e. simplified analytical treatment). When this probability is combined with the number of expected BF events, traditionally determined from the application of the electrogeometric model (EGM) of lightning attachment to TLs, it yields a backflashover rate.

Analytical methods of backflashover analysis are extensively described by the IEEE WGs [5,14] and CIGRE WGs [15]. A comparison between these recommendations is given by Nucci in [16]. Nowadays, it is far-more common to treat the backflashovers on TLs in terms of the numerical simulations, carried-out by means of the EMTP, e.g., [12,13,17]. With the numerical approach to the transient analysis of TL lightning surges, detailed models of the TL components are needed, some of which exhibit non-linear behaviour or frequency-dependence [17–19]. Interested reader is at this point advised to consult the extensive treatment of modelling guidelines for TL lightning-surge numerical simulations provided in Ref.

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[20,Ch. 2]. Further important simulation details, concerning the backflashover analysis on HV transmission lines, can be found in Refs. [21–25].

This paper aims at presenting a novel indicator for measuring performance of HV transmission line tower's ability to tolerate direct lightning strikes without provoking a BF event. It can be determined for any single tower or given for the entire line (using a "representative" tower). This indicator is also a single number, which leverages powerful EMTP simulations in its computation, and measures, in a novel way, tower's tolerance against BF events. It is given in terms of the risk of the BF occurrence, which means it is statistical in nature and depends on the total sum of conditions governing the BF events [26]: local keraunic level, statistical depiction of lightning-current parameters (including statistical correlation between the parameters), EGM of lightning attachment, frequency dependence of TL parameters and electromagnetic coupling effects, TL span length, statistical distribution of lightning strokes along the TL span, tower geometry and surge impedance, tower grounding impulse impedance (with soil ionization if present), lightning-surge reflections from adjacent towers, non-linear behaviour of the insulator strings flashover characteristic, and power frequency pre-strike voltages.

Proposed BF indicator, in addition, utilizes the so-called curve of limiting parameters (CLP), which is derived from repeated EMTP simulations using an original algorithm developed by the authors and described in detail in Ref. [27]. The CLP itself brings into direct relationship shield wire(s) incident lightning currents with the "critical" currents for the BF occurrence. Developed algorithm minimizes the number of EMTP simulation runs using systematic simulations approach, unequal wave-front time increments, and bisection search method for finding "critical" current amplitudes. Consequently, it is orders of magnitude faster then the traditional Monte-Carlo method application.

Furthermore, pseudo-random shield wire(s) incident lightning currents, necessary for the statistical treatment of the phenomenon, are generated from the appropriate bivariate statistical probability distribution, by means of the Gaussian copula approach [28–32]. The copula approach, when combined with the CLP method, provides for an extremely efficient way of obtaining pseudo-random BF currents, unlike the more traditional way of using the Monte-Carlo method (which is known to be very time consuming), e.g. see Ref. [9]. These BF currents are in-turn used to derive a probability density function (PDF) of their statistical distribution, by means of the kernel density estimation (KDE) procedure [33]. The KDE employs Gaussian kernels, with bandwidths determined using the grid search and cross-validation of the estimator performance.

The BF risk, as an indicator, is finally computed from the PDF of the shield wire(s) incident lightning currents and the cumulative distribution function (CDF) of the BF currents statistical distribution. Hence, it merges complete probabilities (instead of working with their point estimates) of obtaining lightning currents striking a tower with probabilities of those currents provoking BF events on that tower (while accounting for any tower peculiarities as such).

The paper is organised in the following manner. In Section 2, a brief outline of the TL model for the BFOR analysis is provided, which is suitable for the implementation in the EMTP software package. Section 3 provides a thorough and comprehensive statistical treatment of lightning currents. This section presents the Gaussian copula approach, along with the EGM application, for obtaining the bivariate probability density of lightning currents incident to transmission lines. It also features BF currents probability distribution, obtained from using the CLP from the prospective tower. Section 4 introduces a novel risk-based BF indicator. A test case of the HV transmission line, along with the sensitivity analysis, is provided in Section 5, which is followed with the conclusion in Section 6.

2. Transmission line modelling for backflashover analysis

The EMTP model of the HV transmission line for lightning surge transient simulation in general, and backflashover analysis in particular, has been thoroughly studied and widely published, see Refs. [17–19,34,35]. A brief outline of the model, as employed for the purpose of this paper, will be presented in this section. The model consists of several components: (i) TL phase conductors and shield wire(s), including spans, line terminations and power frequency voltage, (ii) TL tower, (iii) tower grounding impedance, (iv) insulator string flashover characteristic, (v) lightning current and lightning-channel impedance.

2.1. Phase conductors and shield wire(s)

High voltage transmission line phase conductors and shield wire(s) are modelled as distributed-parameters, untransposed, frequency-dependent, multiphase transmission line, by means of the so-called JMarti model [12,36]. Phase conductors and shield wire(s) positions on the tower (from the most-representative tower within the TL route) are used, along with their maximum allowed sags, cross-sectional dimensions, DC resistances, soil resistivity of the ground return path, etc. Several spans of the transmission line, at each side of the tower being struck by lightning, are modelled in this way. Longer sections are then added on both sides of this chain in order to suppress further reflections from both ends. The line model is finally terminated by an ideal, grounded, power-frequency, three-phase voltage source (with fixed angles) in order to account for the pre-strike phase voltages.

2.2. Transmission line towers

The steel-lattice towers of HV transmission lines are represented as a single conductor, distributed-parameter, frequency-independent lines. The single value of the tower surge impedance is computed from the analytical expressions, based on the theoretical background provided by Sargent in [37], which depend on the tower configuration and can be found in Ref. [20,Ch. 2]. The velocity of the surge propagation along the steel-lattice tower is assumed to be equal to the speed of light in free space.

2.3. Tower grounding impedance

The model of the lightning-struck TL tower grounding impedance is probably the most important single factor influencing the subsequent formation of the overvoltage on its tower top, due to subsequent reflections of travelling waves formed by the said lightning strike, where reflections from the tower base will arrive much sooner at the tower top then reflections from adjacent towers. Hence, the influence of the (apparent) TL tower footing (i.e. grounding) surge impedance on the tower top transient voltage is determined by its response time and current dependence. In cases where the tower grounding cannot be regarded as being concentrated, the frequency-dependent tower grounding impedance model is needed. Its implementation can be difficult [24]. On the other hand, in case of the concentrated grounding, the tower grounding impedance exhibits only current dependence, which can be modelled in accordance with the guidelines provided in Ref. [18]. The following equation is utilised for that purpose:

$$R_{tower} = \frac{R_0}{\sqrt{1 + I_t/I_g}} \tag{1}$$