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Monte Carlo method for estimating backflashover rates on high voltage transmission lines

Petar Sarajcev*

University of Split, FESB, Department of Power Engineering, R. Boskovica 32, HR-21000 Split, Croatia

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ABSTRACT

This paper presents a novel Monte-Carlo based model for the analysis of backflashover rate (BFOR) on high voltage transmission lines. The proposed model aims to take into the account following aspects of the BFOR phenomenon: transmission line (TL) route keraunic level(s), statistical depiction of lightning-current parameters (including statistical correlation), electrogeometric model of lightning attachment, frequency-dependence of TL parameters and electromagnetic coupling effects, tower geometry and surge impedance, tower grounding impulse impedance (with soil ionization), lightning-surge reflections from adjacent towers, non-linearity of the insulator strings flashover characteristic, distribution of lightning strokes along the TL span and power frequency voltage. In the analysis of the BFOR, special attention is given to the influences emanating from the insulator strings flashover characteristic and lightning statistics. The model could be applied to the transmission line as a whole or some of its portions, e.g. first several towers emanating from the substation or several towers crossing a mountain ridge.

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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; nearby lightning strikes have no influence on the HV transmission line (TL) performance. Direct lightning strikes to phase conductors, where shield wire(s) is(are) present on the tower, are accompanied by lightning currents with constrained amplitudes, due to the shielding effect of wire(s); nonetheless, these strikes can provoke a flashover of the TL insulation (i.e. insulator string flashover). The rate at which this is to be expected, per 100 km-years of transmission line, is termed the shielding failure flashover rate (SFFOR). Direct lightning strikes to shield wire(s) and tower tops can also provoke a flashover of the TL insulation, where the strikes to the tower tops are more significant in producing insulator flashovers (and statistically speaking more probable) then the strikes to mid-spans. The rate at which this is to be expected, per 100 km-years of transmission line, is termed the backflashover rate (BFOR). The flashovers away from insulator strings, both in SFFOR and BFOR analysis, are regarded as being far less probable than the insulator string flashovers; hence, only flashovers at the TL insulator strings are considered possible in numerical treatment of the phenomenon. It is the intention of this paper to analyse solely the BFOR of HV transmission lines.

The backflashover occurrence rate is important, along with the mentioned SFFOR, for estimating the outage times/rates of transmission lines due to lightning. It is important in designing the HV substations (or switchyards) overvoltage protection, in terms of the incoming overvoltage emanating from the backflashovers on neighbouring TL towers incident to the station. Furthermore, it is of importance in the decision making process regarding the shielding of TLs using surge arresters (TLA applications on specific parts of the TL route). It has been extensively studied by many researchers, using analytical and numerical methods, and the volume of published material on the subject is overwhelming.

The analytical methods are extensively described by the IEEE WGs [1,2] and CIGRE WGs [3], with additional details provided in numerous references cited therein. A comparison between these recommendations in given in Ref. [4]. Further extensive exposition of analytical methods is provided in Refs. [5, Ch. 10]. Nowadays, it is far-more common to treat the backflashovers on TLs in terms of the numerical simulations, carried-out by means of the Electromagnetic Transients Programs (EMTP), e.g. [6–8]. With the numerical approach to the transient analysis of TL lightning surges, detailed (and often quite sophisticated) models of the TL components are needed, some of which exhibit non-linear behaviour, frequency-dependence, etc. The IEEE WGs and CIGRE WGs offer extensive guidelines when it comes to representing transmission line elements (and other network elements) for numerically simulating

* Tel.: +385 21 305806; fax: +385 21 305776.
E-mail address: petar.sarajcev@fesb.hr

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fast-front (i.e. high-frequency) transients [9,10]. Furthermore, special recommendations exist for particular network components. Interested reader is at this point advised to consult the extensive treatment of modelling guidelines for TL lightning-surge numerical simulations provided in [11, Ch. 2] and references cited therein. Further important simulation details, concerning the backflashover analysis on HV transmission lines, can be found in Refs. [12–17].

Direct lightning strike to the transmission line tower (or its near-vicinity) initiates a travelling wave process in the system of lightning channel, shield wires, TL tower, and tower footing impedance. Accompanying current and voltage transient states, at the various points of the TL tower, are established through the complex propagation pattern of current and voltage travelling waves, including reflection and transmission of those waves on various points of travelling paths wave impedance discontinuities. This process results with a transient voltage being applied on the TL insulator strings with the possibility of their flashover, i.e., when the transient potential of the tower arm exceeds the critical flashover voltage of the insulator strings (itself being a non-linear function of the applied voltage), biased to some extent by the power-frequency phase voltage, it causes a backflashover.

The numerical simulation of the TL backflashover proposed in this paper aims to take into the account following aspects of the phenomenon: transmission line route keraunic level(s), statistical depiction of lightning-current parameters (including statistical correlation between the parameters), electrogeometric model (EGM) of the lightning attachment process, frequency-dependence of TL parameters and electromagnetic coupling effects, 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, TL span length, statistical distribution of lightning strokes along the TL span and power frequency voltage. Furthermore, the proposed approach aims at coupling the Monte Carlo method with the EMTP simulation, in order to establish the statistical probability of backflashovers on HV transmission lines.

The Monte Carlo method has been applied to the problem of calculating BFOR, for example, in Refs. [12,18–22]. However, the here proposed approach is unique in the way it implements the Monte Carlo method and in the way in which it treats the statistical parameters of lightning currents incident to TLs (accounting for the electrogeometric model of lightning attachment along with statistical dependence between lightning-current parameters). On top of that it implements a state-of-the-art TL model for the EMTP backflashover simulation. Monte Carlo procedure applied, for example, in Ref. [22] generates lightning data from the downward (negative) lightning statistics, chooses at random lightning starting points up to some distance from the TL, and, using EGM (from Eriksson), determines whether this lightning will strike the TL or the nearby earth. If there is a strike to the TL, the EMTP simulation is carried-out. Here proposed method, on the other hand, first computes (numerically) the probability density function of the statistical distribution of lightning currents which are, by means of applying the EGM, incident to TL and then from it generates lightning data (accounting for the statistical correlation between parameters) for the EMTP simulations. This reduces the number of samples used for the analysis. The proposed method, through simulations, provides insight into the BFOR behaviour—in the statistical sense—which is due to many influential factors, some of which can be changed between simulation runs. Furthermore, considering the well-established influence of the tower grounding impulse impedance and insulator strings flashover characteristic on the BFOR, these aspects will be numerically investigated within the sensitivity analysis provided in the paper.

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-ATP software package. Section 3 provides necessary statistical treatment of the lightning current parameters. In Section 4 is provided an estimation of the number of direct lightning strikes to transmission line, by means of implementing the electrogeometric model of lightning attachment in combination with the statistical distribution of lightning strokes along the TL span length. This section additionally presents the probability density functions of lightning current amplitudes incident to transmission lines, in accordance with the EGM attachment process. Section 5 provides the information on the implementation of the Monte Carlo method and its coupling with the EMTP simulation running in the batch mode. A test case of the HV transmission line, along with the sensitivity analysis, is provided in Section 6, which is followed with the conclusion in Section 7.

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. [8–10,23,24]. A brief outline of the EMTP-ATP 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 (i.e. archorn) flashover characteristic, (v) lightning current and lightning-channel impedance. A screenshot of the main part of the TL model, constructed within the ATPDraw preprocessor to the EMTP-ATP software package, is presented in Fig. 1.

2.1. Phase conductors, shield wire(s), spans, line termination, power frequency voltage

High voltage transmission line phase conductors and shield wire(s) are modelled as distributed-parameters, untransposed, frequency-dependent, multiphase transmission line, by means of employing the so-called LCC component of the EMTP-ATP which utilises the JMarti TL model [6,7,25]. 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, ground resistivity of the ground return path, etc. The electromagnetic coupling effects of TL phase conductors and shield wire(s) are accounted for by this model. However, the effects of corona on the propagation of lightning surge on the conductors are neglected in this model. Five spans of the transmission line, at each side of the tower being struck by lightning, are modelled in this way, using eight decades with ten points per decade in the JMarti frequency-dependent model, with the modal transformation matrix computed at the (dominant) frequency of 400 kHz [6,7]. After the fifth span, at each side of the struck tower, additional 30 km of the transmission line is modelled in the same way, and the line model is then terminated by an ideal, grounded, power-frequency, three-phase voltage source.

2.2. Transmission line towers

The steel-lattice towers of HV transmission lines are usually represented as a single conductor, distributed-parameter (frequency-independent) lines. The towers of EHV and UHV transmission lines, on the other hand, are represented using more complicated so-called multi-story structures, which are not considered adequate for HV transmission lines, e.g. [14]. The single value of the tower surge impedance is computed from the analytical expressions, based on the theoretical background provided in [26], which depend on the tower configuration and can be found

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