Electrical Power and Energy Systems 90 (2017) 256–266

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

# Transformer insulation coordination using volt–time curve and limit–state surface formulation

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ARTICLE INFO

*Article history:*
Received 11 July 2016
Received in revised form 15 December 2016
Accepted 20 February 2017

*Keywords:*
Insulation coordination
Limit–state surface
Lightning
EMTP–ATP
Systematic simulations
Volt–time curve

ABSTRACT

This paper presents a novel method for the power transformer insulation coordination, based on the risk of failure analysis due to lightning surges, that uses its insulation strength volt–time curve and a limit–state surface formulation. The limit–state surface is derived in a novel way, from the optimal number of systematic numerical simulations of transformer terminal overvoltages—emanating from station impinging lightning surges—while accounting for the transformer insulation volt–time curve and surge arresters protective characteristics and disposition. The proposed method further employs a state-of-the-art transmission line (TL) and substation equipment models for lightning-surge transient analysis, constructed in the EMTP software package. It also uses the electrogeometric model of lightning attachment to TLs, in order to estimate the expected number of direct lightning strikes, along with a bivariate statistical distribution of lightning currents. The main aspects of the proposed method are demonstrated by means of the computational example featuring an air-insulated substation power transformer lightning insulation coordination. Simulation results exhibit many benefits of the proposed method. Sensitivity analysis further reveals different influences that the various model parameters have on the transformer insulation coordination design.



## 1. Introduction

According to the IEC Std. 60071-1, insulation coordination of high-voltage (HV) substations is a complex process of the selection of dielectric strength of equipment in relation to the operating voltages and overvoltages that can appear on the system for which the equipment is intended, while taking into account the service environment and the characteristics and disposition of the available surge-protective devices [1]. This necessitates considering different types of voltage stresses [2–4]: (i) temporary overvoltages, (ii) slow-front overvoltages, (iii) fast-front overvoltages, and in case of gas-insulated switchgear (iv) very-fast-front overvoltages. Temporary overvoltages are of particular importance in determining rated voltages and stresses related to the energy capability of metal-oxide surge arresters (MOSA). Slow-front overvoltages play a vital role in determining the energy duty of surge arresters and in the selection of air-gap insulation distances. Fast-front overvoltages are studied in order to determine the equipment required withstand levels in relation to the physical MOSA disposition, and to evaluate subsequent station performance and risk of failure due to lightning transients.

Three different methods are, in general, available for the substation insulation coordination study [1–3]: (a) deterministic, (b) semi–statistical, and (c) statistical method. Deterministic method of insulation coordination is based on the most representative fixed values of the overvoltage and insulating capacity, and establishes a certain gap (i.e. safety factor) between these values, with which the rated withstand voltages can be calculated. Applications of this type of approach are used in Japan [5] and some other countries. In the semi–statistical and statistical methods, the entire statistical distributions of the overvoltages and insulating capacity must be suitably determined, with coordination achieved by prescribing appropriately graded failure probabilities for insulation dimensioning. In statistical method, furthermore, provision must be provided for all the different configurations of the station which may exist in service. All three methods are employed in estimating slow-front and fast-front overvoltages and can make use of the electromagnetic transients analysis programs (EMTP), which is the preferred way, or they can be more-or-less analytical in nature. Statistical methods can be time consuming, when seen from the CPU time standpoint, due to the high number of simulation runs needed to implement them; this is especially true with the full statistical method. It is the intention of this paper to exclusively deal

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http://dx.doi.org/10.1016/j.ijepes.2017.02.016
0142-0615/

with the substation fast-front overvoltages due to lightning phenomena emanating from the backflashovers on incident transmission line towers.

Classical and statistical insulation coordination procedures are thoroughly explained in [1–4], while further information can be found in, e.g., [6–8]. Different statistical approaches to the insulation coordination have been proposed, e.g., [9–12]. The limit–state surface formulation approach to the insulation coordination can be seen as a part of the ensemble of statistical methods. The main advantage of this approach stems from the fact that it uses a systematic simulation of lightning surge responses and does not need to employ a Monte–Carlo method (which is known to be time consuming and expensive from the CPU time standpoint). One possible approach to insulation coordination—which utilizes the limit–state surface formulation—has been proposed in IEC TR 60071-4. However, this particular approach is limited to the applications concerning the self-restoring insulation and necessitates usage of the statistical distribution of equipment's insulation capacity, which is very difficult to obtain in case of power transformers. With the approach of IEC TR 60071-4, the limit–state surface is established in the coordinate space of lightning current amplitudes and equipment terminal overvoltages. Furthermore, it presupposes a functional (not statistical) relationship between lightning current amplitudes and wave-front times. Another possible approach, which also utilizes the limit–state surface formulation, has been proposed in Ref. [13], where the limit–state surface is established in the coordinate space of lightning current amplitudes and steepnesses (where steepness is obtained indirectly from the time to backflashover and the time-of-arrival of surge at the equipment terminals). This approach, however, assumes that the insulation breakdown characteristic of the investigated apparatus is constant and equal to its basic insulation level (BIL), without any statistical dispersion, and independent of the overvoltage wave-shape or duration. Also, statistical approach proposed in Ref. [11] can be seen in terms of the limit–state surface formulation, where, again, a functional relationship between lightning-current amplitudes and wave-front times was stipulated.

Here proposed method is part of the statistical ensemble of methods and employs the limit–state surface formulation that is here derived in a novel way—by means of the EMTP simulation runs and the usage of the transformer insulation volt–time curve, which is dependent on the overvoltage wave-shape and duration. The limit–state surface is constructed in the coordinate space of lightning current amplitudes and wave-front times, without imposing any functional relationship between lightning current statistical variables. Method execution time is kept low by using systematic simulations approach and optimizing the number of simulation runs, as will be explained later on. Furthermore, proposed method employs a state-of-the-art transmission line (TL) and station equipment models for lightning-surge transient analysis, constructed within the EMTP–ATP software package. It also makes use of the electrogeometric model (EGM) of lightning attachment to transmission lines in order to estimate the expected number of direct lightning strikes. The method also takes regard of the following aspects of the phenomenon: keraunic level; statistical depiction of lightning-current parameters (including statistical correlation); EGM of lightning attachment process; frequency-dependence of TL parameters; tower footing impulse impedance (with soil ionization); non-linear behaviour of the insulator strings flashover characteristic; power frequency voltage; physical layout and disposition of the substation equipment; characteristics of surge–protective devices (including lead length). However, the method does not take into the account following aspects: "open breaker" situation, shielding failures, strokes to midspan, subsequent strokes, positive lightning strokes, lines without shield wire(s), and station reconfiguration due to switching. Notwithstanding that, the method facilitates a relationship between the transformer risk of failure due to lightning, price of that risk, and investment costs of the surge-protective measures—enabling the cost-effective optimization of insulation coordination design.

The paper is organized in the following manner. Section 2 provides the main exposition of the proposed method for the transformer insulation coordination due to lightning surges, utilizing the limit–state surface formulation and a transformer insulation volt–time curve. It also features necessary statistical treatment of lightning current parameters, estimation of the number of direct lightning strikes to transmission line, and the main aspects of the transmission line and substation equipment modelling guidelines for fast-front transients analysis. An air-insulated substation power transformer lightning insulation coordination example is provided in Section 3, which includes a sensitivity analysis and a discussion of results. It is followed with a conclusion in Section 4.

## 2. Transformer insulation coordination due to lightning surges

Substation lightning transients emanate from the shielding–failures and backflashovers on the incident transmission lines, where the backflashover events on the first few TL towers, as seen from the substation entrance, are of particular interest and importance for the station equipment insulation coordination [2,3]. Hence, electromagnetic transient analysis of these events features prominently in any substation insulation coordination procedure. Besides that, substation power transformer, being the most expensive single piece of equipment, deserves special treatment and attention when it comes to the substation insulation coordination design. This is reflected in the selection of the MOSA parameters and in-particular their physical layout. At the same time, investment in the surge-protective equipment and ancillary measures is perceived as buying insurance. Hence, risk assessment and risk-based insulation coordination can bring considerable savings, through the cost-effective optimization of the complex interactions of: equipment insulation levels, MOSA characteristics, equipment disposition and station layout, grounding resistance, etc. The risk is determined, for a certain time window, from the number of dangerous events and the probability associated with those events. Any additional substation peculiarities need to be considered, such as: transformer age (old/new) and importance, site keraunic level, shielding–failure and backflashover rates of incident TLs, height above the sea level, and pollution level.

### *2.1. Transformer insulation strength volt–time curve*

Transformer insulation strength can be represented by a continuous curve, according to the analysis presented in [14, Ch. 13] and [15, Ch. 3]. An original proposal of this curve was introduced in Ref. [16], accompanied by a thorough investigation of the various implications emanating from the transformer ageing and other impacts (overvoltage stresses, moisture ingress, insulation deterioration, etc.). Namely, to proof-test the insulation structure of a transformer a number of tests are applied, e.g., impulse, induced, and high potential tests, where each is designed to test the insulation structure for a different system condition. The purpose of applying this variety of tests is to substantiate adequate performance of the insulation structure for all the various transient, dynamic, and system voltages the unit will see in service [16].

The transformer insulation strength curve is constructed through the following test points [14, Ch. 13]: (1) front of wave test equal to the 1.3–1.5 of the transformer BIL, plotted at a time of 0.5 μs; (2) chopped wave test at 1.1 of BIL, plotted at a time of 3 μs; (3) full wave test voltage, i.e. the BIL, plotted at 8 μs; (4) switching impulse test, i.e. the basic switching level (BSL) equal