Journal of Electrostatics 93 (2018) 43–51

Contents lists available at ScienceDirect

Journal of Electrostatics

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

Application of genetic algorithm in designing high-voltage open-air substation lightning protection system

P. Sarajcev[a,*], D. Jakus[a], J. Vasilj[b], S. Vodopija[a]

[a] *University of Split, FESB, Department of Power Engineering, R. Boskovica 32, HR-21000, Split, Croatia*
[b] *Chalmers University of Technology, Signals and Systems Department, Maskingränd 2, 412 58, Göteborg, Sweden*

ARTICLE INFO

Keywords:
Genetic algorithm
Lightning
LPS
Optimisation
Shielding
Substation

ABSTRACT

This paper introduces application of genetic algorithm (GA) in designing air-termination system of the high-voltage (HV) open-air substation external lightning protection system (LPS). As far as the authors are informed, this is the first proposal for using GA in designing LPS of substations. The complex air-termination system, as a part of the external LPS of HV substation, is known to be cumbersome to design using traditional techniques, where optimisation is often relegated to the trial-and-error approach. In addition, traditional methods are often associated with geometric constraints and implementation difficulties. This paper proposes a novel approach which utilizes a combination of statistical LPS efficiency and GA in designing techno–economically optimal external LPS of open-air substations. The LPS optimisation problem is particularly well suited to the GA solution approach, due to the stochastic nature of lightning, expert knowledge involved in constructing the fitness function, and the fact that the optimal solution is not, strictly speaking, a unique value (it can be obtained using different combinations of the air-termination system elements). Proposed approach offers a LPS designer unique and valuable assistance in optimally arranging elements of air-termination system for obtaining maximum lightning shielding effects with minimum total investments.

1. Introduction

Designing an air-termination system of the external lightning protection system (LPS) of high-voltage (HV) open-air substation (AIS) is a complex task, exacerbated by the stochastic nature of lightning and complicated 3D geometry of the station's equipment arrangement [1–3]. The design of the air-termination system, as a crucial part of the external LPS, is concerned with strategic positioning of vertical conductors (rods) and/or horizontal conductors (wires), in order to obtain lightning protection zones (areas) which surround and encompass station's equipment as far as possible. These zones are fictitious entities, created either by using [3]: (a) shielding angle model, (b) empirical curves, or (c) electrogeometric model (EGM) of lightning attachment. The shielding angle model is based on the simple “rule of thumb” (i.e. uses fixed angles) established by past experience. Empirical curves have been derived from scale model tests and field experience, and they include effects of the structure height on shielding. The EGM model has many different incarnations, from the “rolling sphere” method developed by Lee [4] and Horváth [5], to different variants developed by, e.g., Sargent [6], Linck [7], Mousa [8], and Chowdhuri [9], to name only a few of the more prominent ones. Added to that, several researchers have extended and adapted EGM approach in different ways, most notably Eriksson [10] and D'Alessandro and Gumley [11]. Statistical approach to the LPS design has been initially proposed by Sargent [6] and later extended and adapted in different ways by others, e.g., [12–17]. A strongly disputed and controversial method of lightning protection, which is based on lightning prevention concept (and uses so-called “lightning preventors”), has been proposed by Carpenter and Auer [18]. Finally, several researchers have recently proposed different, very sophisticated, physics-based, lightning attachment models; see Ref. [19] for more information.

In designing external LPS using traditional techniques, further complexities arise from Refs. [2,3,20–22]: (i) differences between IEC and IEEE standards, (ii) allowable stroke current levels with adjustments for open-end points, (iii) differences between EGM variants, (iv) possible usage of different methods for horizontal and vertical shielding elements, (v) usage of different shielding failure rates, (vi) application of partial shielding concepts, (vii) usage of different statistical distributions of lightning amplitudes, (viii) multiple voltage levels within the station, (ix) different keraunic levels and orographic factors, (x) effects of hillside, (xi) possibility of side lightning strikes, and (xii) conservatism exercised by the design engineer.

---

[*] Corresponding author.
E-mail addresses: petar.sarajcev@fesb.hr (P. Sarajcev), damir.jakus@fesb.hr (D. Jakus), vasilj@chalmers.se (J. Vasilj), stipe.vodopija@fesb.hr (S. Vodopija).

https://doi.org/10.1016/j.elstat.2018.03.003
Received 3 October 2017; Received in revised form 31 January 2018; Accepted 8 March 2018

Interested reader is at this point advised to consult [20,21] for more information and further exposition of different traditional approaches to the air-termination system design (also termed station lightning shielding). A review of the “striking distance” concept, with certain repercussions for the EGM, is given by D'Alessandro in Ref. [23]. Several notable critical reviews of the current international lightning protection standards are given in Refs. [22,24–27]. Further information on the state-of-the-art and recently developed physics-based models (not covered by present standards) can be found in Refs. [19,28,29].

In creating LPS shielding zones (areas), designer needs to propose some initial arrangement of shielding conductors and apply one of the above-mentioned methods. If the derived protection zones do not encompass equipment, for a preselect lightning-current level and/or shielding failure rate, designer needs to make changes to the disposition of air-terminations (change position and/or height of existing and/or add additional horizontal/vertical conductors) and conduct another analysis. This process is iteratively continued until satisfactory zones have been created, which is laborious and time-consuming. Moreover, this process of positioning and re-positioning of air-terminations is a trial-and-error process in which designer is guided by past experience and several analytical (and/or graphical) techniques [3]. Namely, there are no certain guarantees that the re-positioning of the parts of the air-termination system, between successive iteration steps, will actually improve the overall LPS design. In other words, there is no comprehensive optimisation involved in the traditional approach to the LPS design. Hence, the main purpose of this paper is to address this deficiency.

The aim of this paper is to recast the problem of the LPS design of the AIS as an optimisation problem, and to further approach it from the statistical perspective in order to fully account for the stochastic nature of the lightning phenomenon. For that purpose, large number of lightning strikes are simulated by means of the Monte–Carlo method [6,14,15,17]. The peak values of the lightning currents are randomly chosen from the appropriate Log–Normal distribution. Each lightning strike starts its descend from a plane above the AIS (i.e. fictitious cloud base) and follows a stochastic path towards the earth surface. Minimal distance from the lightning stroke stepped leader head to the elements of external LPS, AIS equipment, and earth surface is computed after each jump, as will be explained in detail later. If this distance is smaller then the “striking distance,” in accordance with the EGM, lightning will strike its nearest point belonging either to the LPS, station equipment, or the earth surface. Efficiency of the LPS is obtained from a quotient between the number of lightning strikes ending up on the LPS itself and the total number of lightning strikes (where strikes hitting the earth surface are not counted).

In addition, on top of the Monte–Carlo method, genetic algorithm (GA) is employed to guide the LPS design toward the optimal disposition of air-terminations [30], i.e. that which has the highest stochastic efficiency with a minimal design investments. This is the first proposal for using GA in designing LPS of substations, as far as the authors are informed, although GA has been successfully applied in several different engineering fields, e.g., [31–34]. The LPS optimisation problem is particularly well suited to the GA solution approach, due to the fact that the optimal solution is not, strictly speaking, a unique value (it can be obtained using different combinations of air-termination system elements). A particular expert knowledge and heuristics is incorporated in constructing the fitness function of the GA method, as will be explained in detail later. This combination of stochastic efficiency and GA optimisation provides a LPS designer with a valuable assistance in optimally positioning elements of the LPS for obtaining maximum lightning shielding effects with minimum total investment.

The paper is organized in the following manner. Section 2 provides the mathematical background of the stochastic LPS efficiency analysis. Section 3 features exposition of the GA application to the problem of LPS design optimisation, with a particular emphasis on the fitness function construction. An example of the substation LPS design optimisation using GA is provided in Section 4, along with a discussion of results, which is followed by the conclusion in Section 5.

2. Stochastic LPS efficiency

For the purpose of the substation LPS design, only (downward negative) lightning-current amplitude is of importance. It is statistically distributed according to the Log–Normal distribution, with a following complementary cumulative distribution function [35,36]:

$$P(I) = \frac{1}{\sqrt{\pi}}\int_{u_0}^{\infty} e^{-u^2}du = \frac{1}{2}\cdot erfc(u_0) \tag{1}$$

where *erfc* is the statistical complementary error function and

$$u_0 = \frac{\ln I - \ln \mu}{\sqrt{2}\cdot\sigma_{\ln I}} \tag{2}$$

with μ and $\sigma_{\ln I}$ representing, respectively, median value and standard deviation of the (natural logarithm of) lightning current amplitudes. Following parameters are often used: $\mu = 31.1\ (kA)$ and $\sigma_{\ln I} = 0.484$, as recommended in Ref. [36].

A large number of pseudo-random lightning current amplitudes are drawn from the Log–N(μ, $\sigma_{\ln I}$) distribution in the following manner. Lightning probability distribution is first confined to the interval $[I_{min}, I_{max}]$ in order to reduce the number of simulations (i.e. eliminate those with very large amplitudes), and then subdivided into an arbitrary number of classes (N_c), where a span of each class equals to $\Delta I = (I_{max} - I_{min})/N_c$. Random currents are distributed into the appropriate classes, with the aid of random numbers drawn from the standard uniform distribution $r \sim U(0,1)$, as follows:

$$I_c = I_{min}^i + r\cdot(I_{max}^i - I_{min}^i) \tag{3}$$

with a class boundary currents for the i–th class given by:

$$I_{min}^i = I_{min} + (i-1)\cdot\Delta I \tag{4}$$

$$I_{max}^i = I_{min}^i + \Delta I;\quad i = 1, \ldots, N_c \tag{5}$$

Approximate number of random currents belonging to the i–th class can be estimated from the following expression:

$$N_i = N\cdot[P(I_{min}^i) - P(I_{max}^i)] \tag{6}$$

where N is the total number of lightning strikes used for the Monte–Carlo simulation.

The AIS equipment and external LPS elements are represented by straight segments (or triangles in case of surfaces) within the global Cartesian coordinate system, such that the xy-plane ($z = 0$) coincides with the earth surface [6,14,15]. In case that a station (or its part) is situated on a sloping terrain, its geometry is transformed to a flat plane by projecting it with a cosine of the slope angle. Hence, parts of station extended over multi-level terrain, and/or having different voltage levels, can be treated simultaneously. This is an improvement over the traditional approaches, where different voltage levels are associated with different allowable stroke currents and need to be treated separately.

A large number (N) of successive lightning strikes is initiated from the starting surface A_0, representing cloud base and located on some height z_0 above the earth surface (centred above the AIS), satisfying the condition $A_0 \ll A_d$, where A_d is the “collection area” of the AIS [2,28]. It is known that the lightning stroke development, i.e. stepped leader descent, follows a number of quick jumps along a stochastic (and often tortuous) path. During the Monte–Carlo simulation, each lightning strike starts its descent at some point stochastically chosen on the surface A_0 and progresses downward in a series of stochastic jumps towards the AIS or the earth surface. Fig. 1 graphically depicts the situation of a stepped leader development with its head at some point T_{j-1} in the 3D space, between the cloud base and the earth surface, making a jump toward the point T_j. The stepped leader head is associated with