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# Lightning protection system design for distribution networks based on System Average Interruption Frequency minimization

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ABSTRACT

The effects of lightning are the main cause of interruptions in electrical networks (distribution feeders), imposing a crucial impact on power quality and reliability. An exhaustive review of the state of the art shows that avant-garde solutions have not yet presented explicit mathematical models that relate the interdependence of these two phenomena. This paper presents a novel mixed integer linear programming (MILP) model to be utilized in the design of lightning protection systems (LPS) and which aims at minimizing sustained and momentary interruptions in distribution networks while leveraging investment costs. The proposed model considers a selection of different shielding structures and grounding systems. The constraints of the optimization model include technical and economic aspects of LPS implementation. A case study considering a real distribution feeder with 81 buses is presented. Test results highlight the generality of the proposed model and illustrate the potential for real-life application. It is worth pointing out that the proposed optimization model is currently used by a distribution utility as a reliability-oriented tool for LPS design.



## 1. Introduction

The effect of lightning on distribution feeders is manifested in two ways, first by direct impacts on overhead distribution lines and second by indirect discharges that occur when lightning strikes the ground and which induce an overvoltage in the insulation strings. Lightning clearly has a significant influence on power system behavior, that is why this phenomenon has been seriously considered by different countries in order to find strategies that increase the reliability of power systems and reduce outages caused by hazardous weather [1].

Several studies demonstrate that power systems are susceptible to the phenomenon of lightning and attribute frequent interruptions to this phenomenon [2]. Moreover, the South American region has the highest flash peak intensity of the world [3–5].

Distribution feeders are very vulnerable to weather conditions due to their low level of insulation. In this context, it is highly desirable to improve the reliability of the distribution systems. Therefore, an adequate design of structures and grounding is required as protection against lightning. Lightning protection system designs play an essential role in distribution network reliability. Lightning poses an increasing concern for distribution utilities and is considered the most frequent cause of momentary and sustained interruptions on overhead distribution lines [6]. Direct and indirect lightning strokes can cause dangerous overvoltages which result in damages to electrical equipment and in power supply interruptions.

According to Refs. [6] and [7], the methods for improving the performance of overhead distribution systems against lightning are:

- increasing the CFO level of insulation;
- installing lightning arresters at suitable positions;
- increasing the system's CFO by using a wood pole or a standoff;
- installing shielding wire over the phase conductors;

*Abbreviations:* CFO, critical flashover voltage; GAMS, General Algebraic Modeling System; LPS, lightning protection system; MILP, mixed integer linear programming; SAIFI*, System Average momentary and sustained Interruption Frequency Index.

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- decreasing the grounding resistance.

In distribution system planning, the selection and placement of an adequate type of lightning protection systems (LPS) is a challenging task [8,9] due to combinatorial nature of the problem, which could include non-differentiable objective function and constraints. Thus, for LPS design, utilities usually exploit empirical engineering knowledge, historical reliability data and other technical considerations [10–12].

Several studies have shown different focuses of optimization in a LPS design. A cost-effective solution to finding the optimum location of surge arresters on a power network, which in turn can minimize the global risk of the network and improve its reliability based on a genetic algorithm approach is described in Ref. [11]. Insulation and arrester failure as well as lightning performance are considered in the objective function.

The mixed integer linear programming (MILP) applied to power systems optimization shows better convergence characteristics and robustness than other evolutionary-based methods such as particle swarm optimization [15], genetic algorithm [11–14], ordinal optimization [10] and imperialist competition [15–18]; as well as quasi-Newton optimization methods [19]. Whereas empirical methods used by utilities yield reasonable results, power systems' optimization requires information regarding solutions' optimality in order to obtain the best performance. For this purpose, several optimization methods are currently being used. Among them, the MILP has demonstrated reaching the global optimum solution in a reduced computational time [20,21].

According to recently published works [22–27], optimization of LPS for distribution networks is still an open research field. In this paper, a LPS design is addressed through a MILP model in order to minimize a compound index that measures the system's average frequency of momentary and sustained interruptions. The proposed model considers all momentary and sustained interruptions as well as the number of affected customers in a LPS design strategy while leveraging inherent solution costs. The optimal solution of the model is found by using branch and bound-based solvers that guarantee the global optimal solution for MILP models. In order to evaluate the proposed LPS design model, an actual 81 bus distribution network is considered in this paper. Test results show the viability and generality of the proposed optimization model.

The remainder of this paper is organized as follows: Section 2 describes the proposed methodology to obtain the critical current and the fault rate due to lightning incidence, as well as the proposed optimization model. The case study is presented in Section 3. In said case, a reduced system of 4 buses is used for validation and the complete 81 bus system is used to show general results. The conclusions of this work are summarized in Section 4.

## 2. Proposed methodology

In this work the impact of lightning on a system's reliability is quantified by estimating the average number of customers affected by momentary and sustained interruptions due to lightning incidence. The flowchart of the proposed methodology is shown in Fig. 1. Each step involved in the proposed approach will be described in the following sections.

### 2.1. Critical current estimation

Transient overvoltages in electric power systems are strongly dependent on the peak value and on the rise time of the current, and have a significant influence on the supportability of equipment insulation [6]. The most important parameters used in the specification of materials and devices related to lightning protection are:

- surge current characterized by its peak value and waveform;
- energy transferred to the affected equipment.

The assessment of distribution system performance under lightning conditions requires a model of the lightning source and of the system components. Several studies have been published concerning power system modeling in transient analysis [6,28,29].

Direct flashes to the power line and induced overvoltages from flashes occurring nearby may trigger flashovers and back flashovers. The first return stroke current can be described taking into consideration its shape and characteristic parameters. In this work, lightning and system components are modeled in accordance with Refs. [30–36]. The guidelines are summarized below:

- The lightning flash was modeled by a Heidler-type surge current generator [35]. Currently, the Heidler equation has greater acceptance to represent the behavior of the first return stroke current [36].
- The feeders were modeled by three spans at each side of the point of lightning impact. Each span is represented by a multiphase non-transposed line section. The line section is represented by distributed and frequency-dependent parameters (type JMARTI). Parameters were obtained for a frequency of 500 kHz [30–34].
- Line endings were needed at each side of the above-mentioned model so that reflections would not affect the simulated overvoltages around the point of impact. According to Refs. [30–34], this was achieved by the connection of an impedance equal to a 3 km line surge impedance at each end.
- The main grid was modeled by a voltage source and impedance that represents the short circuit impedance of the system [30–34].
- Wooden poles and a grounding system were modeled by series connected impedances. Both impedances were calculated according to Refs. [30–34].
- Insulators were modeled as voltage-dependent switches [30–34]. The insulation failure occurs when the voltage exceeds the CFO.

ATPDraw [37] and TACS-MODELS [38] were used to obtain the critical current for each LPS topology under simulation conditions summarized in Table 1. The peak current of the simulated lightning was gradually increased until a flashover has occurred. This threshold value of the current is defined as the critical current ($i_0$).

### 2.2. Flashover rate estimation

Eq. (1) is used for estimating the probability of a first-stroke current peak value $I_0$ being higher than $i_0$ [6,39,40].

$$P(I_0 \geq i_0) = \frac{1}{1 + \left(\frac{i_0}{31}\right)^{2.6}} \tag{1}$$

Where:

$P(I_0 \geq i_0)$ is the probability that the first return stroke has a peak current $I_0$ that is higher than $i_0$;

$i_0$ is the prospective first return stroke peak current (kA).

Thus, through Eq. (1) it is possible to obtain a probabilistic distribution of lightning currents that may produce a flashover.

#### 2.2.1. Direct strokes

The vulnerability to lightning impact of a distribution feeder may depend on its location with respect to neighboring structures. Feeders located on elevated areas such as mountains or hills are