Surge Arrester Optimal Placement in Distribution Networks: A Decision Theory-Based Approach

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***Abstract*—The study introduces a novel method for optimizing surge arrester placement in the distribution line to mitigate lightning-induced overvoltages, employing a single-objective optimization algorithm. The study assesses the effectiveness of two types of surge arresters concerning discharge energy in reducing lightning overvoltage. Moreover, the comparative analysis takes into account the transfer of overvoltage performance from protected to unprotected towers, highlighting its significance in estimating flashover rates under different protection alternatives. Decision theory analysis is employed in the present study to identify optimal arrester locations. The study aims to minimize the expected flashover rate and identify the most effective protection strategy by considering futures/scenarios associated with different values of peak current and lightning locations. The results of numerical applications also showed the substantial impact of lightning surge transfer within the network, emphasizing the imperative to incorporate this phenomenon into lightning protection modeling.**

***Index Terms*—Lightning-induced overvoltages, surge arresters, lightning protection, medium voltage distribution system, location optimization**

I. Introduction

Lightning is one of the main causes of power outages on distribution networks. Lightning surges cause severe equipment damage in overhead as well as underground distribution networks [1], [2]. The impact of lightning can be particularly significant and frequent in regions with a high ground flash density. Ground flash density is a measure of lightning activity and is typically expressed as the number of flashes per square kilometer per year (flashes/km^2/year) [3]. The lightning events may be direct or indirect, based on the location of the strike. Direct lightning indicates the strike on the conductors or equipment of the overhead power line. The high energy from the produced current of the lightning strike can lead to equipment failure, melted, or burned components, and even structural damage. On the other hand, indirect lightning refers to strikes on the ground or an object nearby, creating a surge of electrical energy [4]. The surge can induce a high voltage in the distribution line, which can travel along the conductors and cause damage to sensitive equipment, such as transformers, circuit breakers, and other electrical devices connected to the distribution network [5]. Therefore irrespective of the type of lightning based on its location, protective measures, such as lightning arresters, grounding systems, and surge protection devices, are crucial to mitigate the potential damage from lightning strikes and ensure the resilience of distribution networks. [6].

This study specifically focuses on protection mechanisms for indirect lightning events in distribution lines. While the protection measures for direct and indirect lightning are generally the same, there is a notable difference in their frequency of occurrence. Indirect lightning events tend to happen more frequently in distribution lines compared to direct lightning strikes [4]. Acknowledging this higher occurrence rate of indirect lightning is crucial for designing effective protection strategies for distribution lines to mitigate the associated risks and ensure reliable power supply. The voltages induced on distribution lines by indirect lightning are typically below 300 kV. For lines with critical flashover voltages (CFO) exceeding 300 kV, the induced flashovers are not a concern, while when dealing with lines with lower CFO values the voltages induced have a greater impact [7].

To mitigate the impact of lightning on distribution networks, various solutions have been proposed, including the installation of surge arresters (SAs), lightning rods, and shield wires (SW) that include overhead ground wire (OHGW) and underbuilt shield wire. These measures can help divert lightning strikes away from critical equipment and reduce the risk of outages [8]–[13]. By understanding the impact of lightning on distribution networks and implementing appropriate measures, utilities can improve the reliability of their networks and minimize the impact of outages on their customers [14].

SAs are effective protective equipment to reduce insulation flashover due to direct and indirect events. SAs are installed parallel to the line insulators between the phase conductor and tower structure and operate with high impedance during normal voltage levels [15]. Installation of SA in the network is simpler than reducing the tower footing resistance and is an alternative to avoid shielding failure [16]. The commonly used surge arrester is the metal oxide varistor (MOV) type, which is gapless and referred to as a non-gapped line arrester (NGLA); an updated device compared to the gapped

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silicon carbide arrester. In the distribution power lines, the MOV heavy-duty type SA is used in the transformers and riser poles (transition point from overhead to underground system and vice versa). MOV normal duty type SAs (tested to a charge level 35% lower than the heavy-duty type) are used in the overhead distribution lines towers and poles [17]. Externally Gapped Line Arresters (EGLAs) represent a modern and innovative approach to mitigating the effects of lightning-induced overvoltages on overhead distribution lines and towers/poles. Unlike the traditional NGLAs that have been used for an extended period, EGLAs have emerged as a solution that overcomes the limitations associated with NGLAs. EGLAs are specifically designed to provide enhanced protection against power outages caused by indirect lightning strikes. One notable feature of EGLAs is the inclusion of an external gap in their design. This gap allows for controlled and precise energy dissipation, ensuring that the SA can handle high-energy lightning currents while maintaining the integrity of the system. By effectively managing overvoltages, EGLAs contribute to the overall reliability and stability of medium-voltage distribution lines [18]–[20].

In the distribution network, the number of intermediate poles between every substation is higher than the transmission line towers. In this case, installing SA in every pole and every phase of the distribution line becomes expensive [21]. The line arrester is usually installed in high-ground flash-density regions and not in all distribution towers due to economic constraints. Upon considering the technical, economic, and atmospheric criteria several researchers focussed on placing SAs in only one phase or at reduced numbers covering the entire network [21]–[24]. In this case, the system is expected to perform effectively at a limited number of SAs without compromising its purpose.

The optimization of SAs requires careful consideration of several important factors. Understanding the transfer voltage mechanism is crucial for optimizing SAs. This mechanism determines how the arrester responds to overvoltages and diverts excessive energy away from the protected equipment. A comprehensive study of transfer voltage mechanisms enables the identification of optimal arrester characteristics and configurations that effectively suppress overvoltages [25]–[27]. Also, in the optimization of the SA location, the transfer voltage effect on adjacent towers needs to be considered. The transfer voltage effect occurs when the SA operates particularly at the installed towers and diverts the lightning surge to the adjacent towers in case it is unprotected, which can cause overvoltages and flashovers on these towers. This effect can significantly impact the performance of the distribution line, leading to more outages and longer downtime. However, many studies on SA placement only consider the tower where it is installed and do not account for the transfer voltage effect on its unprotected adjacent towers. As a result, the lightning performance of the line may not be fully improved. To optimize the SA installation and accurately assess its effectiveness, it is crucial to consider the transfer voltage effect on adjacent towers in the modelling and simulation.

This paper focuses on the protection scheme for a medium voltage distribution network. The analysis is carried out only for indirect lightning events as the distribution lines are more prone to the indirect type than the direct and consider the transfer voltage effect on adjacent towers in the modelling and simulation. Based on previous research results, the effectiveness of the combination of SAs and OHSW has been taken into account [28]–[30]. Among the various types of SAs, the most used two types of arresters have been analysed, that are NGLA and EGLA. As a cost-effective concern, the optimal location of SAs is taken into consideration. Also, as an improvement to the normally adopted approaches, the decision theory approach is used to choose the optimal location of the devices. Particularly, different futures are considered in terms of peak current and location of the lightning and the lightning performance of the distribution line under various protection design alternatives [31]. Based on the results of these multiple-design alternatives, the best protection alternative is chosen as that characterized by a minimum flashover rate.

The remainder of the paper is structured as follows. The modelling of the distribution network, lightning current, and protection devices are given in Section II. The performance of the distribution line is presented in Section III. Section IV describes the decision theory approach for the optimal location of SAs. Section V, reports the results of numerical applications. Conclusions are drawn in Section VI.

II. Network Modelling

The lightning-induced overvoltage response and the insulator flashover due to indirect lightning strikes are modelled and evaluated using EMTP-RV and LIOV toolbox [32]. The entire network is modelled as follows:

A. Tower Modelling

The towers are modelled as frequency-dependent distributed lines of length equal to the height of the tower. The propagation velocity (v_t) of the travelling wave along the tower is considered to be the velocity of the light (c=300m/μs). The surge attenuation constant (α) is 0.89. The tower impedance is calculated according to its height and base radius; the surge impedance (Z_t) and the grounding resistance (R_G) of the tower result to be 300 Ω and 25 Ω, respectively. The cross-arms of the towers are modelled as an inductor with 1 μH/m [33], [34].

B. Distribution Line Modelling

The entire distribution line is considered unenergized and constructed in the EMTP-LIOV toolbox. The LIOV line represents the overhead distribution and ground wires, that are terminated by the LIOV line matching component to avoid reflections. The line configuration, geometrical points and the outer diameter of the conductors are given as input to the LIOV lines and LIOV line matching components. The main time step of the simulation (Δt) is set as 33.33 ns which corresponds to the space step of Δx=10 m.

C. Insulator Modelling

The insulators of the towers are modelled by a voltage-controlled switch, using the integral method based on the disruptive effect criterion to evaluate the occurrence of flashover: a flashover occurs if the time integral D(t) exceeds a given threshold value DE. The Integral D(t) is given by the following expression [35]:

$$D\left(t\right) = \int_{t_0}^{t} \left(\left|V_{ins}\left(t\right)\right| - V_0\right)^k dt \tag{1}$$

where $V_{ins(t)}$ is the voltage across the insulator, V_0 is the minimum voltage to be exceeded before any breakdown can start, and k is an empirical constant set to 1.0 in this study. When the flashover occurs, the ideal switch across the insulator is closed.

D. Lightning Stroke Modelling

The Heidler model used to represent the lightning current waveform is the most common model and is given by:

$$i(0,t) = \frac{I_0}{\eta} \cdot \frac{\left(\frac{t}{\tau_1}\right)^n}{\left(1 + \frac{t}{\tau_1}\right)^n} \cdot \exp\left(-\frac{t}{\tau_2}\right) \tag{2}$$

$$\eta = \exp\left[-\left(\frac{\tau_1}{\tau_2}\right)\left(n\frac{\tau_1}{\tau_2}\right)^{\frac{1}{n}}\right] \tag{3}$$

where I_0 affects the current peak value, η is the peak correction factor, τ_1 and τ_2 are the time constants influencing the current-rise time and current-decay time and n is the current steepness factor considered as 2 in the entire study [36].

E. Protection Devices Modelling

The shield wire considered in the study is the overhead ground wire (OHGW) type, which is modelled as a transmission line coupled to the phase conductors terminated with a characteristic impedance to avoid reflections (LIOV lines). The shield wire is located in a symmetrical position at a height of 1m above the topmost phase conductor.

The SA is modelled by the IEEE recommended frequency-dependent circuit. The two types of arresters considered in the present study are explained below.

1) Non-Gapped Line Arrester (NGLA): Metal oxide NGLA is one of the most conventional and effective types of SA. Fig. 1(a) shows the recommended IEEE frequency-dependant model arrester. The rating of the arrester is 24 kV with a maximum residual voltage of 56 kV, a nominal discharge current of 10 kA, a maximum continuous operating voltage (MCOV) of 20 kV, and an energy capability of 7.8 kJ/kV of MCOV. The lump parameters of the metal oxide arrester are modeled based on the calculation below [37]:

$$R_1 = 100 \cdot d/n \tag{4}$$

$$R_2 = 65 \cdot d/n \tag{5}$$

$$L_1 = 0.2 \cdot d/n \tag{6}$$

TABLE I: V-I Characteristics of the MO arrester

Current [kA]	**Voltage (V_{10})**	
	A0 (p.u)	**A1 (p.u)**
0.01	0.875	-
0.1	0.963	0.769
1	1.050	0.850
2	1.088	0.894
4	1.125	0.925
6	1.138	0.938
8	1.169	0.956
10	1.88	0.969
12	1.206	0.975
14	1.231	0.988
16	1.250	0.994
18	1.281	1
20	1313	1.006

$$L_2 = 15 \cdot d/n \tag{7}$$

$$C = 100 \cdot d/n \tag{8}$$

where d is the height of the arrester assembly (m) and n is the number of parallel columns of the arrester. These filter impedance and capacitance affect the parallel connected non-linear resistances A_0 and A_1. The V-I characteristics of this non-linear resistance are given in Table I

2) Externally Gapped Line Arrester (EGLA): EGLA consists of an active part of the metal oxide varistor and a non-active series gap as shown in Fig. 1(b). The active part of the arrester is the IEEE frequency-dependent model as described in NGLA. The critical component in determining the turn-on voltage of the arrester is the length of the EGLAs gap in the non-active external circuit. This gap of the EGLA is important to be large enough to withstand temporary overvoltage events, but small enough to spark over before the protected insulator flashes over. The minimum acceptable gap G_{min} setting of an EGLA is determined by three factors: the system voltage (V_{sys}), the expected temporary overvoltage levels (TOV), and a safety factor (SF) [18], [19].

$$G_{min} = 39.37\left[\frac{e^{(V/750)} - 1}{0.55}\right] \tag{9}$$

where V is the minimum gap flashover voltage of the EGLA calculated by

$$\text{V} = \frac{V_{sys}}{1.73} \cdot TOV \cdot SF \tag{10}$$

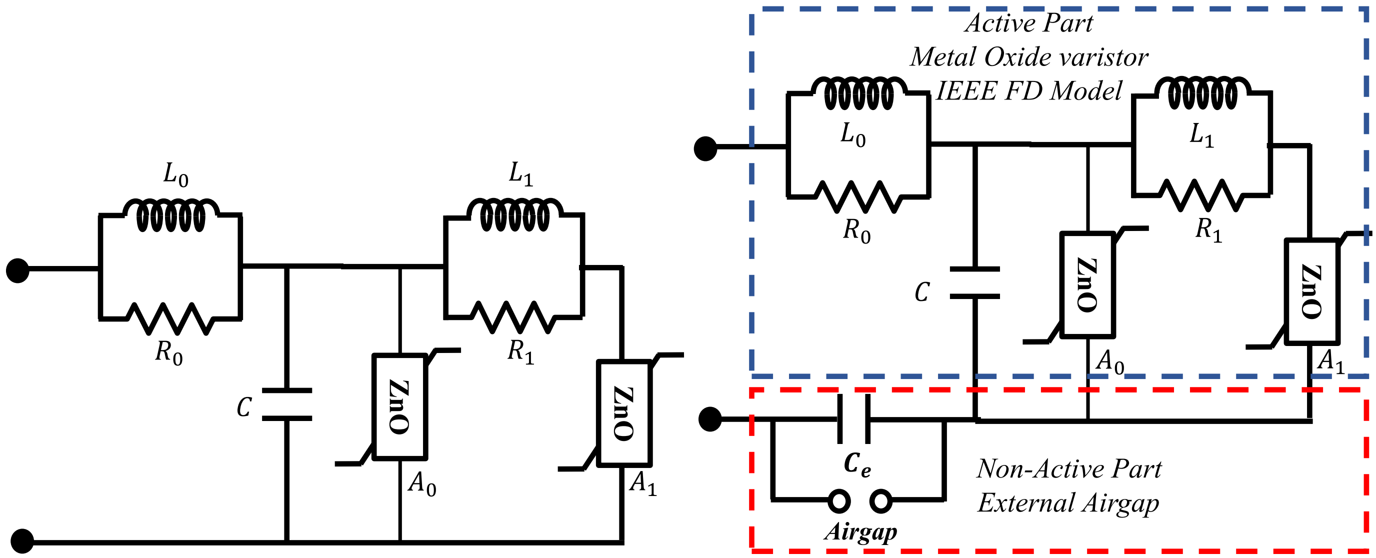
Similarly, the maximum acceptable G_{max} gap is set by the CFO of the protected system and safety factors [20], [27].

$$G_{max} = \frac{V_{CFO} \cdot 0.85}{e_0} \tag{11}$$

where V_{CFO} is the CFO of the insulator string and e_0 is the corona initiation gradient (kV/mm).

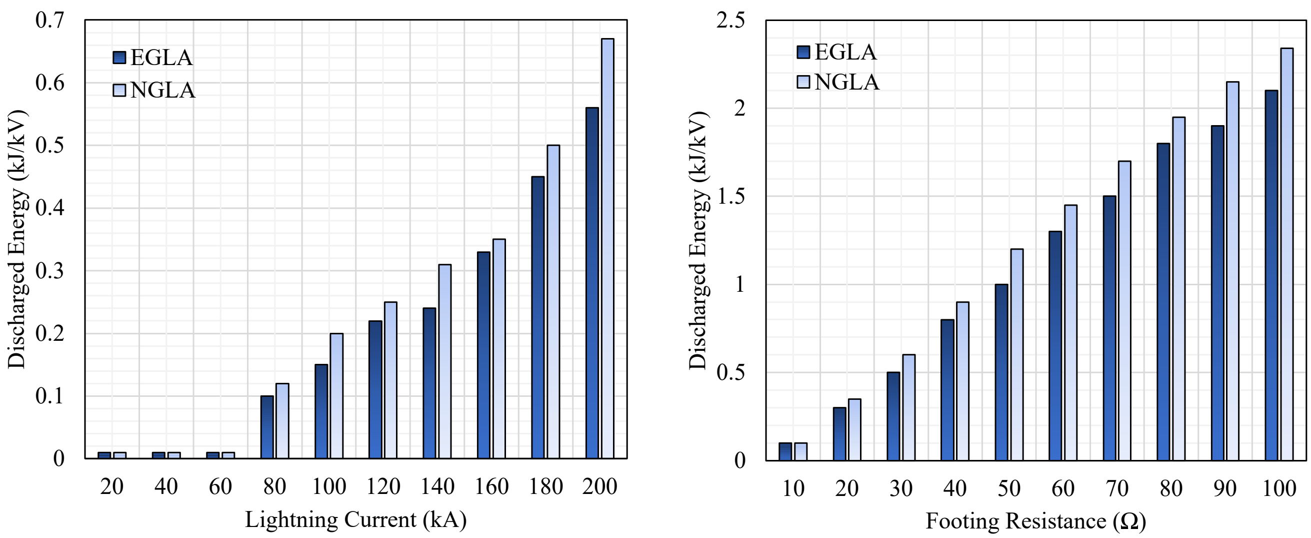
3) Discharged Energy of Arresters: The energy absorbed by the SA before it fails is its energy absorption capability. This absorbed and discharged energy is analyzed for the types of arresters during its operation to measure the probability of arrester failure. The arrester energy is given by

$$E = \int_{t_0}^{t_t} V_A(t) \cdot I_A(t) dt \tag{12}$$



(a) (b)

Fig. 1: (a) Non-gapped line arrester (NGLA) and (b) Externally gapped line arrester (EGLA) model



(a) (b)

Fig. 2: Arrester discharged energy comparison with different (a) lightning current (I_p) and (b) tower footing resistance (R_g)

where E refers to the arrester absorbed energy (kJ), V_A, and I_A are the discharge voltage and current of the SA, respectively, from the instant t_0 of lightning occurrence. The maximum arrester capacity is 7.8 kJ/kV of MCOV.

In Fig. 2(a), the comparison of the discharged energy of the SAs (NGLA and EGLA) is reported for different I_p values ($0\ kA > I_p < 300\ kA$) keeping the R_g constant at 25 Ω. Similarly, the discharged energy comparison with the varying tower footing resistance (R_g = 10 Ω to 100 Ω) at a constant I_p of 31 kA (typical first stroke) is analysed in Fig. 2(b).

III. Indirect Lightning Performance of the Distribution Line

A distribution line setup is considered for the illustration of performance comparison, and indirect lightning strikes are simulated in front of the line towers. The system consists of ten distribution line towers, 60 m apart from each other. Fig. 3 illustrates the arrangement of the towers (T_1 - T_{10}).

A. Transfer Voltage Mechanism

This analysis is conducted on the same distribution line as depicted in Fig. 3. To demonstrate the transfer voltage mechanism, the spacing between successive SAs is set as two towers. For example, among the towers T_1 to T_4, towers 1

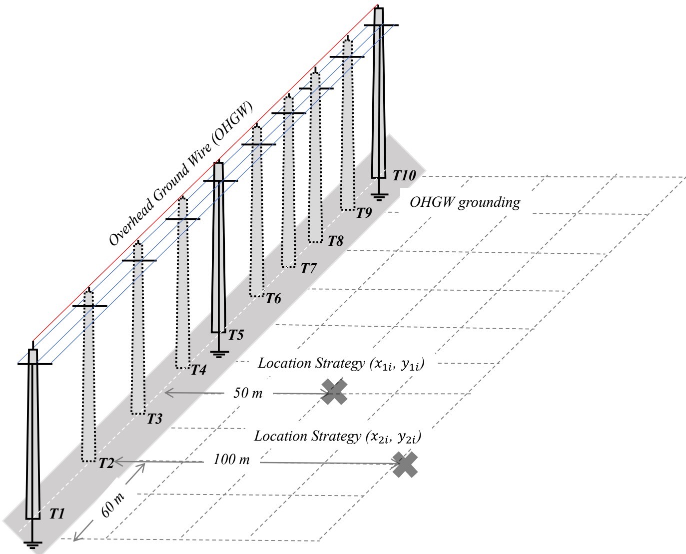


Fig. 3: Representation of simulated distribution line

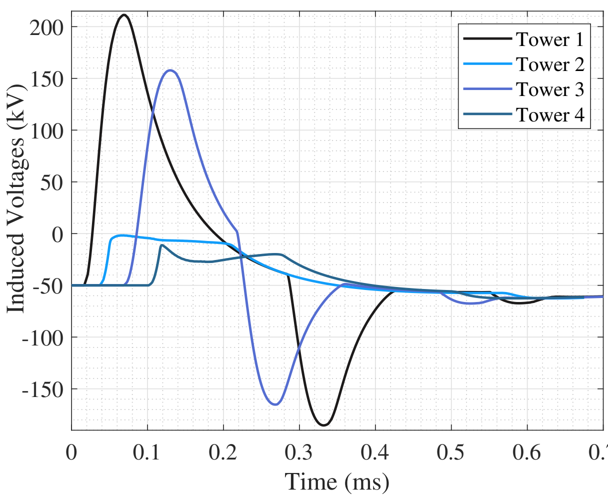


Fig. 4: Illustration of Transfer Voltage Mechanism: Insulator Overvoltage across towers (T_1-T_4)

and 3 are left unprotected, while the remaining towers are equipped with surge protection. By capturing and conducting the surge current, the SAs limit the voltage rise on the protected tower, preventing damage to the tower structure and the connected equipment [26]. While the SA installed on a tower protects that specific tower from lightning-induced overvoltages, nearby unprotected towers may still be susceptible to lightning overvoltages transferred from the protected towers even though they are not struck directly. The following analysis proves the importance of considering the transfer voltage effect in an optimization problem which is an issue that is typically not considered in the technical literature. During the simulation, a lightning strike is induced 50 m in front of tower T_1. This setup allows for the investigation of the transfer voltage phenomenon in the distribution line, considering the specific arrangement and placement of surge arresters along the line under indirect lightning strikes. The results presented in Fig. 4 reveal that the insulator flashover occurs at 623 kV for Tower T_1. Tower T_2, protected by SAs, remains unaffected by flashover. However, the transfer of voltage to the unprotected Tower T_3 leads to an insulator flashover at 565 kV. Tower T_4, being protected, successfully prevents flashover, maintaining the voltage between 70 to 80 kV (MCOV). The analysis indicates that the transfer voltage effect occurs depending on the lightning strike intensity, affecting multiple unprotected towers. This effect is observed for both EGLA and NGLA arrester types. From this analysis, it is evident that regardless of the type of arrester used, the transfer of overvoltage in the distribution line occurs when not all towers are protected. This finding emphasizes the importance of considering this particular point during the optimal allocation of surge arresters.

B. Flashover rate estimation

The lightning performance in this study was analyzed for the installation of EGLA and NGLA on both the unshielded and shielded distribution lines, considering the transfer voltage effect. Also, in this case, the arrangement of Fig. 3 has been considered for the analysis. The geometrical and structural points of the towers (T1 to T10) are given as input in the LIOV lines of the EMTP-LIOV toolbox. The flashover rate analysis addresses the flashover occurrence with the random nature of the lightning events and is calculated as

$$FOR = \frac{N_{FO}}{N_{TOT}} \cdot A \cdot N_g \tag{13}$$

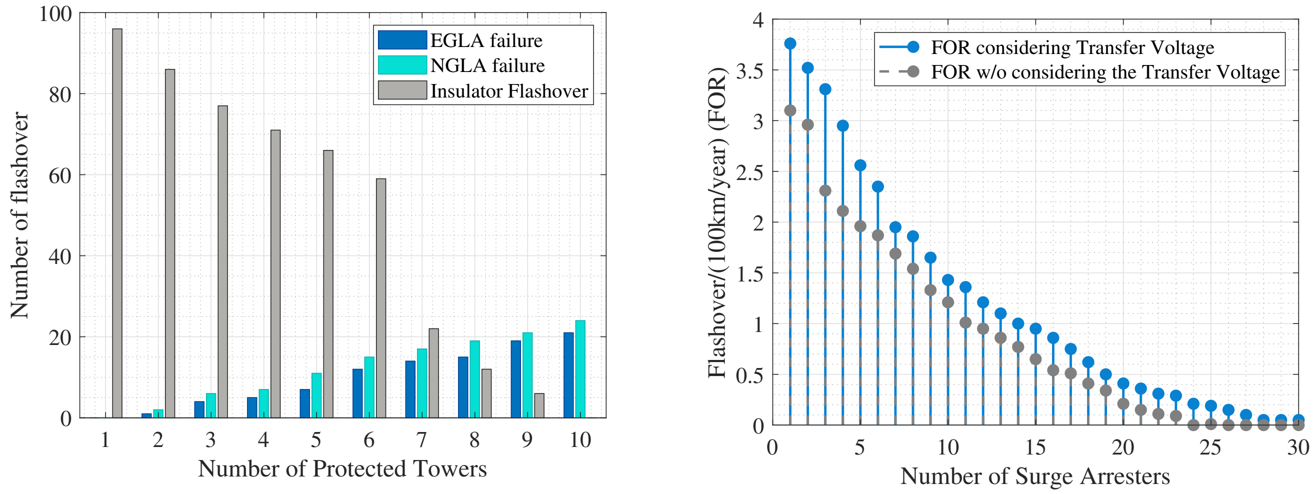
where N_{TOT} is the total number of random lightning events generated in the area A to assess; N_{FO} refers to the recorded number of flashover events that occurred for the entire 'n' number of lightning events; N_g is the ground flash density of the location (flashes/km/year) [38]. In this procedure, the random indirect lightning is generated using the Monte Carlo method together with the PAMSUITE[1]. The randomness of the lightning parameters, i.e. the peak current of the return stroke I_p, and front time t_f, are replicated according to the log-normal distribution as recommended in the technical literature [38]. The statistical values for a typical first stroke and return stroke considered in the present study are given in Table II. Random location of the 'n' number of lightning events

TABLE II: Statistical Lightning Current Parameters

Parameters	First Stroke		Return Stroke	
	Mean	Standard Deviation	Mean	Standard Deviation
Current Amplitude [kA]	31	0.46	13	0.641
Tail Time [µs]	5	0.54	0.31	0.66
Rise Time [µs]	10	0.56	20	0.67

$L(x_n, y_n)$ is generated along the lateral and vertical distance of the tower covering the entire area (600 m x 100 m) following a uniform distribution. The lightning location is

[1]This front-end standalone application works with EMTP-RV for parametric modelling.



(a)

(b)

Fig. 5: (a) Total number of insulator flashover and SAs damages (b) FOR comparison including the transfer effects of lightning surges

considered to have a single return stroke and is classified as direct or indirect by using the electro-geometric model (EGM) [34], [39]. This study only analyses the impacts of indirect lightning, so the direct lightning locations are excluded from the lightning population. For $n = 1....N_{TOT}$ events the PAM suite generates random values of lightning locations according to the uniform distribution and random values of peak current parameters according to the lognormal distribution. Then, for the N_{TOT} events, the EMTP-LIOV calculates the overvoltage levels and flashover occurrence.

Fig. 5(a) shows the number of flashovers that occurred for 100 randomly generated lightning events (1.2/50 μs standard impulse voltage stress [2]) along the distribution line. Particularly, in the figure, the grey bars are the insulator flashovers occurring with different numbers of protected towers; the blue bars refer to the number of failures of the EGLA devices in correspondence with different numbers of protected towers; the cyan bars refer to the number of failures of the NGLA devices for the different numbers of protected towers. This evaluation is performed to understand the effectiveness of the SAs in the distribution line. An increase in the number of SAs effectively protects the insulator from flashover and failure. Another observation with respect to the type of arrester is that EGLA with low discharged energy per kV is likely to have a lower failure rate than the NGLA for the same number of lightning hits at similar voltage stress.

The second type of analysis reveals that unless all the towers included in the study are protected by SAs, it is not possible to completely prevent damage due to the transfer of voltage from the SAs. This observation is depicted in Fig. 5(b) while analyzing the EGLA type of arrester. Each blue dot in the graph represents the FOR calculated using Eq. (13) for the distribution line with a specific number of SAs (SA_{max} is 30 in the present study: i.e., arrester every three phases of 10 towers). This FOR estimation takes into account the effect of voltage transfer from the protected towers to the unprotected ones. The analysis is repeated by incrementing the number of SAs up to SA_{max}. On the other hand, the grey dots in the figure represent the FOR estimated for a specific number of SAs without considering the transfer voltage effect. It can be observed that for all the considered numbers of SAs, the estimated FOR is higher when the transfer effect is taken into consideration.

This clearly demonstrates that excluding the transfer effect from the FOR calculation leads to incorrect optimal design and inadequate protection of the distribution system. It is essential to account for the transfer voltage effect to ensure accurate analysis and effective protection of the distribution system.

IV. Decision Theory Applied to the Optimal Allocation Problem

The present study aims to examine different protection alternatives and enhance the overall performance of distribution lines by analyzing the capability and effects of a specific type of arrester based on their locations (if placed at intervals). However, evaluating flashover rates is significantly influenced by the random nature of lightning intensity and location. Traditionally, Monte Carlo simulation is employed to replicate the lightning effect using a log-normal distribution and assess the performance of the distribution line. However, when multiple protection scenarios are involved, conducting Monte Carlo simulations can be time-consuming and the accuracy of the solution increases with an increase in the number of samples considered [40]. Moreover, in realistic scenarios with a large number of network buses, the complexity becomes even more challenging. To address these issues and reduce computational burdens while maintaining the integrity of the analysis, a scenario-based approach is utilized. By employing

[2]"1.2/50μs" refers to the rise time and duration of the waveform of the lightning current. The rise time of 1.2μs represents the time it takes for the current to rise from 10% to 90% of its peak value. The duration of 50μs represents the time to reach the 50% of its peak value.

this methodology and leveraging probabilistic approaches, the study offers a practical and efficient way to assess the performance of distribution lines under various protection scenarios, considering the uncertainties associated with lightning events. A proper optimization for both the choice of protection system and the location of a reduced number of SAs is applied. This proposal allows having a positive impact on the total installation, operation, and post-lightning maintenance cost. Particularly, a scenario-based approach has been used which considers a limited number of futures in terms of lightning intensity and location, each characterized by a probability of occurrence. Several alternatives are also considered in terms of protection solutions (i.e. surge arrester location). Then, decision theory is used to choose the optimal location of the surge arresters taking into account the costs and scenarios' probabilities [41]. Two methods are proposed for choosing the surge arresters' optimal siting, the former is based on the probabilistic choice idea and chooses those solutions that minimize a cost function over the set of futures considered; the latter is based on the risk analysis paradigm and is aimed at minimizing the regret. Compared to the classical Monte Carlo method which implies repetitive random sampling of the involved random variables to provide a very high number of scenarios, the proposed approach allows for reducing the computational burden while preserving the accuracy of the results. Particularly, the following four-step procedure is applied:

- A set of possible futures is specified, each characterized by a probability of occurrence. In this paper, each future is associated with a different level of lightning peak and distance (x_n,y_m) from the distribution line.
- Several possible protection design alternatives are specified. Each design alternative is based on the type and location of SA used and hybridizing it with the overhead ground wire type SW.
- Total flashover rates are calculated for each future specified in the first step and for each alternative specified in the second step. Particularly, for each design alternative A_p and future F_q, the FOR has been evaluated by Eq. (13). The obtained values are arranged in a matrix, referred to as a decision matrix.
- The decision theory is applied to choose, among the alternatives of Step 2, the best protection solution (i.e., the solution corresponding to the minimum FOR) by considering the futures with their probabilities, as specified in Step 1. The applied decision theory approaches are the minimization of the expected flashover and the min-max weighted regret.

More specifically, a set of design alternatives denoted as A_p (where $p = 1, 2, \ldots, n_a$) is available, along with a set of potential scenarios or futures denoted as F_q (where $q = 1, \ldots, n_f$) that may occur. Each future is assigned a probability of occurrence, which represents the likelihood of lightning events happening. These probabilities are represented as ω_q (where $q = 1, \ldots, n_\omega$). It is important to note that the sum of all these probability values is equal to one, reflecting a complete coverage of all possible scenarios. It should be noted that the engineer designing the protection mechanism selects alternatives and futures of Steps 1 and 2 and assigns the future probabilities. To estimate the probabilities to be assigned when the future uncertainties are modeled probabilistically three possible approaches are typically used:

- The first approach is fully based on the observed information.
- The second approach is based on the subjective judgment of the lightning activity in the area.
- The third approach is a mix of the above two, and combines the lightning resource information with the observed information.

More details on the three approaches can be found in [41]. In this paper, we used the second approach (subjective judgment of the lightning activity [31], [41], [42]). It may seem unreasonable to assign values of probabilities with little or no empirical information. Still, it is well-known that positive results can be obtained when the decision maker has a good understanding of the nature of the uncertainties relevant to the problem [31].

Regarding the decision theory criteria, the first criterion, namely expected cost minimization, is based on the minimization of the expected total FOR. For each alternative, A_p, the expected total FOR (EF_T) associated with all the n_f futures is evaluated as:

$$EF_T\left(A_p\right) = \sum_{q=1}^{n_f} \omega_q F_T\left(A_p, F_q\right) \quad p = 1, \ldots, n_a \qquad (14)$$

where (F_T) is the FOR associated to alternative A_p and future F_q. The best alternative A_{best}, among all the n_a alternatives, is the one associated with the lowest value of the EF_T. The criterion of the expected FOR minimization suggests design alternatives that are the best on the average of the futures. This choice implies that, if the future which really occurred does not happen close to the average, high regrets can derive.

The second criterion is based on the minimization of the maximum weighted regrets. The regret can be defined as follows: once the future occurs, the regret felt when the optimal decision for the really occurred future was not made will be evaluated. For each future, the minimum total FOR can be easily found as:

$$F_T^{opt}\left(F_q\right) = \min_p F_T\left(A_p, F_q\right) \quad q = 1, \ldots, n_f \qquad (15)$$

After that, the regret $R(A_p, F_q)$ felt for having chosen the design alternative A_p when the future F_q occurred is:

$$R\left(A_p, F_q\right) = F_T\left(A_p, F_q\right) - F_T^{opt}\left(F_q\right) \quad p = 1, \ldots, n_a, \quad q = 1, \ldots, n_f \qquad (17)$$

and the weighted regret $R_w(A_p, F_q)$ is:

$$R_w(A_p, F_q) = \omega_q R(A_p, F_q) \quad p = 1, \ldots, n_a, \quad q = 1, \ldots, n_f \qquad (18)$$

TABLE III: List of chosen protection alternatives (A_p)

Alternatives (Ap)	Type of arrester	Arrester coverage *	Shielding Nature**
A_1	NGLA	Every 4 towers	Unshielded line
A_2	EGLA	Every 2 towers	Unshielded line
A_3	NGLA	Every 4 towers	Shielded
A_4	EGLA	Every 2 towers	Shielded
A_5	NGLA	Every 4 towers	Unshielded line
A_6	EGLA	Every 2 towers	Unshielded line
A_7	NGLA	Every 4 towers	Shielded
A_8	EGLA	Every 2 towers	Shielded

* *TSA installed in all three phases of the tower*
** *Overhead ground wire (OHGW) type of shielding*

For each design alternative, the maximum weighted regret can be identified as:

$$R_w^{max}(A_p) = \max_q R_w(A_p, F_q) \quad p = 1, \ldots, n_a$$

Then, the best alternative A_{opt} among all the n_a alternatives is the one associated with the minimum among the maximum weighted regrets.

V. Numerical Application

A. Selection of Protection Alternatives (A_p)

Lightning protection of overhead lines (OHLs) can be achieved with overhead shielding wires (SWs) and/or surge arresters (SAs), apart from line insulation. Recently, applications of surge arresters and shielding wires have been extensively discussed with numerical calculation. The performance of the considered two types of SAs is analyzed for the shielded and unshielded lines. The alternatives (A_p) considered in this study which include both types of arresters are shown in Table III.

More specifically, SAs refer to NGLA (A_p - with p odd numbers) and EGLA (A_p - with p even numbers). In the protection scenario, overhead ground wires are considered and assumed to be placed at 1 m above the top of the conductor. The OHGW is grounded every 300 m (i.e., at towers T_1, T_5 and T_{10} (see Fig. 3). For each of these four alternatives with the considered two types, the arrester is considered within three different probabilistic futures. In the context of protecting towers T_1 to T_{10}, there are different possibilities for implementing SAs based on specific criteria. For the criteria of protecting 50% of the towers with an SA placed every two towers, there are two potential locations to start from, either tower T1 or tower T_2. This means that if the protection starts from T1, the SAs would be installed at towers T_1, T_3, T_5, T_7, and T_9. On the other hand, if the protection starts from T_2, the SAs would be installed at towers T_2, T_4, T_6, T_8, and T_{10}.

Similarly, for the criteria of protecting 25% of the towers with an SA placed every three towers, there are three possible starting locations: T_1, T_2, or T_3. If the protection starts from T_1, the SAs would be installed at towers T_1, T_4, T_7, and T_{10}. These different possibilities allow for flexibility in the placement of SAs, taking into account the desired level of protection and the specific tower configuration.

B. Selection of Scenarios/Futures (F_q)

In the study, several scenarios/factors were considered to analyze the flashover of the distribution line, with the main terms being the lightning current and its location (in detail, the lightning current magnitude, current waveform, lightning strike location and line configuration and insulation). By exploring these scenarios and factors, the study aimed to gain a comprehensive understanding of the flashover phenomenon and identify key parameters that significantly influence the performance and reliability of the distribution line during lightning events. This analysis would enable better design and planning of the line to mitigate flashover risks and enhance system resilience. The possible scenarios or futures taken into account in the present study are as follows:

- *Lightning Current* (f_q): Different magnitudes of lightning currents were considered to investigate their impact on the flashover behavior of the distribution line. By varying the current levels, the study aimed to understand the correlation between lightning current strength and the vulnerability of the line to flashovers. Considering the randomness of the lightning event, the spatial distribution of f_q, is analyzed for the probability-based approach. The lightning return stroke current is characterized by both amplitude (I_{peak}) and waveform (T_{front} and T_{half}). To enhance computational efficiency, a reduced domain of amplitude is adopted for a 1.2/50 μs lightning waveform. The probability distribution of current amplitude denoted as f_q where $q = 1, \ldots, 3$, is considered. The occurrence rates for amplitudes of 30 kA, 50 kA, and 80 kA are specified as 0.6, 0.3, and 0.1, respectively. This means that the amplitude of 30 kA (I_1) has a 60% chance of occurrence, the amplitude of 50 kA (I_2) has a 30% chance of occurrence, and the amplitude of 80 kA (I_3) has a 10% chance of occurrence. By incorporating these probabilities, the study accounts for the different likelihoods of lightning current amplitudes, allowing for a more realistic and representative analysis of the distribution line's response to lightning events. respectively.
- *Lightning Location* ($f_{\hat{q}}$): The location of the lightning strike with respect to the distribution line was a crucial parameter. Various strike positions were examined, including direct strikes on the line, nearby strikes to surrounding objects, or strikes on the ground in close proximity to the line. Each scenario provided insights into the different mechanisms and risks associated with flashovers. The lightning return stroke locations $f_{\hat{q}} = L(x_{\hat{q}}, y_{\hat{q}})$ are considered with a uniform distribution probability. Note that this probability does not consider the line configuration and nearby structure influence shown in Fig. 3. The variable $x_{\hat{q}}$ is considered at and in between towers, ranging from 0 to 600 meters distance along the line:

$$x_{\hat{q}} = (\hat{q} - 1) \cdot 30, \quad \text{for } \hat{q} \in \mathbb{N}, 1 \leq \hat{q} \leq N_T \tag{16}$$

where N_T represents the total number of towers. This

TABLE IV: Flashover rate of different Protection Mechanism

Protection Mechanism	Lightning Strike 50m			Lightning Strike 100m		
	30 kA	**50kA**	**80kA**	**30 kA**	**50kA**	**80kA**
50% of tower protected by SAs at all Phases						
NGLA	0.91	1.80	1.80	0.00	0.68	1.80
EGLA	1.26	1.80	1.80	0.00	0.53	1.80
NGLA+OHSW	0.00	0.00	0.03	0.00	0.00	0.00
EGLA+OHSW	0.00	0.00	0.03	0.00	0.00	0.00
25% of the towers protected by SAs at all phases						
NGLA	1.16	2.16	2.16	0.00	1.76	3.76
EGLA	1.11	2.16	2.16	0.00	1.79	3.64
NGLA+OHSW	0.00	0.06	0.04	0.00	0.00	0.03
EGLA+OHSW	0.00	0.07	0.03	0.00	0.00	0.01

equation calculates the value of $x_{\hat{q}}$ based on the tower index q, with each tower spacing being 30 m. In the study, the variable $y_{\hat{q}}$ is considered in two instances: y_1 represents the lateral distance in front of the tower below which a lightning strike is considered to directly affect the distribution line (The electro-geometric model (EGM), which is a widely used approach to differentiate between direct and indirect lightning strikes on structures, has been applied to make this differentiation [43]: y_2 represents the lateral distance in front of the tower that denotes the maximum distance at which a lightning strike is still considered as indirect lightning-induced voltage on the distribution line. Beyond this distance, the effects of the lightning strike may diminish, and other factors may become more significant in determining the voltage induced on the distribution line. By defining these distances, the study aims to establish boundaries for analyzing the influence of lightning strikes on the induced voltage and the associated risks to the distribution system. These boundaries help in distinguishing between direct lightning strikes and indirect lightning-induced effects, allowing for a more accurate assessment of the potential impacts on the distribution line.

Without loss of generality, to avoid verbose presentation of the results, uncertainties considered in the numerical application of this paper refer to 1.2/50 μs first strokes. Thus, each future scenario F_q is determined by the peak current f_q at the specific location $f_{\hat{q}}$, considering the possibility of occurrence at different SA location (F_q can be represented as $(f_q f_{\hat{q}})$. By considering these elements together, we can effectively characterize and evaluate each future scenario within the decision matrix.

C. Criteria Implementation and Results

For all the considered design alternatives, a decision matrix comprising 2736 rows and 8 columns was created to evaluate the FOR for each alternative across different future scenarios. The decision matrix represents the total FOR values corresponding to the 2736 design alternatives assessed. Table IV provides an example of FOR values evaluated for one of the numerous possibilities. When considering the future scenarios

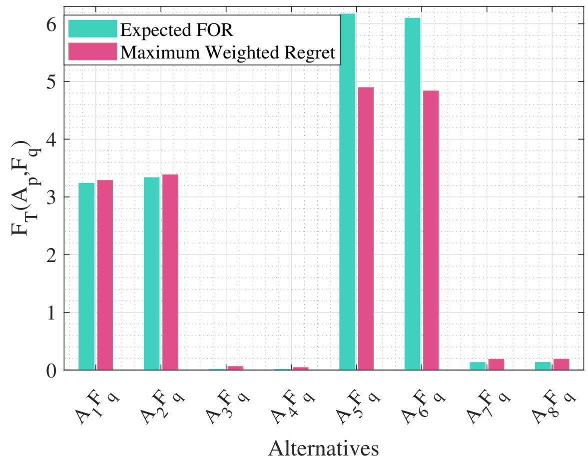


Fig. 6: FOR of design alternatives for all the futures (A_1: 50% NGLA, A_2:50% EGLA, A_3: 50% NGLA+OHSW, A_4:50% EGLA+OHSW, A_5: 25% NGLA, A_6: 25% EGLA, A_7: 25% NGLA+OHSW, A_8: 25% EGLA+OHSW)

with their associated probabilities ω_q, the criterion of minimizing expected costs leads to the selection of design alternative A_4 - (i.e., 50% of the distribution line is protected by EGLA type arrester and OHSW) as the best (A_{best}) choice among all n_a alternatives, as it has the lowest value of the $EF_T(A_p)$ for the considered futures; $F_T(A_p, F_q)$. However, the design alternatives, namely A_1 and A_2, (i.e., 50% protection with NGLA and 50% protection with EGLA), A_5, and A_6 (i.e.,25% protection with NGLA and 25% protection with EGLA) have higher EF_T.

On the other hand, when using the criterion of minimizing the maximum weighted regrets, the optimal solutions are design alternatives A_4 and A_3 (i.e., 50% of the distribution line is protected by NGLA type arrester and OHSW). Specifically, within the domain of satisfying this criterion, we find that A_4 performs well under scenarios F_{112} and F_{212}, while A_3 outperforms under scenario F_{213}.The comparison of alternative A_4 and A_3 with all the futures is shown in Fig. 7

These findings highlight the trade-off between minimizing expected FOR and minimizing maximum weighted regrets when evaluating the design alternatives. While A_4 consistently demonstrates strong performance, there are instances where other alternatives, such as A_3, can also be considered optimal based on the specific criterion employed.

VI. Conclusion

The present study identifies optimal protection solutions to mitigate lightning-induced overvoltage in terms of the type of protection strategy and location of protection devices. Particularly, two types of surge arresters were considered, namely EGLA and NGLA, investigating the possibility of combining them with the OHGW type SW. The following key observations are made:

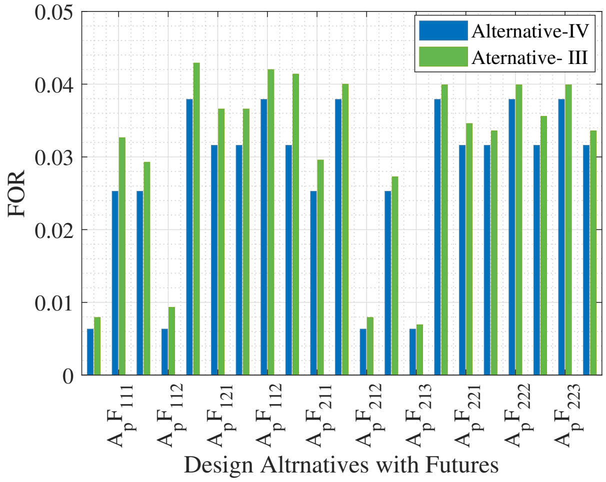


Fig. 7: FOR of best design alternatives for all the futures (F_q) (determined by the peak current f_q at the specific location $f_{\hat{q}}$, considering the possibility of occurrence at different SA location)

- In terms of discharged energy, the EGLA outperforms the NGLA, making it a better option for FOR mitigation on distribution lines.
- The transfer voltage effect is present with both types of arresters and needs to be taken into account during the FOR analysis.

To address the FOR mitigation analysis, a scenario-based method was employed. This approach incorporates probabilistic techniques to provide a practical and efficient means of evaluating the performance of distribution lines across different protection alternatives while accounting for the uncertainties associated with lightning events.

In this study, a comprehensive set of possible futures and design alternatives was considered. The FOR was calculated for each combination, taking into account the specific characteristics and parameters of the distribution system and the lightning phenomenon. By utilizing decision theory, the proposed method allowed identifying the optimal protection solution by considering the probabilities associated with each future.

It has been determined that the design alternative of incorporating the externally gapped type arrester with OHGW exhibits a lower FOR when compared to other design alternatives for all the considered futures. This decision-theory framework ensures that the mitigation analysis is not solely based on deterministic factors but also accounts for the likelihood of different outcomes. The methodology streamlines the analysis process by integrating various factors into a unified framework. This integration reduces the computational burden and facilitates efficient evaluation and comparison of different protection scenarios.

It has to be noted that, in this paper, a simple configuration has been simulated for comparison purposes. More complex configurations will be addressed in future work. Also, in future analysis, the authors plan to further investigate the impact of ground conductivity and lightning current time (front and tail) on FOR mitigation. By incorporating these variables into the analysis, they aim is to improve the accuracy and reliability of the results.

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