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T. Hamel, S. Bedoui, A. Bayadi

Impact of transmission line lightning performance on an operational substation reliability considering the lightning stroke incidence angle

***Introduction**. This study investigates substation failures caused by lightning strikes, which significantly affect operational reliability. Given the random nature of lightning strikes, a robust statistical approach is essential for accurately assessing their effects. **Method.** The research develops a comprehensive procedure to analyse the random distribution of non-vertical lightning strikes on transmission lines using the Monte Carlo method, a widely recognized statistical simulation technique. The **goal** of this work is to evaluate the performance of air-insulated substations under various lightning strike scenarios affecting the connected transmission lines. This is assessed in terms of mean time between failures (MTBF), determined by the basic insulation level of the equipment. The study incorporates both vertical and non-vertical strikes to address a critical gap in the literature, offering practical insights to enhance the reliability and safety of air-insulated substations. By considering the angle of lightning strikes, the study improves the accuracy of evaluating lightning performance using precise modelling of system components. **Results**. MATLAB and EMTP software were used to simulate and analyse the substation's response to lightning-induced surges at various strike angles. The results are more representative of real-world conditions and reveal that non-vertical lightning strikes significantly reduce MTBF, underscoring the importance of advanced protective measures. **Practical value.** The findings highlight the necessity of accounting for the angle of lightning strikes when assessing substation reliability.* References 32, table 4, figures 13.

Key words: **lightning, substation, stroke angle, mean time between failure, basic insulation level, Monte Carlo method**.

***Вступ**. У цьому дослідженні вивчаються відмови підстанцій, спричинені ударами блискавки, які суттєво впливають на експлуатаційну надійність. Зважаючи на випадковий характер ударів блискавки, надійний статистичний підхід необхідний для точної оцінки їх наслідків. **Метод**. У дослідженні розробляється комплексна процедура для аналізу випадкового розподілу невертикальних ударів блискавки у лінії електропередачі з використанням методу Монте-Карло, широко визнаного методу статистичного моделювання. **Метою** даної роботи є оцінка продуктивності підстанцій з повітряною ізоляцією при різних сценаріях ударів блискавки, що впливають на підключені лінії електропередачі. Це оцінюється з погляду середнього часу між відмовами (MTBF), що визначається базовим рівнем ізоляції обладнання. Дослідження включає як вертикальні, так і невертикальні удари, щоб заповнити критичну прогалину в літературі, пропонуючи практичні ідеї для підвищення надійності та безпеки підстанцій з повітряною ізоляцією. Розглядаючи кут ударів блискавки, дослідження підвищує точність оцінки продуктивності блискавки з використанням точного моделювання компонентів системи. **Результати**. Для моделювання та аналізу реакції підстанції на стрибки напруги, викликані блискавкою при різних кутах удару, використовувалися програми MATLAB та EMTP. Результати більш репрезентативні для реальних умов і показують, що невертикальні удари блискавки значно скорочують MTBF, що наголошує на важливості розширених заходів захисту. **Практична цінність**. Результати наголошують на необхідності врахування кута удару блискавки при оцінці надійності підстанції.* Бібл. 32, табл. 4, рис. 13.

Ключові слова: **блискавка, підстанція, кут удару, середній час між відмовами, базовий рівень ізоляції, метод Монте-Карло.**

Introduction. Lightning strikes are a major threat to the electrical power system, causing power outages, equipment damage, and even fires. Overhead transmission lines are particularly vulnerable to lightning strikes, as they present a tall and exposed target to the lightning discharge [1, 2]. The random nature of lightning strikes makes difficult to predict the exact form, location, time and lightning strike angle. To address this challenge, engineers and scientists have developed various models and simulations to evaluate the performance of the power system under lightning strikes [2–7].

A vertical flash is generally assumed for the stroke leader on the shielding analyses of transmission lines recommended by the international standards; however, a previously proposed statistical distribution for the stroke angle is more realistic [8, 9].

The majority of lightning strikes on overhead transmission lines are not vertically downward, but instead are inclined at some angle relative to the vertical. Non-vertical lightning strikes can have different impacts on the transmission line compared to vertically downward strikes [10]. The electric and magnetic fields produced by non-vertical lightning strikes can be much higher in magnitude and longer in duration, causing more severe damage to the transmission line and consequently the substation connected [11].

One approach to evaluate the performance of transmission lines under non-vertical lightning strikes is the use of random sampling techniques. These techniques randomly generate the lightning strikes parameters, then use numerical models to simulate deferent phenomenon produced by lightning strikes. This process is repeated many times to generate a large sample of possible lightning strikes, and the results are used to estimate the probability of damage or failure of studied system [12].

In [13], the authors conducted a simulation study to calculate lightning flashover rates of transmission lines using the Monte Carlo method. The authors have done some parametric calculations to analyze the influence of stroke parameters and determine the range of values that may be concerning. Note that the study has been done only for the case of vertical lightning strikes. In [14] the authors investigate how a non-vertical channel of the stroke leader influences the lightning flashover rate of overhead transmission lines. They emphasize that the stroke angle is a critical factor in lightning analysis for overhead lines. The findings of this study indicate that assuming a non-vertical path for the stroke leader may impact the lightning flashover rate of transmission lines.

In [15] the authors assessed how incorporating a cumulative probability distribution of the stroke angle affects the shielding failure flashover rate (SFFOR) of three-phase overhead transmission lines using a modified electric geometric model (EGM). The authors also confirmed the necessity of evaluating the stroke angle distribution in lightning analyses of transmission lines, but this analysis has not been sufficiently applied to substations.

In 2014, the same authors published a conference paper [16] in which they investigated the effects of considering vertical and non-vertical strokes on the SFFOR estimated in IEEE Flash program together with the effects of the various EGMs. They state that the assumption of a particularly vertical leader reduces conductors' exposure area and therefore leads to shielding outage rates underestimated in around 20 %.

Very few studies [17, 18] have been published with the objective of evaluating the performance of air-insulated substations considering the statistical nature of lightning strikes. The authors have conducted parametric calculations to analyse the influence of certain line and stroke parameters and to determine their applicable range of values. Despite the high number of parameters involved in lightning calculations, the authors have only used some of them. Specifically, they only consider lightning strikes with a vertical angle, which can affect the accuracy of the results obtained.

From the above, it is clear that most of the work has focused on the performance of transmission lines subjected to lightning strikes based on their angle of incidence. However, to the authors' knowledge, there remains a significant gap regarding the influence of lightning strike angles on the performance of high-voltage substations, whether they are air-insulated or gas-insulated. Future studies should consider these factors to enhance the accuracy and reliability of lightning risk assessments in high-voltage substations. The necessary modifications have been incorporated in the original procedure to account stroke leader angle distribution [17, 18].

The **aim** of this work is to evaluate the performance of air-insulated substations under various lightning strike scenarios affecting the connected transmission lines.

This paper summarizes findings of simulation investigations showing the critical importance of considering the incidence angle of lightning strikes in the reliability assessment of a 220 kV substation. The paper examines the impact of the lightning strikes with different incidence angles on the Mean Time Between Failures (MTBF) on which the Basic Insulation Level (BIL) (insulation strength) of substation equipment is usually selected.

MATLAB procedure employs a statistical Monte Carlo method, utilizing the EMTP/ATP program to estimate lightning overvoltages.

By addressing these aspects, our study offers a more precise and realistic evaluation of substation reliability under lightning strike conditions, filling the gaps left by previous models.

Modeling of electrical system components. The studied system is a 220 kV substation equipped with conductors, towers, insulators, measuring and protection devices, breakers, bus bars, arresters and power transformers. The modeling of each of these components is essential to carry out this study [19].

Transmission line model. To represent the transmission line, multiple distributed parameter line spans are required. This representation is achieved by utilizing a frequency-dependent or a constant parameter model, as described in [20]. ATP-EMTP provides several models that have been applied in transmission line systems. The J. Marti model, is a suitable choice for that purpose, this model accounts for frequency attenuation, conductor geometry and material (Fig. 1,*a*). Electrical data is calculated by the EMTP program.

It is worth noting that the J. Marti model assumes an infinite line length in both directions, which helps prevent wave reflections at both ends of the line.

Transmission tower model. Towers, typically made of metal, are used to elevate electric cables above ground level for the purpose of transmitting electricity over long distances. An example of a transmission tower can be seen in Fig. 1,*b*.

There are several models to represent towers. The model used for this work is based on modeling each metallic part of the tower as a single-phase line section [20]. This model requires the following data:

- the propagation velocity assumed in this case to be 300 m/μs.
- the characteristic impedance, determined according to the following formula:

$$Z = 60\left(\ln\left(\sqrt{2}\,\frac{2h}{r}\right) - 1\right), \quad (1)$$

where h is the tower height; r is the arms horizontal distance of the tower.

Insulator modeling. The line insulation flashover model is represented in this work by using voltage-dependent switch that is connected in parallel with the insulator (Fig. 1,*c*). The capacitors simulate the way in which the conductors are coupled to the tower structure [21]. The flashover model, as proposed by CIGRE, is expressed as:

$$v = K \cdot V \cdot \left[\frac{V}{D - L} - E_0\right], \quad (2)$$

where v is the arc velocity, m/s; K is the constant (0.8 $m^2 \cdot kV^{-2} \cdot s^{-1}$) [19]; D is the insulator length or gap length (2.5 m); V is the instantaneous voltage across the insulator or across the gap, kV; L is the leader length, m; E_0 is the critical electric field strength (600 kV/m [19]).

To calculate the leader length L at time, given the leader velocity v at time T, you can use the following formula:

$$L(T + \Delta T) = L(T) + v \cdot \Delta T. \quad (3)$$

The leader propagation stops if the gradient in the unbridged part of the gap falls below E_0.

Grounding modeling. A precise model of grounding impedance must consider a decrease in resistance as the discharge current increases. It is recognized that resistance is higher for low lightning currents, and its variation concerning low current and low frequency values is only significant for soils with high resistivity. When considering the effect of soil ionization, the grounding impedance model can be represented by a nonlinear resistance R_T, as expressed in the provided equation [22–24]

$$R_T = \frac{R_0}{\sqrt{1 + I/I_g}}. \quad (4)$$

The grounding resistance R_0 is around 20 Ω at low current and low frequency. The limiting current I_g that initiates the soil ionization and the stroke current I that passes through the resistance are also important factors in the grounding impedance calculation (R_T). The formula for calculating the limiting current I_g is [25]:

$$I_g = \frac{E_g \rho}{2\pi R_0^2}. \quad (5)$$

This current is calculated using the soil resistivity ρ, [Ω·m] and the soil ionization gradient E_g = 400 kV/m.

The model used in this study is particularly suitable for soils with a specific resistivity greater than 500 Ω·m. This selection is based on empirical data and established standards that confirm the model's accuracy in such conditions.

This information is used to model the earth electrode of a steel tower as a type-91 nonlinear resistor which is controlled by models, as shown in Fig. 1,*d*.

Surge arrester model. In this work, the surge arrester has been modelled using a modified version of the IEEE-recommended model (Fig. 1,*e*), with parameters optimized using genetic algorithms [26]. This model is referred to as the frequency-dependent model which can accurately represents the dynamic behavior of ZnO surge arresters under steep front surge conditions, which is crucial for ensuring proper insulation coordination in power systems. For this model the non-linear V-I characteristic of the arrester is represented with two sections of nonlinear resistance designated A_0 and A_1. The two non-linear sections A_0 and A_1 are separated by an R-L filter and are represented by the exponential non-linear resistive model available in the ATP-EMTP program [27]:

$$i = p\left(V/V_{ref}\right)^q, \quad (6)$$

where i is the arrester current; V is the arrester voltage; p, q, V_{ref} are the constants of the device.

As stated in the EMTP rule book, the reference voltage V_{ref} is theoretically arbitrary. It is used to normalize the equation, and to prevent numerical overflow during exponentiation. Then constants p and q are unique parameters of the device. The surge arrester installed in the substation is a SIEMENS 3EP2 model, and its technical specifications are summarized in Table 1.

Table1

Technical Data of the SIEMENS surge arrester

3EP2	1/2 µs	8/20 µs				30/60 µs	
I, kA	10	5	10	20	40	1	2
U, kV	491	435	463	519	579	384	403

The optimized parameters using the developed genetic algorithms as part of this work are summarized in Table 2.

Table 2

Optimized parameters of the modified IEEE model

R_0, Ω	R_1, Ω	L_0, µH	L_1, µH	C_0, pF	C_1, pF
318.55	205.55	0.668	4.8	19.70	19.9
p_0, A	q_0	V_{ref0}, kV	p_1, A	q_1	V_{ref1}, kV
4.61	20.93	562.39	204	14.93	548.05

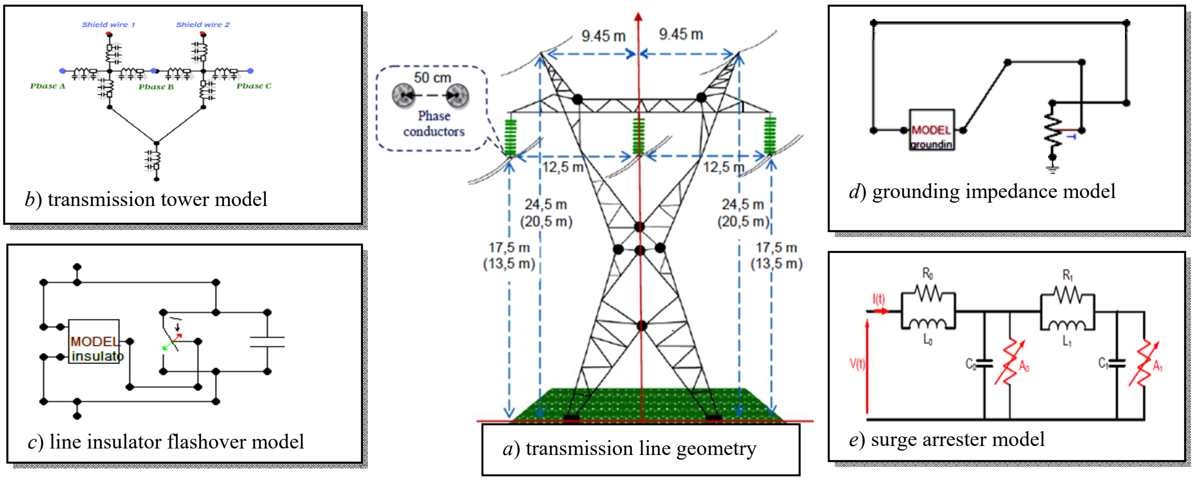

Fig. 1. Modelling of the system elements

Electric geometric model. The EGM is a mathematical model used as a tool to adjust protection and assess the risk of lightning strike on a structure. The model takes into account both the electrical properties and the physical geometry of the structure to determine the probability of an impact and the potential damage that may result. The EGM divides the structure into different zones, each with its own electrical properties, and calculates the risk of impact based on the configuration of the structure and the distance between the zones. Despite the limitations, the EGM is still considered a useful tool for designing an appropriate lightning protection system.

The analysis begins by considering a section of line, and then the study is generalized to the entire line. The first decision made by the EGM is the impact point of the lightning strike if it's directed towards towers, towards conductors or ends on the ground. To make this decision, attraction zones for each point on the line are determined based on the theoretical radius as [28]:

$$r_c = A \cdot I^{\gamma}; \quad r_g = B \cdot I^{\delta}, \quad (7)$$

where $A = B = 8$, $\gamma = \delta = 0.65$ are the constants that depend on the object and the lightning peak current [2]; r_c is the theoretical radius created by the field around the phase conductors and the ground wire in [m]; r_g is the theoretical radius created by the horizontal plane field of the ground in [m]; I is the lightning stroke current amplitude in [kA].

The radius of the sphere used in the EGM was chosen based on established empirical standards. Specifically, the equations presented by Mousa [2] and IEEE-1995 [2] were adopted for this purpose. This approach relies on field data, which demonstrates that using the same radius for both the footing and the wire can yield accurate results within certain limitations. For a specific value of stroke current, the arcs are drawn, there are two possible situations [17]:

A) the arcs of towers and span center do not intersect;

B) the arcs of towers and span center intersect above the horizontal plane.

Each of these situations is represented in Fig. 2, 3. In addition, a geometric solution is proposed for each case. Since the geometric information is extensive for each case, two ways to solve the problem can be found.

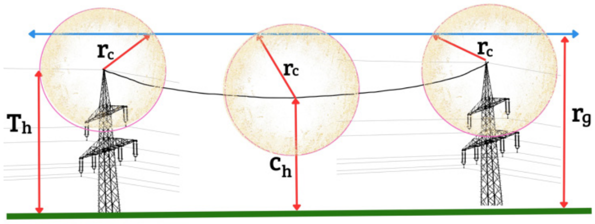

Fig. 2. Representation of EGM with a profile view (case *A*)

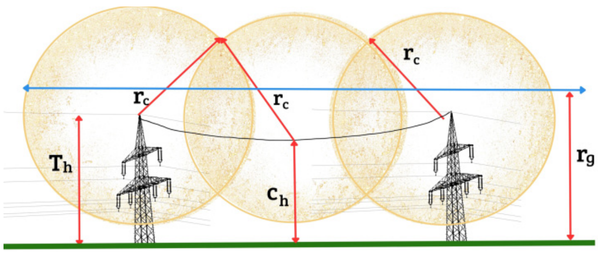

Fig. 3. Representation of EGM with a profile view (case *B*)

Modified electric geometric model (MEGM). MEGM is a refinement of the traditional EGM that has been widely used in the lightning studies. The model provides a more accurate representation of the phenomenon of lightning strikes by taking into account the non-vertical direction of the lightning as well as its random behavior.

In most studies, most significant natural considered to be vertical, when in reality they often hit the ground in a non-vertical manner. MEGM takes this point into account by introducing an angular deviation parameter, denoted by the Greek letter Ψ, which represents the angle between the direction of the lightning strike and the vertical direction. This parameter allows a more accurate description of the lightning path as it makes its way to the ground [15].

Additionally, the angles of lightning display a random behavior that can be modeled using a probability density function described as [10]:

$$p(\Psi)=\begin{cases}0, & \text{if } \Psi<-\pi/2;\\ k\cos^{m}\Psi, & \text{if } -\pi/2<\Psi<\pi/2;\\ 0, & \text{if } \Psi>\pi/2;\end{cases} \qquad (8)$$

where Ψ is the angle deviation the direction of a lightning strike and the vertical direction (see Fig. 4).

Figure 5 displays the distribution curves for the stroke angle, and the appropriate distribution function proportional to *m* values is identified. Specifically, a uniform distribution function is observed for $m = 0$, while *m* values greater than 2 tend to follow a Gaussian curve. Typically, a value of $m = 2$ is used in computations (in this study, $m = 2$ and $k = 2/\pi$) [28].

The parameters for evaluating lightning impacts are categorized based on the orientation of the lightning strokes. For vertical strokes (Fig. 4) defines the relevant variables, leading to the derivation of (9) – (12), where D_v represents the shielding failure width [28]:

$$\alpha=\tan^{-1}\left(\frac{d}{Y_g-Y_c}\right); \qquad (9)$$

$$\varphi=\sin^{-1}\left(\frac{r_g-Y_c}{r_c}\right); \qquad (10)$$

$$\beta=\sin^{-1}\frac{(Y_g-Y_c)\cdot\sqrt{1+\tan^2\alpha}}{2\cdot r_c}; \qquad (11)$$

$$D_v=r_c\cdot[\cos\varphi-\cos(\alpha+\beta)], \qquad (12)$$

in (10) – if $r_g \le Y_c$, then $\varphi = 0$.

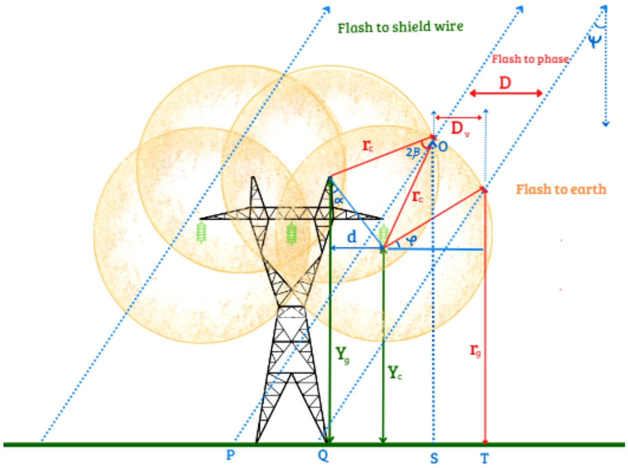

Fig. 4. The scheme of the MEGM

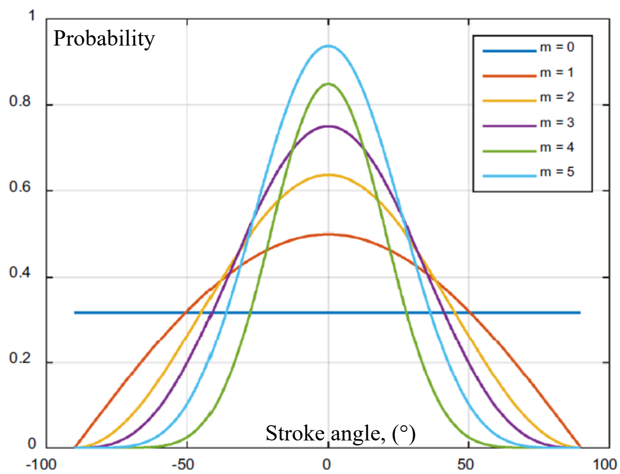

Fig. 5. Probability density function of the stroke angle

For non-vertical strokes in Fig. 4 outlines the associated variables, resulting in equations (13) – (16). In this context, *D* is the shielding failure distance for a non-vertical flash, with ψ denoting the deviation from the perpendicular direction:

$$SO=Y_c+r_c\cdot\sin(\alpha+\beta); \qquad (13)$$

$$PS=SO\cdot\tan\psi; \qquad (14)$$

$$QT=r_g\cdot\tan\psi; \qquad (15)$$

$$D=PS+D_v-QT. \qquad (16)$$

The distance *D* is critical for determining the strike point – whether it hits the phase conductor, the shield wire, or the ground.

Calculating shielding failure for both vertical and non-vertical lightning strokes involves relatively straightforward programming, often requiring only a few lines of code in computational software. This distinction is crucial because the angle at which lightning strikes can significantly impact the path and distribution of the electrical discharge.

Traditional EGM primarily focus on the stroke radius on a plane, which works well for vertical strokes. However, incorporating the incidence angle of non-vertical strikes provides a more comprehensive understanding of lightning impact. Non-vertical strokes alter the electric field distribution in ways that vertical strokes do not affecting the shielding effectiveness and overall reliability of electrical substations.

By including these variations, we achieve more precise modeling of lightning impacts, ensuring that our assessments of shielding effectiveness and grounding reliability are accurate and reflective of real-world scenarios. This approach is essential for optimizing the design and protection strategies of electrical infrastructure.

Monte Carlo procedure. The lightning stroke parameters statistical variability has been modeled based on the assumption of a log-normal distribution, utilizing the probability density function as referenced in [29–31]:

$$p(x)=\frac{1}{\sqrt{2\pi}x\sigma_{\ln x}}\exp\left[-\frac{1}{2}\left(\frac{\ln x-\ln x_m}{\sigma_{\ln x}}\right)^2\right]; \quad (17)$$

where $\sigma_{\ln x}$ represents the standard deviation of ln$x$, and x_m corresponds to the median value of x. Table 3 shows the values used for the lightning parameters.

Table 3

Statistical parameters of lightning strikes [17]

Parameter	x_m	$\sigma_{\ln x}$
I_{100}, kA	34	0.74
t_f, μs	2	0.494
t_h, μs	77.5	0.577

An assumption has been made about a non-zero correlation coefficient between the probability density functions of the peak current magnitude and the rise time. To generate random variables following the joint probability distribution described in (18), the process relies on the conditional probability density function of the rise time (t_f) for a given peak current magnitude (I_p), as shown in (20) [13, 28, 32]:

$$f(I_p,t_f)=\frac{1}{2\pi\cdot I_p\cdot t_f\cdot\sigma_{\ln I_p}\cdot\sigma_{\ln t_f}\cdot\sqrt{1-\rho_c^2}}\cdot\exp(-A); \quad (18)$$

where:

$$A=\frac{1}{2\left(1-\rho_c^2\right)}\left[\begin{array}{l}\left(\frac{\ln I_p-\ln\bar{I}_p}{\sigma_{\ln I_p}}\right)^2+\left(\frac{\ln t_f-\ln\bar{t}_f}{\sigma_{\ln t_f}}\right)^2-\\ -2\sigma_c\left(\frac{\ln I_p-\ln\bar{I}_p}{\sigma_{\ln I_p}}\right)\left(\frac{\ln t_f-\ln\bar{t}_f}{\sigma_{\ln t_f}}\right)\end{array}\right]; \quad (19)$$

where ρ_c = 0.47 is the correlation coefficient; $\ln\bar{I}_p$ is the mean value of lnI_p, where $\bar{I}_p$ is the median value of I_p; $\sigma_{\ln Ip}$ is the standard deviation of lnI_p; $\ln\bar{t}_f$ is the mean value of lnt_f, where $\bar{t}_f$ is the median value of t_f; $\sigma_{\ln tf}$ is the standard deviation of lnt_f:

$$p\left(t_f/I_p=I_{p0}\right)=\frac{p\left(I_p,t_f\right)}{p\left(I_p\right)}=\frac{\exp\left(-\frac{\left(\ln t_f-b\right)^2}{2\sigma^2}\right)}{t_f\sigma\sqrt{2\pi}}; \quad (20)$$

where

$$b=\ln\bar{t}_f+\rho_c\frac{\sigma_{\ln t_f}}{\sigma_{\ln I_p}}\left(\ln I_{p0}-\ln\bar{I}_p\right); \quad \sigma=\sigma_{\ln t_f}\sqrt{1-\rho_c^2}.$$

Simulation results. By employing statistical approximations, engineers can enhance their understanding of the system of lightning performance and design more reliable systems. Therefore, in this research we use statistical approximations based on multiple conditions which makes the data of the study very accurate and close-to-reality. Figure 6 illustrates the ATPDraw circuit used to evaluate the lightning performance of the tested system. As reliability is the opposite of failure, and when failures occur randomly, probabilistic studies can be determined to be the most suitable in this case.

Furthermore, it is important to understand how lightning strikes may affect the power system parts in order to analyze the lightning performance of the tested system, here the EGM is applied. Particularly, this model is used to determine the random variables associated with lightning strikes, such as the location of the strike and the current that is generated.

In this work, a developed approach is proposed to assess the lightning performance of a transmission line by generating 10000 combinations of random numbers to obtain the lightning surges incoming to the substation. These cases are analyzed and filtered using the EGM. This means that the model is used to determine which strikes would hit the ground wire, the phase conductor or the ground.

After applying the filtering process, the total number of lightning strikes is reduced to 4514 strikes that hit the line, considering the non-vertical strike case. For the case when only the vertical strikes are considered, we obtained only 3621 case which strikes the transmission line. It is important to note that cases where the lightning strike ends on the ground are ignored in this analysis.

It should also be noted that this study focuses on lightning strikes affecting phase conductors and shield wires. Lightning strikes to footings, which account for approximately 30 % of all strikes on overhead lines, have not been considered in this analysis. These strikes can significantly influence back flashover and substation reliability, and warrant further investigation. Future research will address the distribution and impact of lightning strikes on footings to provide a more comprehensive understanding of lightning performance.

The transmission line is modeled by taking 7 spans from the substation, each span with a length of 300 m. This means that the model focuses on the behavior of the transmission line over a distance of approximately 2.1 km. By using this approach, researchers can gain a better understanding of how lightning strikes may affect the transmission line over a significant distance.

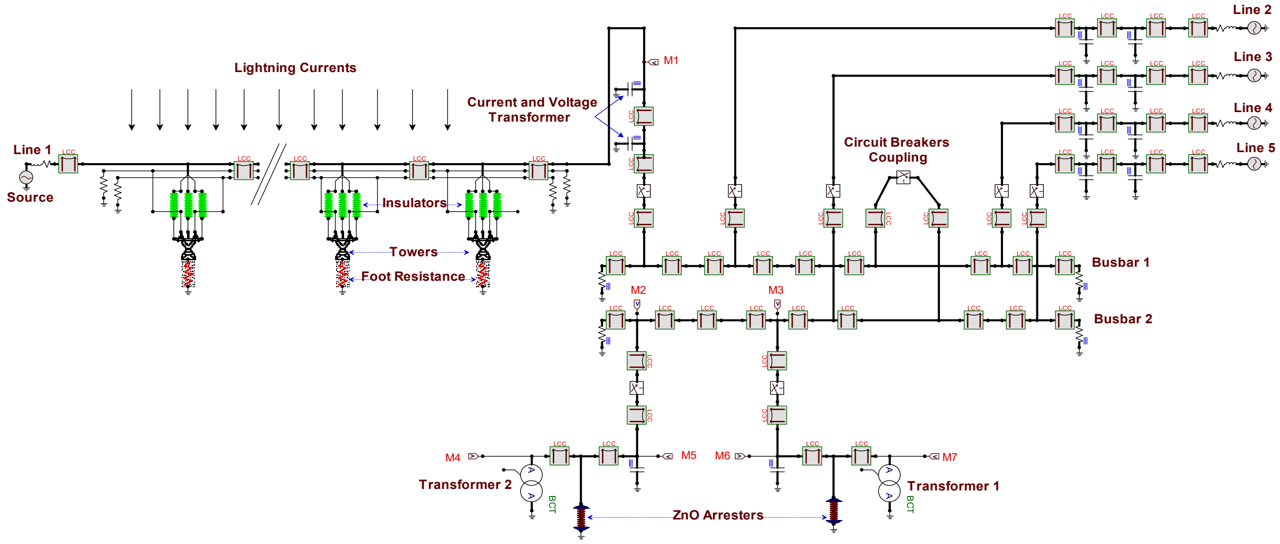

Fig. 6. Complete model of the substation (220 kV) implemented in ATPDraw

In our comprehensive study, we initially analyzed the overall distribution of lightning currents along the transmission line. Figures 7, 8 serve to illustrate the statistical distribution of vertical and non-vertical lightning strikes, respectively. In Fig. 7 the currents most likely to occur (probability of 0.0054) fall within the amplitude range of 26.07 to 41.15 kA, accounting for 813 of the 3569 strokes impacting the shield wire. Similarly, Fig. 8 shows that 4179 strokes impacted the transmission line, with the highest probability (0.0062) occurring for currents ranging from 26.07 to 41.15 kA, representing 935 strokes. This analysis indicates that the probability of lightning currents from non-vertical strikes is higher than that from vertical strikes. Additionally, it is important to note that the probability of vertical lightning currents striking the phase conductor is nearly non-existent as well as occurrences of lightning currents exceeding 500 kA are very rare. These findings underscore the necessity of modeling the transmission line with consideration to lightning angles to enhance the accuracy of our results and ensure the robustness of the electrical infrastructure against variable types of lightning strikes.

This information is very important to understand the lightning damage rate on the transmission line and for developing a strategy to reduce this risk. For example, if non-vertical lightning strikes are more common, it may be necessary to take additional precautions to protect the line from direct lightning damage, such as installing a surge arrester or improving the line's grounding system.

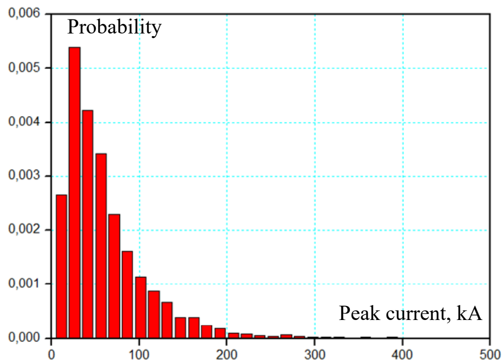

Fig. 7. Statistical distribution of vertical lightning strikes on the transmission line

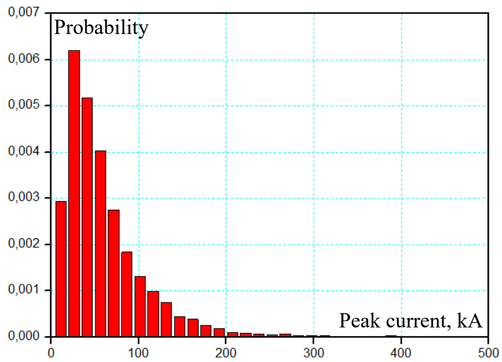

Fig. 8. Statistical distribution of non-vertical lightning strikes on the transmission line

Figure 9 shows the statistical distribution of non-vertical lightning strikes on the shield wire. In this case, the currents having the highest probability (0.0054) have an amplitude ranging from 26.07 to 41.15, it's corresponding to 815 among 3569 strokes impacting the shield wire.

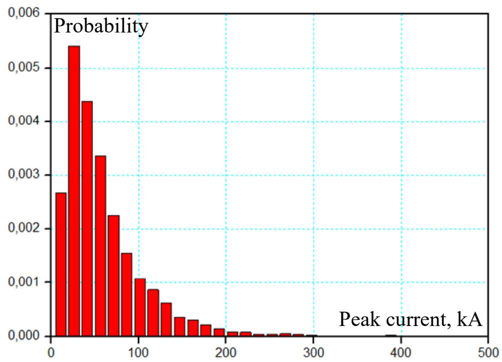

Fig. 9. Statistical distribution of non-vertical lightning strikes on the shield wire

Influence of the lightning stroke incidence angle. In order to improve the assessment of lightning performance of the substation, the influence of the lightning strike angle is investigated in this section.

Figure 10 represents the statistical distribution of non-vertical lightning strikes on phase conductors (610 strokes) where the highest probability (0.00088) occurring for currents ranging from 28.14 to 45.93 kA, representing 158 strokes.

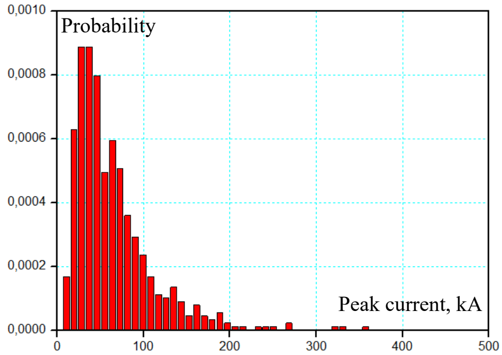

Fig. 10. Statistical distribution of non-vertical lightning strikes on phase conductors

The obtained results for the statistical distribution of lightning strikes on transmission line L_1 as a function of the incidence angle are shown in Fig. 11. As can be seen, the plot reveals the lightning strikes in this case range between –90° and 90°, with a highest probability for those having an angle equals to 20°. In addition to that, the majority of these strikes are concentrated around 0°. Figure 12 shows the distribution of lightning strikes on the shield wire as a function of incidence angle. It is easy to observe that the distribution presents a similar trend as in Fig. 11 indicating that the lightning strikes impacting the shield wire are mostly near-vertical strikes. Distribution of lightning strikes on the phase conductors as a function of incidence angle is shown in Fig. 13. The plot exhibits symmetry around 0° (vertical strike) indicating that phase *B* is not impacted at all independently from the incidence angle. These findings suggest that non-vertical lightning strikes are also important to take into account underscoring the need for enhanced protective strategies against such strikes. The analysis of lightning stroke angles on electrical transmission systems reveals that the distributions on transmission lines, shield wires, and phase conductors follow Gaussian curves. Improving grounding systems and installing surge arresters can significantly contribute to safeguarding electrical infrastructure from potential lightning damage. Additionally, while the use of a common radius for the footing and wire in our model simplifies the calculations, it may introduce some limitations in terms of accuracy. We discuss these limitations in the context of our results and suggest that further refinement of these parameters could lead to more precise modeling outcomes. The assumptions made are based on well-established empirical practices but should be considered with caution in future studies.

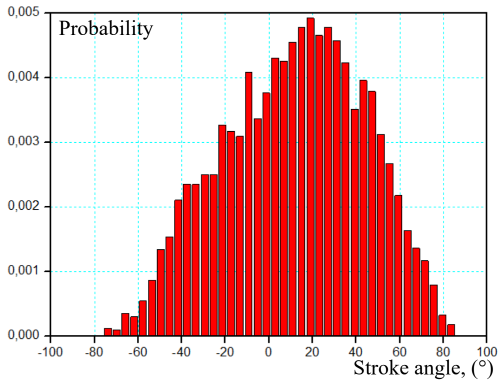

Fig. 11. Statistical distribution of lightning strikes on the transmission line as a function of stroke angle

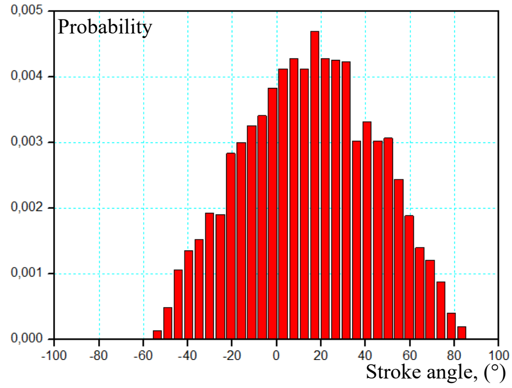

Fig. 12. Statistical distribution of lightning strikes on the shield wire as a function of stroke angle

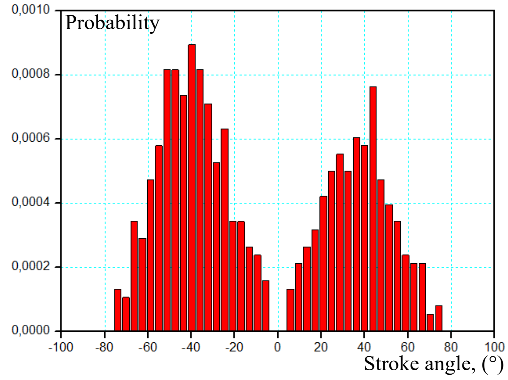

Fig. 13. Statistical distribution of lightning strikes on the phase conductors as a function of stroke angle

The MTBF of the substation. In engineering, reliability is a critical factor in system design and implementation. Generally, reliability refers to the ability of a system to operate without disturbance or failure. To evaluate the reliability of a system, engineers use several methods, one of which is the MTBF that represents the average expected time that elapses between inherent failures of a system during operation. This process is widely used in engineering to assess the systems reliability, such as electronic devices, machines, and other complex systems.

A low MTBF value indicates a high frequency of overvoltages exceeding the equipment's insulation strength, which consequently leads to a higher probability of equipment failure. This measure is used to compare the reliability of systems and to assess the effectiveness of any improvements made to them.

The aim of this part is to evaluate the MTBF for a whole substation. The presented results derived when all the transmission lines are connected to the test substation (line 1 is stroked in this case).

The following expression is used to obtain the MTBF:

$$\mathrm{MTBF} = Y_s / n_f. \qquad (21)$$

Taking into account the incoming surges to the substation, the distribution of overvoltages in several basic measuring points in the substation (entrance, circuit breaker, bus bar, surge arrester, auto-transformer) were firstly recorded and compared to the insulation strength. Table 4 presents a summary of the obtained results where the MTBF (years) is determined using the number of faults recorded at the substation equipment (n_f) (overvoltage's number that exceed the equipment BIL value) and the number of years being simulated (Y_s).

The results presented in Table 4 indicate that the higher the selected BIL is, the higher the MTBF will be.

As can be seen, the MTBF values range from 9 years for non-vertical strikes at 850 kV BIL to 12.25 years for non-vertical strikes at 1175 kV BIL. For vertical strikes, MTBF increases substantially, with values starting from 24.48 years at 850 kV BIL.

These findings underscore the critical influence of strike angle and insulation strength on substation reliability. Non-vertical strikes generally result in lower MTBFs, indicating more deleterious effects compared to vertical strikes. This emphasizes the need for accurate modeling in order to improve the system reliability based on adequate technical measures.

Table 4

Simulation results – substation

	BIL, kV	MTBF, years
Non-vertical lightning strikes	850	9.01
	950	9.99
	1050	11.33
	1175	12.25
Vertical lightning strikes	850	24.48
	950	26.75
	1050	28.77
	1175	31.12

Conclusions. This work highlights the critical importance of considering the incidence angle of lightning strikes in the reliability assessment of a 220 kV substation. This work had evaluated the performance of air-insulated substations under various lightning strike scenarios affecting the connected transmission lines. This was assessed in terms of MTBF, determined by the BIL of the equipment. The study has incorporated both vertical and non-vertical strikes to address a critical gap in the literature, offering practical insights to enhance the reliability and safety of air-insulated substations. By considering the angle of lightning strikes, the study improves the accuracy of evaluating lightning performance using precise modelling of system components. Our analysis reveals that the MTBF decreases significantly when lightning strikes occur with non-vertical angles. Specifically, the MTBF values for non-vertical strikes range from 9 years at 850 kV BIL to 12 years at 1175 kV BIL. In contrast, vertical strikes yield higher MTBF values, starting from 24 years at 850 kV BIL. This stark difference underscores the more deleterious effects of non-vertical strikes on substation reliability. Our study utilized an electric geometric model to simulate 10000 random combinations of lightning surges, ultimately reducing the total number of relevant strikes to 4514 when considering non-vertical strikes case and 3621 considering vertical strikes one. The analysis focused on a connected transmission line spanning of about 2.1 km from the substation, revealing that non-vertical strikes have a higher probability of generating damaging currents. For instance, the most likely current amplitude for non-vertical strikes ranges from 26 to 41 kA, occurring with a probability of 0.0062 and representing 935 out of 4179 strokes. Conversely, vertical strikes within the same current range have a probability of 0.0054 representing 813 out of 3569 strokes. These findings demonstrate that non-vertical strikes present a significant risk and are frequent enough to necessitate serious consideration in protective strategy planning. Therefore, instead of recommending the installation of new surge arresters, the study suggests enhancing existing systems by strategically adding surge arresters at critical points, such as the substation entrance or in parallel with line insulators. This optimization would better protect against the risks posed by non-vertical lightning strikes. Future research should focus on assessing the performance of these enhanced systems against non-vertical strikes to better mitigate the associated risks.

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T. Hamel[1], *PhD Student,*
S. Bedoui[1], *Doctor of Science*,
A. Bayadi[2], *Professor*,
[1] Laboratory of Electrical Engineering and Automatic (LGEA), University of Oum El Bouaghi, Algeria,
e-mail: hameltaher04@gmail.com;
bs_1182@yahoo.fr (Corresponding Author)
[2] Automatic Laboratory of Setif (LAS), University of Setif-1, Algeria,
e-mail: a_bayadi@univ-setif.dz

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