Implementation of Heuristic Techniques to Evaluate the Indirect-Lightning Performance of Distribution Networks.

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Resumen

Título: Implementación de técnicas heurísticas para evaluar el desempeño de redes de distribución ante el impacto de rayos indirectos. *

Autores: Carlos Enrique Leal Torres, Nelson Fernando Flórez Orjuela. **

Palabras Clave: Técnicas heurísticas, sobre-tensiones inducidas por rayos, Yaluk-Draw, voltajes críticos de falla, tasa de fallas, desempeño de rayos indirectos, topología de red, conductividad del suelo, esfuerzo computacional, error medio, porcentaje de eventos descartados.

Descripción: En este artículo, utilizamos tres técnicas heurísticas diferentes aplicadas al análisis de desempeño de tres topologías de red cuando se ven afectados por el impacto indirecto de rayos como nuestro tema de estudio. Las técnicas seleccionadas incluyen la técnica heurística de Borghetti et al, la técnica de Rusck-Fórmula, y una técnica de regresión multivariable no lineal presentada por Soto et al. Los casos de prueba propuestos son una configuración de red de línea recta, una en forma de T y una en forma de H, con tres conductividades del suelo típicas. El principal objetivo es implementar cada técnica para reducir el número total de simulaciones inicialmente obtenidas usando el método de Monte Carlo para estimar la tasa de fallas de cada caso incluido en este estudio. Luego, los resultados se comparan en términos de esfuerzo computacional y precisión. Como resultado de la implementación de las técnicas heurísticas mencionadas, entre el 74 % y el 97,5 % de los eventos fueron descartados del número total de simulaciones con un error medio mínimo y máximo de 0 % y 17 %, respectivamente.

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* Trabajo de Grado.

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Abstract

Title: Implementation of Heuristic Techniques to Evaluate the Indirect-Lightning Performance of Distribution Networks. *

Authors: Carlos Enrique Leal Torres, Nelson Fernando Flórez Orjuela. **

Keywords: Heuristic techniques, lightning-induced overvoltages, Yaluk-Draw, critical flashover voltages, flashover rate, indirect-lightning performance, network topology, ground conductivity, computational effort, mean error, percentage of discarded events.

Description: In this paper, we use three different heuristic techniques applied to the performance analysis of three network topologies when impacted by indirect lighting strikes as our subject of study. The selected techniques include the Borghetti et al heuristic technique, a Rusck-Formula technique, and a Multi-nonlinear regression technique presented by Soto et al. The proposed test cases are straight-line, T shape, and H-shape configurations with three typical ground conductivities. The main goal is to implement each technique to reduce the total number of simulations initially obtained using the Monte Carlo method to estimate the flashover rate of each case included in this study. Then, the results are compared in terms of computational effort and precision. As a result of implementing the mentioned heuristic techniques, between 74 % and 97.5 % of events were discarded from the total number of simulations with overall minimum and maximum mean error values of 0 % and 17 %, respectively.

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* Undergrad Work

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Introduction

In the electrical engineering industry, lightning strikes are a phenomenon that affects distribution networks, causing them to fail due to the induction of overvoltages that exceed the insulation level of the line. Based on this problem, it becomes vital to understand, analyze and calculate the indirect-lightning performance of these distribution lines.

Different studies have been proposed through several scientific publications that use mathematical methodologies to obtain the performance of the distribution lines when impacted by indirect lightning (11; 10; 6) including the proposed in (10) that uses the Monte Carlo method to obtain the flashover rate of the overhead lines by generating a significant number of lightning strikes near the lines, followed by a density probability model set by CIGRÉ. Then, it calculates the induced voltages with the Rusck Formula (5). The lightning-induced overvoltage (LIOV) code is proposed in (16), adapted to calculate induced overvoltages when the lightning strike phenomenon occurs near an overhead distribution line. Similar methods have implemented the LIOV code, like the LIOV-EMTP code proposed in (17), which incorporates the LIOV code with the electromagnetic transient program (EMTP), allowing the calculation of more complex network configurations; or the method found in (6), which suggests the usage of the LIOV code alongside the Monte Carlo method (LIOV-MC).

A general modeling approach is recommended by the IEEE STD. 1410-2010 (1), which suggests more elaborate models like the one proposed by Nucci and Rachidi (16) and the Agrawal et al electromagnetic coupling model in (2), both implemented into a computer code as proposed in (17).

The implementation of the previous procedures to calculate the performance of distribution lines represents a high computational cost. It is worth mentioning that these analyses relate the induced overvoltages with parameters such as the return stroke current peak, front duration, and impact coordinates, taking into account other factors, including the soil conductivity and network topology. Therefore, the complexity of the statistical analyses, taking into account all aforementioned parameters, tends to increase the computational effort.

For real-life applications, reducing the computational effort and providing a reliable analysis in an admissible period of time becomes important for distribution line designers and other stakeholders in the industry, acknowledging the expenses and resource losses that a failure on the distribution lines may represent.

Several works have proposed various heuristic techniques (7; 21; 4; 8; 9; 15; 14; 22) in an attempt to obtain similar statistical outcomes while reducing the total number of required simulations, directly decreasing the computational effort. The first known approach is the Borgheti et al (7) heuristic, introducing a procedure that discards indirect strike events when certain conditions are met, graphically comparing parameters with all previously calculated events. A Multi-nonlinear regression technique is presented in (21) and (22), proposed by Soto et al, achieving the calculation of an induced voltage by using the results of other already simulated strikes within a given sub-area.

Later on, other techniques were proposed, including Napolitano et al. (15), a technique that admits a significant reduction in the number of simulations based on the total calculated by the Monte Carlo method and the LIOV-EMPT code. It uses a sampling-stratified approach to avoid computing the events in the time-domain that are not expected to generate as much damage to the line as all the previously calculated events, dividing the total striking area into subdomains and estimating the probability and variance of only the calculated events that exceed an admitted peak voltage.

Mestriner et al (14) have also proposed an interesting method that evaluates the dependence relation between the estimated induced voltage and some independent variables such as front time, peak current, and distance from the stroke location to the line in Y_F coordinates on a designated X_F interval, using a least squares regression method to present an approximate formula within a certain domain determined by the Rusck and Rusck-Daverniza formulas.

A heuristic technique presented in (22) establishes an approach to the Rusck-Formula that models the behavior of distribution lines, considering the stroke location (which is generated by the Monte Carlo method and limited by the Rusck formula), return stroke speed, and height of the line, among other variables, and calculates the induced overvoltages of interest that surpass a specific critical voltage Vc.

In this paper, three heuristic techniques proposed in (7; 21; 22) are selected and implemented in different scenarios, in order to compare their results and analyze which technique represents a greater reduction of computational cost while estimating—accurately—the indirect-lighting performance of simple and complex distribution network topologies.

This paper is structured as follows: Section II presents the selected heuristic techniques to be implemented and the features that will be evaluated to compare all three techniques. In section III, the designed base case and simulated test cases are presented. Section IV presents the results obtained by implementing all heuristic techniques on all test cases and analyses. Section V finally exhibits conclusions based on an overall comparison of the results.

1. Objectives

1.1. General Objective

To implement, compare and categorize, using different heuristic techniques, the methods that represent the lowest computational cost possible to evaluate the performance of distribution networks when impacted by indirect lightning strikes.

1.2. Specific Objectives

- To implement at least three heuristic techniques to reduce the computational cost when obtaining the indirect-lightning performance of distribution networks under the IEEE 1410-2010 STD. guidelines.

- Calculate the flashover rate of a ramified distribution network using the chosen heuristic techniques.

- Analyze which of the heuristic techniques has a better performance comparing the obtained results in terms of computational effort and accuracy.

2. Indirect lightning performance evaluation method and heuristic techniques

In order to calculate the indirect-lightning performance of a distribution line, the proposed methodology by the IEEE STD. 1410-2010 (1) is adopted. The Monte Carlo procedure generates a total number of strikes, defined as n_{tot}, located within a striking area A. Each stroke location is randomly generated, with x and y coordinates that follow a uniform probability distribution model. Peak current Ip and front time t_f correlated values adopt log-normal distribution probabilities established by CIGRÉ, as shown in (1991).

Several events considered direct strikes are discarded from $n_{t_{ot}}$, according to the lightning incidence model parameters and the electro-geometric method (1990), only keeping indirect strikes for further calculation.

Yaluk-Draw software (18) simulates all generated events within a striking area A and calculates the lightning-induced voltages using the Agrawal coupling model (2), which is linked to the ATP transient program and includes the effect of soil resistivity. Yaluk-Draw uses the TL or MTLE lighting channel models and a Heidler function (13) for the channel-base current.

The software uses the Master and Uman equations to compute the electromagnetic field (23) and considers the Cooray-Rubinstein approach (19) for soil conductivity (σ). Once all simulations are calculated, the software estimates the flashover rate with the following equation:

$$F_p = \frac{n}{n_{tot}} \cdot N_g \cdot A \tag{1}$$

In (1), n is the number of strikes that exceed the expected CFO (Critical flashover voltage) of the line, n_{tot} is the total number of simulation strikes. N_g is the annual ground flash density (flashes/km/yr), and A is the striking area (km^2) where the strokes are located.

With the data collected for each case, three heuristic techniques are implemented individually to analyze and compare how each one reduces the computational effort required to calculate the performance of a distribution line as the subject of study. This reduction is achieved by accurately estimating the annual rate of flashover events using only a certain percentage from the total simulated events (n_{tot}) but aiming to keep the lowest acceptable error in the obtained flashover rate.

The following heuristic techniques were chosen since they present an approach to reducing computational cost in the evaluation of the performance of distribution lines, keeping a moderate error. Also, these techniques focus on providing accurate results while being implemented from very ideal scenarios to more complex network topologies and line designs with different ground conductivities.

2.1. Borghetti et al heuristic

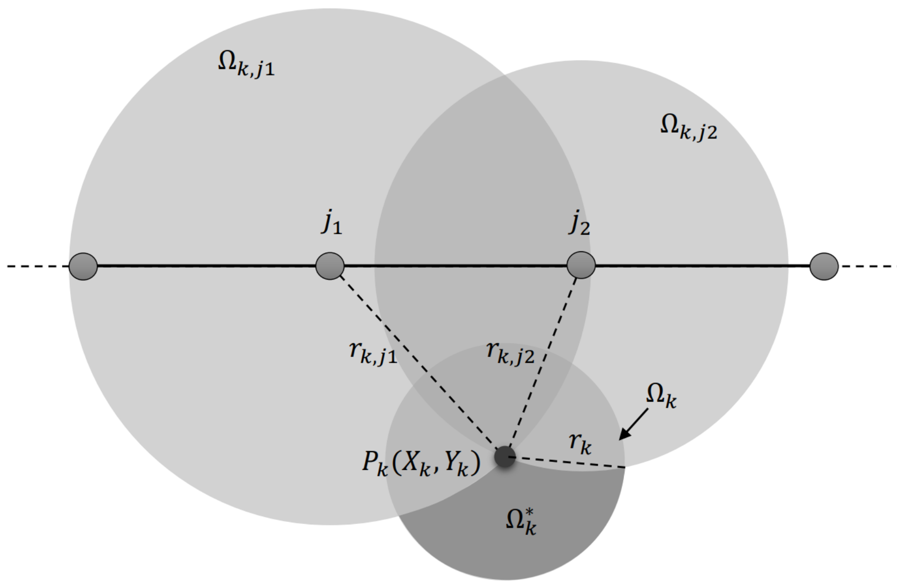


Figure 1. Borghetti et al heuristic technique scheme: top view of the overhead line defining radii between j_1 and j_2 poles, and stroke location $P_k(X_k, Y_k)$ and Ω_k and Ω_k^* areas. Taken from (7).

This heuristic technique presented in (7) discards events through a graphic procedure where two radii ($r_{k,j1}$, and $r_{k,j2}$) are defined from a distance between the strike position and the closest poles to it, creating two circular areas centered on each pole of interest ($\Omega_{k,j1}$ and $\Omega_{k,j2}$, respectively), a circular area (Ω_k) centered on each strike position is created, as shown in Fig. 1. Then, comparing the maximum induced voltage value ($V_{max,k}$) calculated at each line pole for a current event "k" with the maximum induced overvoltages of all previously-calculated events (i-1 events). It also considers the following parameters and conditions for each event, being Ik the current amplitude, $t_{f,k}$ the time to peak or front time, and Pk the stroke location with x_k and y_k coordinates:

a) $P_i \in \Omega_k^*$ with $V_{max,k} < \bar{V}$;

b) $I_i \leq I_k$;

c) $t_{fi} \geq t_k$;

where $\Omega_k^* = \Omega_k - \{\Omega_{k,j1} \cup \Omega_{k,j2}\}$ and $\bar{V}$ is the minimum accepted insulation level of the conductor. If the current event complies with all previous conditions, compared to all pre-calculated induced overvoltages relevant to the i-th event, then the induced voltage for the event in question is not simulated, excluding it directly from the total number of strikes that can potentially cause a flashover.

2.2. Multi-nonlinear regression technique (MLRT) Soto et al

This Multi-nonlinear regression technique proposed in (21) and (22) divides the total area A into squared sub-areas with a side of value L, and then calculates the induced voltage based on nearby previously-calculated strikes until a minimum amount of strikes (n_f) is reached within each sub-area, using a least squares fit to follow the dependence of the presented regression model:

$$V_{i_{nd}} = I_p^a \times t_f^b \times R_0^c$$

$$\ln(V_{i_{nd}}) = a \cdot \ln(I_p) + b \cdot \ln(t_f^b) + c \cdot \ln(R_0^c) \tag{2}$$

Logarithmic terms are used to approximate the dependence behavior between the induced voltage ($V_{i_{nd}}$) and the variables I_p, t_f, and R_0, where I_p is the peak current, t_f is the front time, and

R_0 is the closest distance possible between the line and each lightning strike. What Multi-nonlinear regression achieves is to find adequate values for the coefficients a, b, and c in order to provide a valid model for a specific network.

2.3. Rusck-Formula heuristic technique

This heuristic technique applied in (22) can be described in two stages. First, it uses the Rusck formula, as proposed in (5), to limit the domain of the strike locations generated by the Monte Carlo method and determine the dependence between each calculated lightning-induced voltage and the different variables that are part of the following equation:

$$V_r = \frac{Z_0 I_0 h}{d}\{1 + \frac{v}{\sqrt{2 \cdot c^2 - v^2}}\} \tag{3}$$

where Z_0 is an impedance with an approximate value of 30 Ω, I_0 is the return stroke current amplitude assumed as a step function (in kA), h is the height of the line (in m), d is the shortest distance from the stroke coordinates to the line (in m), v is the return stroke speed (m/µs) and c is the speed of light constant (in m/µs).

The second step is to use Yaluk-Draw software (18) to compute only the events that surpass the minimum critical voltage (V_c) chosen for a specified distribution network, discarding the events that are unlikely to generate a flashover based on the results from (3).

There are two relevant features of each distribution network topology and conductivity when calculated by means of the three heuristic techniques adopted in this paper: the percentage of discarded events against the total number of simulations from the base case (PDE), calculated by the following equation:

$$PDE = \frac{n_{dis}}{n_{ind,tot}} \times 100 \quad (4)$$

where n_{dis} is the amount of discarded strikes that were not used in the calculations of each heuristic technique and $n_{ind,tot}$ is the total number of simulated indirect lightning strikes (previously discarding all direct strikes) for each test case.

The second feature is the mean error (E %) between the flashover rates obtained by the heuristic techniques ($F_{p,test}$) against the reference Fp values obtained in the base case ($F_{p,ref}$) using (1) by simulating the total number of indirect lightning strikes. It is evaluated by the following equation:

$$E\,\% = \frac{1}{N_c}\sum_{i=1}^{N_c} |F_{p,test} - F_{p,ref}|/F_{p,ref} \quad (5)$$

In (5), N_c is the total number of calculated points selected in the flashover rate curve.

3. Base case and Test cases

The distribution line, as a test subject, must be designed under specific parameters in accordance with current regulations for medium voltage network installations; these parameters are defined by the manufacturing standard ASTM B232 (Astm).

3.1. Base Case

For all simulations and network topologies, the distribution line base case in this paper is defined by certain parameters and specifications. The ACSR (Astm) line chosen is a Raven model, 1 AWG gauge, one class A zinc-coated steel core, and six 1350-H19 aluminum wires concentrically wired. This design selection establishes, alongside other parameters for the base case, a single conductor with a 5 mm radius, a 10 m height, and a finite overall length of 2 km. Regardless of the configuration or topology, the line design will have poles every 100 m and fixed-value resistors with a value of 497.3 Ω added at the extremities of the lines to avoid reflection (matched ends); this value corresponds to the characteristic impedance of the line and depends on the length and height of the distribution line in question.

3.2. Test Cases

The type of conductor selected in our base case for distribution network installations is commonly used in the industry, as are the three different topologies contemplated for the test cases in this paper.

Table 1

Test Cases: Network topology classification

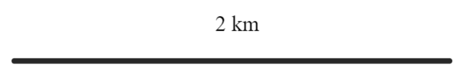
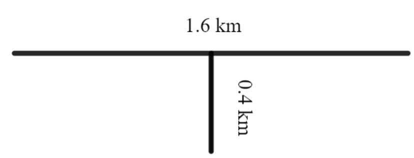
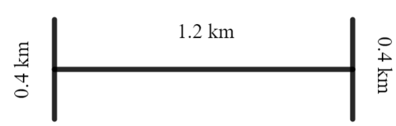
Test Cases	**Network Topology Shapes**
Straight-line configuration	
T-shaped configuration	
H-shaped configuration	

Table I shows that the first test case is a 2 km straight-line configuration. The second test case is a T-shape network with a 1.6 km main feeder and a 0.4 km middle branch. A third test case presents an H-shaped network, with a 1.2 km main feeder and 4 laterals with a 0.2 km length each, keeping the 2 km length in its entirety for each test case. It is worth mentioning that all topologies are tested with three assumed typical ground conductivity (σ) values: infinite, 0.01 S/m, and 0.001 S/m.

Striking areas are chosen differently depending on the test case network topologies shown in Table I since their symmetry varies from one to another. For the straight-line and H-shaped test cases, a quarter of the total striking area is sufficient to achieve proper calculations, being, for the straight-line test case, a 2 x 1 km rectangle for infinite conductivity and 3 x 2 km rectangle for finite conductivities, and for the H-shaped test case, a 1.6 x 1.2 km rectangle for infinite conductivity and 2.6 x 2.2 km rectangle for finite conductivities. The symmetry of the T-shape test case requires at least half of the total striking area, setting a 1.8 x 2.4 km rectangle and a 2.8 x 4.4 km rectangle for infinite and finite conductivities, respectively.

An MTLE model with a chosen attenuation constant equal to 2000 m is selected for the lightning channel, with an assumed return stroke speed of 120 m/µs. The channel base current is set to be a double Heidler function, as described in (13).

For the purpose of this paper, it is worth mentioning that all the Broghetti et al results were obtained with rk = 400 m, as it is found in (7) that r_k values between 100 and 400 m provide the most accurate results with a considerably 70 % reduction from all simulated events. For the MLRT Soto et al technique, n_f will have a value between 15 to 25, and side L will have a value between 200 and 400 m, selecting the most suitable value combinations for each ground conductivity, as these are found to be the best possible value ranges in (21) in terms of the percentage of discarded events and the mean error (precision).

The best performance for the straight-line configuration was found by selecting an L value of 400 m and an n_f value of 15 for finite conductivities. The selected values for an infinite ground conductivity were 300 m and 25, respectively.

The selected values for the T-shape configuration are L = 400 m (square sub-area side size), n_f = 25 for infinite conductivity, and n_f = 15 for finite ground conductivities.

The best performance results, in terms of PDE and E %, on the H-shape configuration were achieved by setting L to 400 m and n_f to 20 for all conductivities.

Note that the minimum insulation level $\bar{\text{V}}$ and the critical voltage V_c are 50 kV for Borghetti et al and Rusck-Formula techniques, respectively.

4. Analysis of computational effort reduction and accuracy results

The base case previously presented for each network topology is first fully simulated for a total of 10,000 lightning strikes, using no heuristic techniques, so it is possible to compare the flashover rate (F_p) values obtained by means of the three aforementioned heuristic techniques, considered as test results, with the results from the original calculations made using the total number of simulations for each ground conductivity. The comparison between the test results—which are similar to the ones obtained in previous studies (7; 21; 22)—and the base case results can also illustrate the reduction of computational cost and time in terms of the amount of discarded events that, according to each technique, do not need to be calculated in order to achieve the expected results.

Fig. 2, 3, and 4 present the $F_{p,test}$ results for the straight-line, T-shape, and H-shape test case, respectively, by applying each heuristic technique, Borghetti et al, MLRT Soto et al, and the Rusck-Formula heuristic, in comparison with the reference $F_{p,ref}$ curve, called Base Case, for all three ground conductivities. This shows how the flashover rates increase when lower soil conductivities are given. It also illustrates how fitting each heuristic technique is and the accuracy of the test case results when compared to the reference curves.

4.1. Implementation of all techniques on the Straight-line test case

Table II shows the performance of the three heuristic techniques applied to the straight-line test case. PDE and E% values for each conductivity are presented. Given the results in Table II and Fig. 2, it is seen that the Rusck-Formula heuristic achieves, in general, the highest percentage of discarded events (PDE) and lower mean error values (E%).

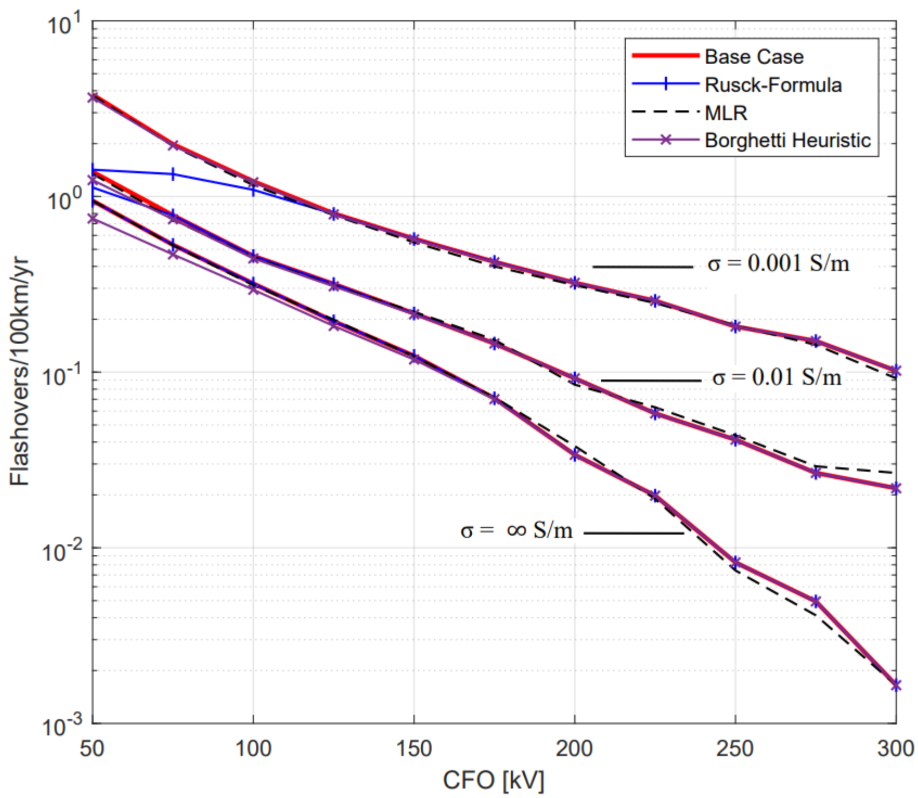


Figure 2. Flashover ($F_{p,test}$) curves of the straight-line test case by means of all 3 heuristic techniques compared against the reference flashover ($F_{p,ref}$) curve for all 3 conductivities.

Rusck-Formula presents a considerable increase in the PDE for lower soil conductivity values, while the MLRT technique keeps similar PDE and E% values, not following any pattern

Table 2

PDE and E% results by implementing all heuristic techniques in the straight-line test case

		Borghetti et al		**MLRT**		**Rusck-Formula**	
Test Cases	**σ (S/m)**	**PDE**	**E%**	**PDE**	**E%**	**PDE**	**E%**
Straight-line	∞	84.13	4.74	92.78	4.53	81.58	0.00
	0.01	85.09	2.06	93.93	6.58	94.07	1.69
	0.001	74.36	0.82	93.93	3.82	94.07	9.68

in particular. Borghetti et al heuristic technique presents a proportional behavior regarding the soil conductivity values; for lower conductivities, PDE and E% decrease, with a mean error as low as 0.82%, obtaining more accurate results but requiring a higher computational cost. This technique also shows the lowest variability in mean error values for finite conductivities, keeping them between 0.82% and 2.06%, while the other techniques have a more considerable change in E% values.

The MLRT heuristic provides a more appropriate approach regarding finite soil conductivities, obtaining the second-lowest mean error from the three heuristic techniques, lower than 7%, for this test case.

Between the three presented heuristic techniques, the Rusck-Formula heuristic shows, for finite conductivities, the highest percentage of discarded events (94.07%) while getting the lowest E% value of 0% on infinite soil conductivity and 1.69% on a soil conductivity of 0.01 S/m.

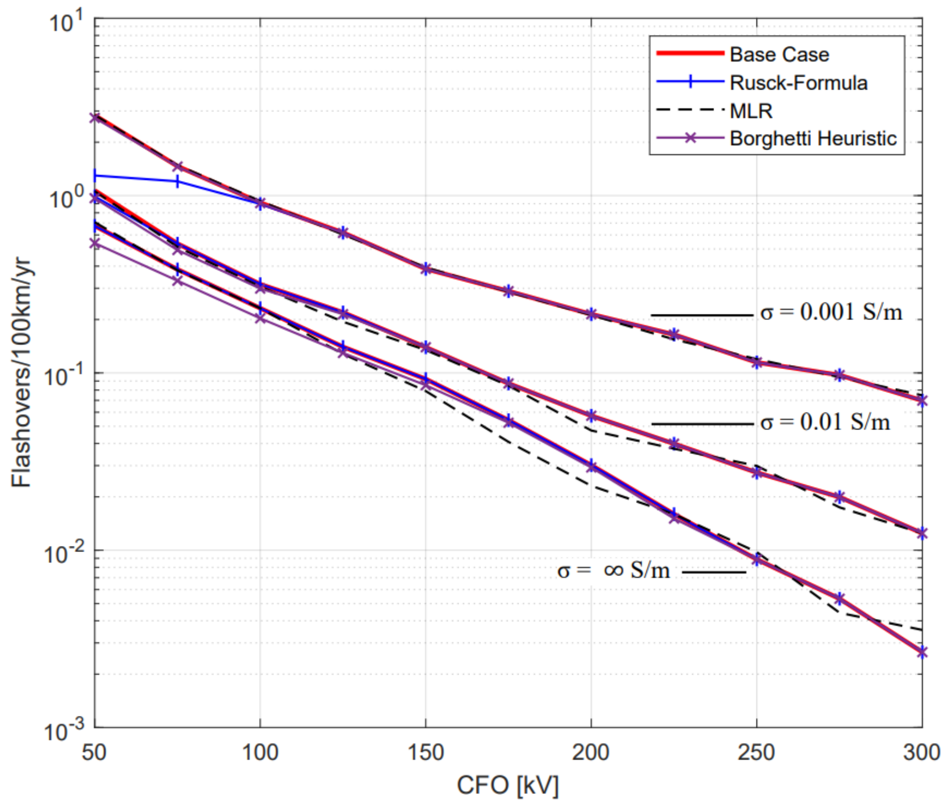


Figure 3. Flashover ($F_{p,test}$) curves of the T-shape test case by means of all 3 heuristic techniques compared against the reference flashover ($F_{p,ref}$) curve for all 3 conductivities.

4.2. Implementation of all techniques on the T-shape test case

Table III shows the performance of the three heuristic techniques applied to a T-shape test case. PDE and E % values for each conductivity are presented.

For infinite conductivity, the Rusck-Formula heuristic shows a percentage of discarded events of 84.11 % with a 0 % mean error, achieving the most precise results possible for this T-shape configuration. MLRT Soto et al heuristic technique presents the highest mean error (12.49 %) but

Table 3

PDE and E% results by implementing all heuristic techniques in the T-shape test case

		Borghetti et al		**MLRT**		**Rusck-Formula**	
Test Cases	**σ (S/m)**	**PDE**	**E %**	**PDE**	**E %**	**PDE**	**E %**
T-Shape case	∞	84.42	6.64	92.29	12.49	84.11	0.00
	0.01	81.27	2.30	88.32	6.48	94.72	0.67
	0.001	74.09	0.43	88.31	2.76	94.72	6.70

discards the highest number of events for this test case (92.29%). Note that E% diminishes while the soil conductivity decreases. However, in terms of finite conductivities, PDE values remain the same.

MLRT heuristic reaches the most relevant E% reduction, going from 12.49% (infinite ground conductivity) to 2.46% in a 0.001 S/m soil conductivity.

E% and PDE values obtained by Borghetti et al heuristic decrease for lower conductivity values. This could mean that Borghetti et al heuristic is not the most ideal technique to reduce computational effort, but it provides the most reliable estimation of flashover rates (Fig. 3) for low ground conductivities in this particular test case.

4.3. Implementation of all techniques on the H-shape test case

Table IV shows the performance of the three heuristic techniques implemented in the evaluation of an H-shape test case. PDE and E% values for each conductivity are presented.

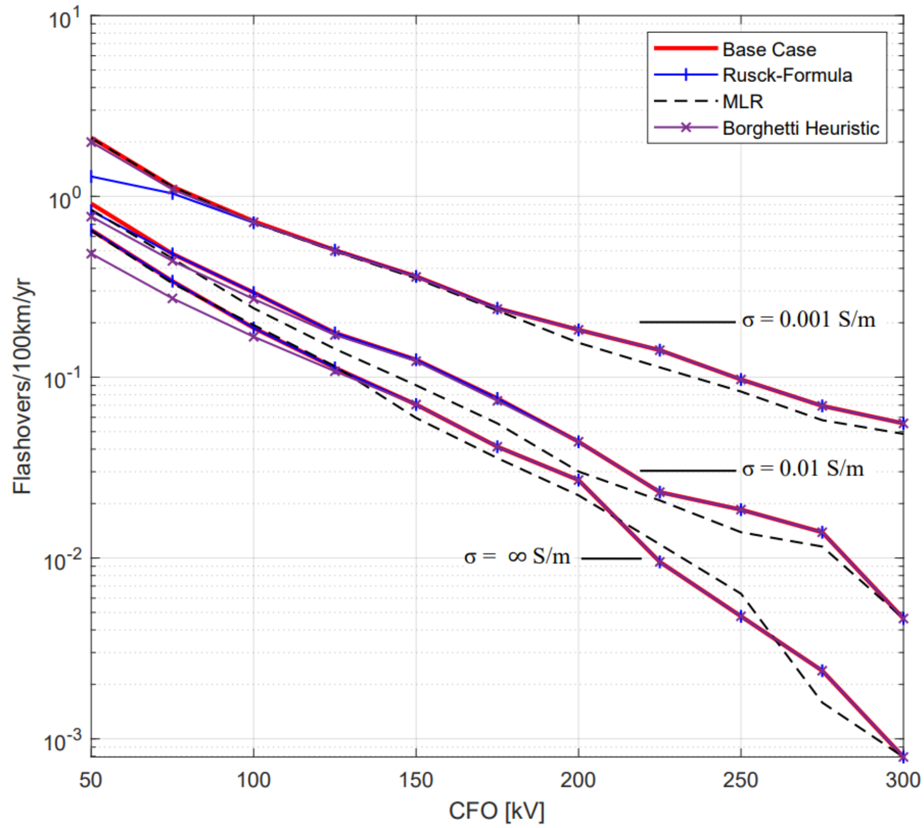


Figure 4. Flashover ($F_{p,test}$) curves of the H-shape test case by means of all 3 heuristic techniques compared against the reference flashover ($F_{p,ref}$) curve for all 3 conductivities.

In this test case, the highest PDE value is obtained by the MLRT Soto et al heuristic for infinite conductivity (97.52 %). It also presents the highest mean error, 13.48 % for infinite conductivity and 17.09 % for 0.001 S/m conductivity.

Borghetti et al heuristic discards more than 80.34 % of all simulated events while presenting acceptable E % values, equal to 5.5 % or less, considerably lower than the mean error values obtained by MLRT.

Table 4
PDE and E% results by implementing all heuristic techniques in the H-shape test case

		Borghetti et al		**MLRT**		**Rusck-Formula**	
Test Cases	**σ (S/m)**	**PDE**	**E %**	**PDE**	**E %**	**PDE**	**E %**
H-Shape case	∞	87.56	5.50	97.52	13.48	82.34	0.00
	0.01	86.40	3.57	91.50	17.08	94.35	0.80
	0.001	80.34	1.16	91.50	7.97	94.35	4.46

The Rusck-Formula technique exhibits the most accurate results, achieving a 0% mean error for infinite ground conductivity and slightly increasing for finite conductivities, while E% remains below 5%. It also achieves the highest PDE value (94.35%) among all three techniques for finite conductivities.

4.4. Comparison between heuristic techniques

The nature of the previous results for each applied heuristic technique, on all test cases, are compared and analyzed to have a better comprehension of the precision that each one offers on different scenarios, regarding the reference base case, also to identify how the techniques behave in terms of accuracy (mean error E%) and amount of discarded events (PDE) while the test-case complexity increases.

By analyzing the reference curves and the achieved results by means of the three heuristic techniques on different network topologies, it is seen that due to its symmetry and the main-feeder length, the straight-line test case presents higher flashover rate curves than the other two—more compact—topologies, T-shape and H-shape, respectively.

It is also possible to notice the importance of the ground conductivity and its effect on the flashover rates due to its influence on the lightning electromagnetic pulse (LEMP) propagation explained in (6). Fig. 2, 3, and 4 illustrate how the base case performance improves for higher ground conductivity values regardless of the network topology.

The Rusck-Formula technique allows discarding the highest amount of simulated events for finite conductivities on any network topology presented, achieving a PDE between 94.07 % and 94.35 % and reasonable E % values that do not exceed 10 %, reaching the lowest possible mean error (0 %) in all infinite soil conductivity test cases. It is also seen that E % increases for lower soil conductivity values but tends to decrease, overall, on more complex topologies. On the contrary, MLRT heuristic increases its E % values when the topology complexity increases (from the straight-line configuration to the H-shape configuration, respectively), and Borghetti et al heuristic does not follow any identifiable pattern.

The mean error values obtained by MLRT Soto et al technique indicate no proportional relation with L values (sub-area side values) or nf values. When choosing the appropriate values for each test case and ground conductivity, this technique accomplishes a reduction of simulated events between 88.31 % and 97.52 % with admissible E % values higher than those obtained with the Rusck-Formula technique.

Regarding the aforementioned techniques, Borghetti et al present the lowest percentage of discarded events for any network topology. Although its PDE values are the lowest compared to the other techniques, it eliminates between 74.09 % and 87.56 % of the total number of simulations. This is still a significant reduction in the computational effort. Note that this technique obtained lower E % values than the MLRT heuristic for all conductivities, being the second most accurate technique found after the Rusck-Formula heuristic.

Regarding the mean error, Borghetti et al. show a decreasing behavior since it reaches lower E % values when evaluating lower ground conductivities, becoming a reliable technique for low ground conductivities in any network topology.

5. Conclusions

Three heuristic techniques have been implemented in order to reduce the computational cost—in terms of the number of discarded simulated events—to evaluate the performance of different distribution networks when influenced by indirect-lightning strikes while keeping acceptable mean error values for accuracy purposes. The first technique, proposed by Borghetti et al, compares certain parameters graphically and discards events that do not generate a considerable overvoltage above a critical insulation level. The second one is a Multi-nonlinear regression technique proposed by Soto et al, which uses a logarithmic multi-variable model to approximate the dependence behavior between the induced voltages and other parameters relevant to the calculations, also dividing the total striking area in sub-areas with specific L side values and n_f numbers of strikes considered within each sub-area. The third technique is the approach of the Rusck Formula presented in (22), defining the domain of the relevant parameters and only calculating the events that can induce voltages higher than an established critical flashover voltage value. The results have been presented and compared for three conductivity values and three different network topologies representing increasing complexities, starting from a straight-line configuration to a T-shape configuration and an H-shape topology.

The implementation of the Borghetti et al heuristic technique on the straight-line test case allows a reduction between 74.3 % to 85 % of the total simulated indirect lightning strikes. When implemented on more complex topologies, it discards up to 84.4 % on a T-shape test case and up to 87.5 % on an H-shape test case, providing an expected reduction in computational effort. This technique presents a decreasing mean error for lower ground conductivity values, also obtaining the second lowest overall E %, becoming the second most accurate technique after the Rusck-Formula heuristic.

The application of MLRT Soto et al shows a reduction between 92.7 % and 93.9 % of all simulated events on a straight-line test case while achieving a PDE of up to 92.3 % and 97.5 % on T-shape and H-shape test cases, respectively. Although it provides the best performance regarding computational cost reduction, it presents the highest mean error values, reaching up to 17 % on a complex H-shape network topology. This technique can be considered the most effective in reducing computational cost but the least accurate among the others.

The Rusck-Formula technique eliminates up to 94 % of the total number of simulated strikes in a straight-line test case and up to 94.7 % and 94.3 % of the total simulations in the T-shape and H-shape test cases, respectively, obtaining the second-highest percentage of discarded events for all topologies and ground conductivities. What makes Rusck-Formula the most reliable technique is that it greatly reduces computational costs, in terms of PDE, on all test cases while providing the most accurate flashover rates compared to the other techniques. In all test cases, it achieves a total accuracy (E % = 0 %) for infinite ground conductivity, also reaching error values as low as 1.7 % for 0.01 S/m conductivity and lower than 10 % for 0.001 S/m conductivity on all network topologies.

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