PREPRINT

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Optimisation of the Distribution System Reliability with Shielding and Grounding Design under Various Soil Resistivities

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ABSTRACT

Lightning strikes can cause equipment damage and power outages, so the distribution system's reliability in withstanding lightning strikes is crucial. This research paper presents a model that aims to optimise the configuration of a lightning protection system (LPS) in the power distribution system and minimise the System Average Interruption Frequency Index (SAIFI), a measure of reliability, and the associated cost investment. The proposed lightning electromagnetic transient model considers LPS factors such as feeder shielding, grounding design, and soil types, which affect critical current, flashover rates, SAIFI, and cost. A metaheuristic algorithm, PSOGSA, is used to obtain the optimal solution. The paper's main contribution is exploring grounding schemes and soil resistivity's impact on SAIFI. Using 4 grounding rods arranged in a straight line under the soil with 10 Ωm resistivity reduces grounding resistance and decreases SAIFI from 3.783 int./yr (no LPS) to 0.146 int./yr. Unshielded LPS has no significant effect on critical current for soil resistivity. Four test cases with different cost investments are considered, and numerical simulations are conducted. Shielded LPSs are more sensitive to grounding topologies and soil resistivities, wherein higher investment, with 10 Ωm soil resistivity, SAIFI decreases the most by 73.34%. In contrast, SAIFIs for

ARTICLE INFO

Article history:
Received: 14 June 2023
Accepted: 18 December 2023
Published: 04 April 2024

DOI: https://doi.org/10.47836/pjst.32.3.15

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ISSN: 0128-7680
e-ISSN: 2231-8526

1 kΩm and 10 kΩm soil resistivities show minor decreases compared to SAIFIs with no LPS. The study emphasises the importance of considering soil resistivity and investment cost when selecting the optimal LPS configuration for distribution systems, as well as the significance of LPS selection in reducing interruptions to customers.

Keywords: Distribution system reliability, grounding system design, lightning protection system, lightning transient model, metaheuristic optimisation

INTRODUCTION

Lightning strikes can result in substantial consequences for power distribution systems, leading to power blackouts, equipment impairment, and potentially endangering public safety. Lightning can cause power outages by directly impacting overhead lines or inducing an overvoltage in the wiring. Researchers worldwide are continuously working to enhance the dependability of power distribution systems by improving lightning protection systems (LPS), aiming to decrease power outages caused by dangerous weather conditions (Executive Office of the President, 2013). When people plan how to protect distribution systems from lightning strikes, deciding on the appropriate lightning protection system (LPS) and its placement can be challenging. Therefore, the utilities use much information like past experiences and reliability data, as well as technical knowledge to make good decisions for LPS design (Katic & Savic, 1998; Orille-Fernández et al., 2004; Shariatinasab et al., 2014).

According to IEEE 1410-2010 (2011), one approach to enhance the distribution system's reliability is to make it resistant to lightning by installing lightning arresters in appropriate locations. Another method to minimise the risk of power outages involves using insulators with high critical flashover (CFO) voltage and installing a shielding wire above the phase conductors. Additionally, reducing the grounding resistance of the system is crucial, necessitating a study of soil resistivity and the design of the grounding system to impact grounding resistance.

The IEEE 998-2012 (2013) says that adding shielding wires can help improve the lightning protection performance of transmission lines. Some researchers have studied these shielding effects and found that installing shielding wires can reduce the number of flashovers or overvoltage caused by lightning strikes on transmission lines (Metwally & Heidler, 2003; Paolone et al., 2004).

The previous paper (Shariatinasab et al., 2014) proposed a method for optimising arrester location based on a risk assessment approach that considers both the probability and consequences of overvoltage events to mitigate the risk of lightning-induced overvoltage. The authors noted that while an arrester was installed, it could reduce the risk of overvoltage, but improper location of arresters could result in inadequate protection and increased costs.

However, using the hybrid approach for risk assessment and arrester optimisation in this paper is complex compared with recent studies.

A recent study by Zhang et al. (2020) proposed a model that simulates the electromagnetic transients caused by indirect lightning in a distribution network. The model considered scenarios with and without protection measures, such as lightning wires and lightning arrestors, and found the optimal LPS configuration with cost constraints using mixed-integer linear programming (MILP). Zhang et al. (2021) have also recognised the character of the problem of multiple objectives interacting with each other and proposed an optimised multi-objective interdependency model while considering the combination of LPSs with cost constraints. However, only three LPSs are combined, so the selectivity of LPSs can be increased to further optimise the system's reliability.

In previous studies (Cabral et al., 2012, 2013), the lightning electromagnetic transient model can simulate the electromagnetic transient process caused by lightning in distribution networks. The authors used a feeder model to simulate and evaluate the performances of shielding of feeders and grounding resistances against lightning. The system with a shielded feeder and lower soil resistivity can withstand larger lightning currents. Based on the studies above, Cabral et al. (2018) and Bretas et al. (2018) have developed an optimisation strategy for the combination of shield wires and grounding designs as a lightning protection system (LPS) that considers multiple distribution reliability indexes. Additionally, the authors have considered constraint conditions to ensure the best possible protection for the system. These two papers analysed the effectiveness of lightning rods and lightning wires on the distribution system's reliability based on cost constraints. Neither of these references mentioned the effect of soil resistivity on various soil types. These two papers only considered 5 types of grounding design; many more grounding designs described in IEEE 142-2007 (2007) can be further studied.

In summary, the publications above have indicated that optimising LPS for distribution networks remains a subject of ongoing research. Lightning strikes can significantly impact power distribution systems, and proper lightning protection measures are essential to prevent damage and ensure system reliability. Grounding, surge protection, and shielding are essential components of lightning protection systems, and their effectiveness should be evaluated through simulations and field testing.

This paper presents a MILP model to minimise a reliability index that quantifies the average frequency of sustained interruptions in a distribution system while considering the associated costs. An 80-line section distribution system (Bretas et al., 2018) is utilised in the model to assess the effectiveness of the proposed LPS design model. The model incorporates an LPS design strategy that takes into account both sustained interruptions and the number of affected customers for every line section. By utilising the PSOGSA (Particle Swarm Optimisation with Gravitational Search Algorithm) metaheuristic algorithm, globally optimal LPS configurations are able to be obtained for the distribution system. The test results confirm the feasibility and robustness of our optimisation model.

This paper explains the proposed approach for determining the critical current using the ATPDraw transient model, estimates the fault rate resulting from lightning strikes, and introduces the optimisation model. Firstly, only one type of LPS configuration is applied to the whole system. Then, 4 test cases with different investment costs are compared to find the best LPS solutions under the costs. Finally, the inferences drawn from our research are summarised.

METHODOLOGY

The main objective of the proposed optimisation is to find the best Lightning Protection System (LPS) for the distribution network while minimising both the System Average Interruption Frequency Index (SAIFI) and the cost investment. The study by Cabral et al. (2012) provides information on the characteristics, specific parameters, and models related to the overhead distribution feeder and the system's transient response. The LPS optimisation models and parameters proposed by Cabral et al. (2018) and Bretas et al. (2018) are also reviewed and referenced.

Figure 1 illustrates the methodology employed for optimising the distribution system's reliability. It elucidates the system's response characteristics to lightning under different LPS conditions, which are taken into account when deriving and optimising the system reliability model.

ATPDraw Lightning Simulation

Grounding resistance is the resistance of the connection between the electrical system and the earth. In a power distribution system, grounding is an essential safety measure that helps to protect people and equipment from the harmful effects of electrical faults and lightning strikes. When a fault occurs in an electrical system, such as a short circuit, excess current flows through the ground, which can be dangerous to people and equipment. Grounding provides a low-resistance path for this current to flow to the earth, minimising the risk of electrical shock or damage to equipment.

The arrangement of grounding rods and the type of soil can significantly affect the grounding resistance of a power distribution system. The grounding rod is the electrode that is buried in the earth and provides the connection between the electrical system and the ground. The soil surrounding the grounding rod determines the resistance of the grounding system. The effect of soil resistivity on the ground resistance of power distribution systems is an important consideration in designing effective lightning protection systems. The soil resistivities of various soil types used in this paper can be found in IEEE 80-2013 (2015), as shown in Table 1.

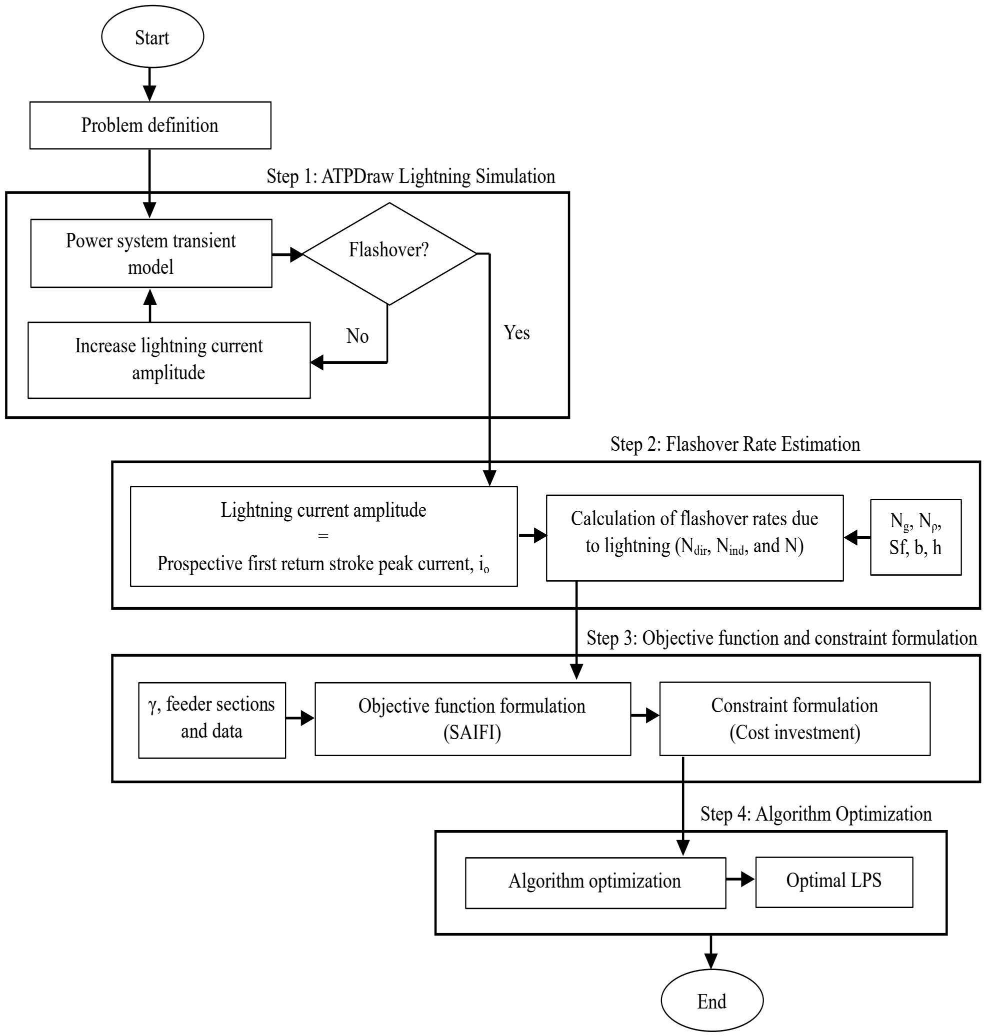

Figure 1. Data flow chart of distribution system reliability optimisation

Table 1
Soil resistivity of different soil types (IEEE, 2015)

Soil Type	Soil Resistivity (Ωm)
Wet organic soil	10
Moist soil	100
Dry soil	1k
Bedrock	10k

Five types of grounding designs are considered in this paper, and Equations 1 to 5 are used to determine the grounding resistance of each design, respectively. The arrangement of grounding rods can be found in IEEE Std. 142 and Military Handbook MIL-HDBK-419A (Department of Defense, 1987).

1. Single vertical rod

$$R_g = \frac{\rho}{2\pi L}\left(ln\frac{4L}{r} - 1\right) \quad [1]$$

2. Single horizontal rod

$$R_g = \frac{\rho}{\pi L}\left(ln\frac{2L}{\sqrt{2rd}} - 1\right) \quad [2]$$

3. Two vertical rods

$$R_g = \frac{\rho}{4\pi L}\left[ln\left(\frac{2L + \sqrt{s^2 + 4L^2}}{s}\right) + \frac{s}{2L} - \frac{\sqrt{s^2 + 4L^2}}{2L} + ln\frac{4L}{r} - 1\right] \quad [3]$$

4. Straight line of multiple vertical rods

$$R_g = \frac{\rho}{2\pi L N_1}\left(ln\frac{4L}{r} + \frac{2L}{s}ln\frac{2N}{\pi} - 1\right) \quad [4]$$

5. Square array of vertical rods

$$R_g = \frac{\rho}{2\pi L}\left(ln\frac{4L}{r} - 1\right) \times + \frac{K}{N_2} \quad [5]$$

Where R_g is ground resistance in Ω, ρ is soil resistivity in Ωm, L is the length of the grounding rod in m, r is the radius of the grounding rod in m, d is the horizontal rod depth in m, s the spacing between the rods in m, and N_1 is the number of straight-line rods, N_2 is the number of square array rods, and K is the resistance ratio for a square array equally spaced of equal length rods, in s=L curve can be obtained in Figure 2. The ground resistances for each grounding topology under different soil resistivity are calculated and tabulated in Table 2. In the case of the feeder without shielding and an ungrounded system, the grounding resistance remained consistently at 1000 Ω, irrespective of the changes in soil resistivity, which ranged from 10 Ωm to 10 kΩm (Cabral et al., 2014).

The placement of shielded guard wire near the phase conductors on overhead distribution feeders aims to lower the occurrence of lightning strikes and mitigate induced voltages from external sources (Comassetto et al., 2008). Figure 3 illustrates various pole structures for the LPSs. At the same time, Table 3 details the LPS configuration marked as "j", which comprises a combination of unshielded or shielded feeders and different grounding designs.

Flashover Rates due to Lightning

Lightning strikes can have both direct and induced effects on electrical systems, including power distribution systems. Direct lightning effects occur when lightning strikes an electrical component or conductor, such as a power line or transformer. Direct lightning strikes can cause damage to the component or conductor and can result in an electrical fault or outage. The high voltage and current associated with a lightning strike can cause

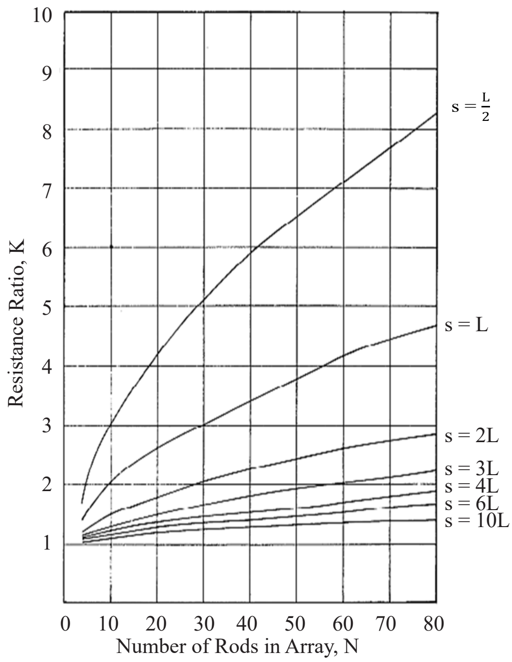

Figure 2. The ratio of the actual resistance of a rod array to the ideal resistance of N rods in parallel (Department of Défense, 1987)

Table 2
Ground resistance in Ohm (Ω) for grounding designs under various soil resistivities

Grounding Resistance (Ω)	Soil Resistivity (Ωm)			
	10	100	1k	10k
Ungrounded	1000	1000	1000	1000
Single vertical rod	3.60	35.99	359.86	3598.62
Single horizontal rod	2.92	29.15	291.55	2915.48
Two vertical rods	1.97	19.74	197.43	1974.27
Straight line of 4 vertical rods	1.09	10.86	108.56	1085.61
Square array of 4 vertical rods	1.26	12.60	125.95	1259.52

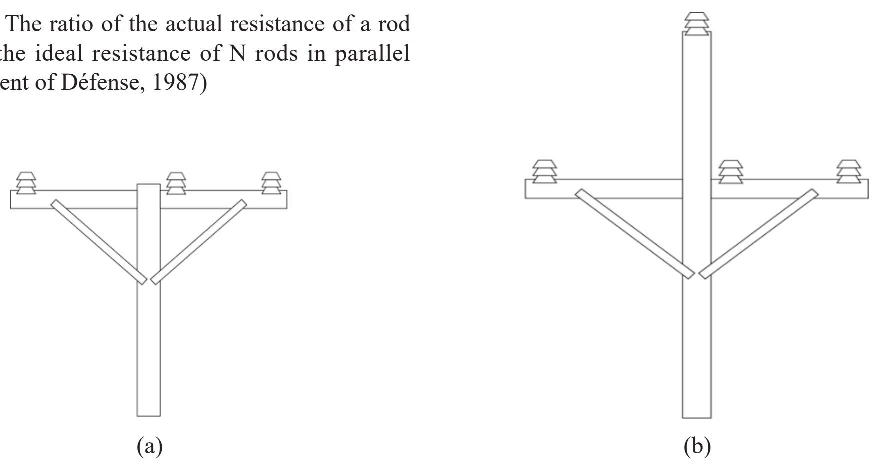

Figure 3. Pole structures of (a) unshielded and (b) shielded with wire guard

Table 3
LPS configuration for a combination of pole structure and grounding designs

Pole Structures	Grounding Designs	j
Unshielded feeder	Ungrounded (no LPS)	1
	Single vertical rod	2
	Single horizontal rod	3
	Two vertical rods	4
	Straight line of 4 vertical rods	5
	Square array of 4 vertical rods	6

Table 3 *(Continue)*

Pole Structures	Grounding Designs	j
Shielded feeder	Single vertical rod	7
	Single horizontal rod	8
	Two vertical rods	9
	Straight line of 4 vertical rods	10
	Square array of 4 vertical rods	11

insulation breakdown and create arcing, leading to equipment failure and posing a risk to public safety.

Induced lightning effects occur when lightning strikes nearby, and the resulting electromagnetic fields induce voltages or currents in nearby conductors. These induced effects can result in transient overvoltage and current surges, damaging equipment and leading to electrical faults or outages. Induced lightning effects are more common than direct ones and can occur even if the lightning strike is not close to the electrical system.

The process involves establishing a specific threshold current, the critical current, which triggers a flashover event for a given LPS. This critical current serves as the potential peak current (i_0) for the first return stroke. It is utilised in reference [6] to determine the likelihood of the first return stroke having a peak current (I_0) that surpasses i_0. By substituting the critical current of the LPS, it becomes possible to compute the direct and induced flashover rates, as well as the flashover rate (N) for each section of the feeder, based on different LPS configurations.

The failure rate of the feeder caused by the direct and indirect impacts of lightning strikes can be evaluated by examining the characteristic parameters and the amplitude of the first return stroke current by Equation 6, which is the probability law specified in the IEEE 1410-2010 (2011) guidelines:

$$P(I_0 \geq i_0) = \frac{1}{1 + \left(\frac{i_0}{31}\right)^{2.6}} \quad [6]$$

where $P(I_0 \geq i_0)$ is the probability that the first return stroke has a peak current I_0 that exceeds i_0, and i_0 is the prospective first return stroke peak current (kA).

The estimation of direct impact flashovers on the overhead distribution system can be achieved using Equation 7 by taking into account the distances between the distribution feeders and nearby structures, as well as the probability of lightning current occurrence. This assessment allows for considering the impact of neighbouring structures on safeguarding the distribution system against lightning strikes. If no structures like buildings or trees are nearby, the shielding factor (Sf) is regarded as zero in those regions. Nonetheless, flashovers can still happen even when nearby structures fully shield distribution lines (Sf = 1).

$$N_{dir} = N_g \left(\frac{b + 28h^{0.6}}{10} \right) P(I_0 \geq i_0)(1 - Sf) \qquad [7]$$

where N_{dir} represents the number of flashovers caused by direct impacts (flashes/100 km/yr), N_g denotes the ground flash density (GFD) measured in flashes per km^2 per year and estimated based on the keraunic level, h represents the height of the highest conductor at the pole (m), b represents the width of the structure (m), and Sf represents the environmental shielding factor, which ranges from 0 to 1.

When a structure located close to an energised line is struck by lightning, it can create an induced overvoltage and lead to power failures. Consequently, when nearby structures shield the line from direct lightning strikes, it also affects the number of indirect flashovers. Equation 8, provided by IEEE 1410-2010 (2011), can be utilised to estimate the number of induced flashovers for distribution circuits:

$$N_{ind} = N_\rho N_g \left(\frac{h}{10} \right) P(I_0 \geq i_0) \qquad [8]$$

where N_{ind} represents the number of flashovers caused by induced overvoltage (flashes/100 km/yr), N_g denotes GFD measured in flashes per km^2 per year, h represents the height of the highest conductor at the pole (m), and N_ρ is the induced flashover rate (flashes/100 km/yr).

Figure 4 displays the occurrence rate of flashover in relation to the critical flashover (CFO) voltage. The flashover data pertains to a 10 m tall, infinitely long line comprising a single conductor positioned above a conductive ground. The values have been normalised based on a ground flash density (GFD) of N_g = 1 flash/km^2/yr and can be proportionally adjusted according to the GFD.

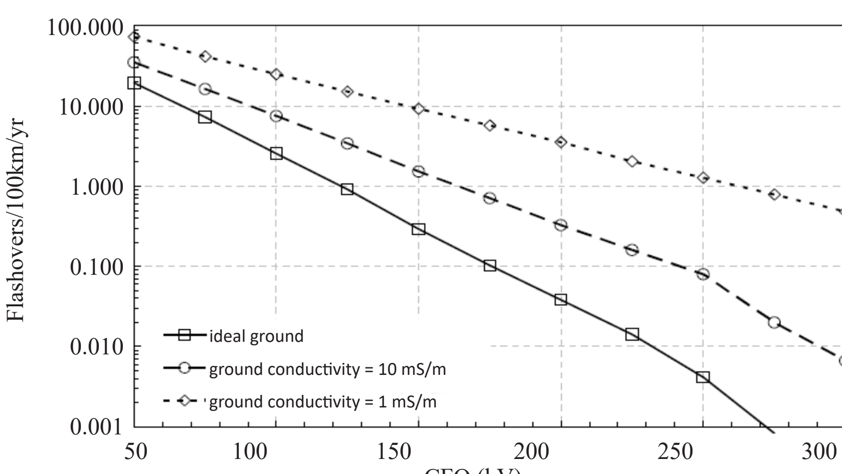

Figure 4. Number of induced-voltage flashovers versus distribution-line insulation level (IEEE1410-2010, 2011)

Hence, as Equation 9 shows, the total number of flashovers caused by lightning can be determined by considering the rates of both direct and indirect flashovers:

$$N = N_{dir} + N_{ind} \qquad [9]$$

where N represents the total number of flashovers due to lightning (flashes/100 km/yr).

Therefore, it is possible to establish a matrix N that incorporates the flashover rates N_{ij}, taking into account the LPS topology "j" for each line section "i". Flashovers typically cause momentary faults that are resolved within a few seconds, as well as sustained faults that may last until human intervention for repair. This research concentrates on permanent interruptions that can arise in distribution systems, assuming that flashovers will lead to sustained faults as a conservative estimate. The sustained failure rates for each feeder are determined using Equation 10.

$$\gamma = \bar{\gamma}.N \qquad [10]$$

where γ is the permanent failure rates (failures/100 km/yr), $\bar{\gamma}$ is the ratio between the number of permanent faults and total faults.

System Reliability Index and Constraint Formulation

Reliability measures for system services are determined by how often the system experiences interruptions. The widely used reliability index for measuring permanent interruptions is the System Average Interruption Frequency Index (SAIFI). In general, overcurrent protection plays a crucial role in minimising the adverse impact of lightning events on the reliability of electric power distribution. When lightning strikes a wire, it can cause a fault, but with proper distribution system design, overcurrent protection can swiftly resolve the fault before any harm occurs. This study assumes that the coordination between protection devices in the distribution systems remains intact, regardless of the fault's location (Cabral et al., 2018). This paper proposes the reliability index SAIFI as the objective function by constructing a mathematical model in Equation 11 for each line section and Equation 12 for the whole system, which takes into account the affected customers in each section, relying on Equations 6 to 10. The average SAIFI of 80-line sections measures the reliability of the whole distribution system.

$$saifi_{\_ij} = \frac{\gamma_{ij} {C_i}^P}{C_T} \qquad [11]$$

$$SAIFI = \frac{\sum_{i=1}^{ns} \sum_{j=1}^{ne} SAIFI_{ij}}{ns} \qquad [12]$$

Where γ_{ij} refers to the rate at which permanent faults occur in the LPS "j" on feeder section "i" as defined in Equation 10, C_i^P represents the count of customers who are located downstream from line section i and closest to the protective device upstream whose service is interrupted by fault P, C_T indicates the total number of customers being served, and ns denotes the overall number of distribution network sections, and ne represents the total number of different LPS conditions.

The cost investment is the constraint of the LPS optimisation for the distribution system, including the cost of the shielded wire and the grounding rods, and the labour cost is not considered in this paper. The market price of the lightning shield wire is about 800 dollars/km, the lightning rod costs 300 dollars/unit, and the grid conductor cost for a 2x2 square array of 4 vertical rod designs is 5 dollars/m. There are 4 test cases with different investment costs have been presented.

Algorithm Optimisation

Talbi (2002) discussed various hybridisation techniques for heuristic algorithms, each with pros and cons. One such method is PSOGSA, which is an optimisation algorithm that merges Particle Swarm Optimisation (PSO) with the Gravitational Search Algorithm (GSA). PSOGSA combines the capabilities of both algorithms, running them simultaneously to generate the best solutions (Mirjalili & Hashim, 2010). It uses PSO for exploration and diversity while incorporating GSA for exploitation and convergence towards optimal solutions. This hybrid approach better balances exploration and exploitation, improving optimisation performance.

PSOGSA demonstrates superior convergence and robustness compared to other evolutionary methods like PSO (Sadati et al., 2009), genetic algorithm (Katic & Savic, 1998), ordinal optimisation (Orille-Fernández et al., 2004), and imperialist competition (Soroudi & Ehsan, 2012). Although mixed integer linear programming (MILP) (Bretas et al., 2018; Jooshaki et al., 2023) achieves the global optimum solution quickly, PSOGSA has advantages over MILP: it handles continuous and discrete problems without requiring linear programming formulation, has good global search capability, has a simpler implementation, handles non-linear objectives, and is naturally parallelisable for faster optimisation in distributed computing.

RESULTS AND DISCUSSION

After simulation using ATPDraw, the critical lightning current is obtained for each LPS configuration. The critical lightning current values are then used to calculate flashover rates, and the distribution system's reliability is further optimised by a metaheuristic algorithm, PSOGSA, using MATLAB.

An 81-bus distribution system in Brazil is used for testing purposes, and Figure 5 depicts the single-line diagram of the radial distribution feeder, which consists of 80 sections (ns = 80). The number of customers for each line section is shown in Table 4, and the relevant system data can be found in a study by Bretas et al. (2018). In this study, the permanent fault rate () is set at 0.2, with N_g being 10 lightning flashes/100km/yr and *Sf* being 0, according to a study by Cabral et al. (2014). The wood cross-arm *(b)* is 1.8 m for the overhead distribution feeder, and the pole height (*h*) is 9 m for the unshielded feeder and 10 m for the shielded feeder.

The characteristics and data of aluminium conductor steel reinforced ACSR LYNX is used as the line conductor, and the aluminium clad steel ACS 7/8 AWG is used as shield wire. With consideration of bare conductors and a 180 kV CFO voltage, the critical current (i_0), SAIFI and the total cost under unshielded and shielded distribution feeders and various grounding topologies for the whole distribution system against soil resistivity are tabulated in Table 5.

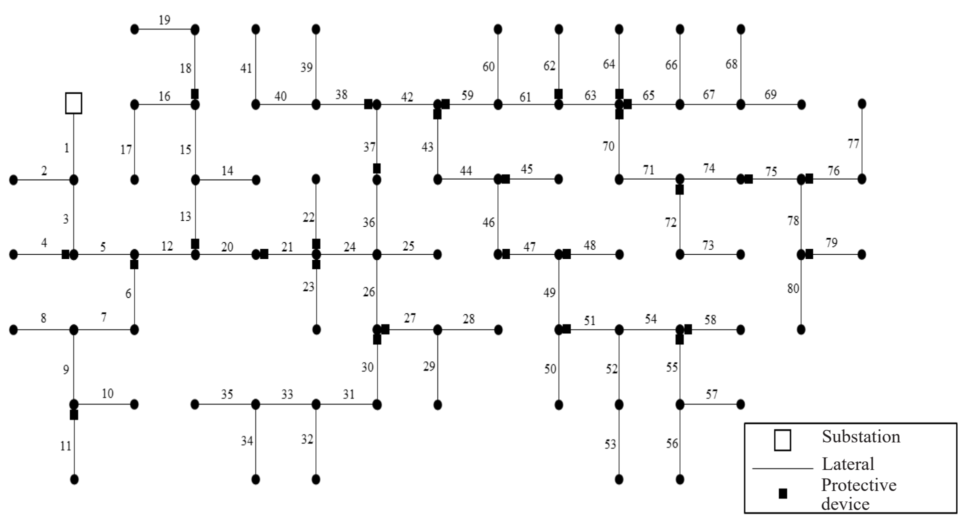

Figure 5. Radial distribution system with 80-line sections

Table 4
Number of customers for each line section

No. Sec	No. Cust.	No. Sec	No. Cust.	No. Sec	No. Cust.	No. Sec	No. Cust.
1	0	21	401	41	235	61	74
2	104	22	44	42	85	62	240
3	99	23	145	43	124	63	85
4	63	24	141	44	120	64	97
5	43	25	125	45	318	65	0
6	249	26	0	46	50	66	46
7	266	27	186	47	22	67	79
8	139	28	81	48	85	68	0
9	410	29	86	49	92	69	105
10	187	30	100	50	1	70	21

Table 4 *(Continue)*

No. Sec	No. Cust	No. Sec	No. Cust	No. Sec	No. Cust	No. Sec	No. Cust
11	172	31	217	51	7	71	20
12	143	32	84	52	58	72	0
13	359	33	19	53	55	73	0
14	488	34	100	54	1	74	28
15	115	35	199	55	1	75	20
16	40	36	96	56	1	76	32
17	12	37	65	57	3	77	1
18	14	38	67	58	31	78	0
19	1	39	197	59	68	79	27
20	392	40	45	60	216	80	13

Table 5 presents the results when the system only applies one LPS configuration. The unshielded LPS does not significantly affect the critical current for soil resistivity ranging from 10 Ωm to 10 kΩm. In contrast, SAIFIs between the soil resistivities are gapped due to different induced flashover rates measured by the soil resistivities. SAIFI for the feeder without LPS is 3.783 int./yr for 10 Ωm of soil resistivity, 3.813 int./yr for 100 Ωm of soil resistivity, 5.471 int./yr for 1 kΩm of soil resistivity, and 8.232 int./yr for 10 kΩm of soil resistivity. The best LPS configuration is the shielded feeder with the straight line of 4 vertical rods (j = 10) where the SAIFIs are 0.146 int./yr and 0.774 int./yr for 10 Ωm and 100 Ωm respectively, decreased by 96% and 80% from SAIFIs of no LPS and unshielded LPSs. The LPS with a shielded structure has excellent sensitivity to the grounding topologies and the soil resistivities, in which the critical current is affected by the 10 kΩm of soil resistivity, ranging from 43.59 to 5.98% less than which of an unshielded-structure LPSs.

In the 2x2 square array (j=11), there is a greater likelihood of current crowding and interference between adjacent rods, affecting the current flow and leading to higher resistance. On the other hand, the configuration with four rods aligned in a straight line (j = 10) does not experience this interference problem, as each rod functions independently. The electrical current tends to distribute more evenly along the line of rods. It can result in a more efficient current dissipation into the ground, leading to lower ground resistance. However, it is important to note that when soil resistivity is exceptionally high, such as in this case (10 kΩm), the influence of grounding systems becomes less pronounced because high soil resistivity limits the effect of a grounding system by increasing ground resistance, reducing the area of influence, and impeding the system's ability to provide a low-resistance path for current dissipation. Therefore, j=10 tends to get lower SAIFI compared to j=11 for all three-soil resistivity except for 10 kΩm or higher soil resistivity.

Table 5
Simulation results for each LPS configuration

LPS configuration, j	Cost (US$)	Soil Resistivity (Ωm)							
		10 Ωm		100 Ωm		1 kΩm		10 kΩm	
		i_0 (kA)	SAIFI (int./yr)	i_0 (kA)	SAIFI (int./yr)	i_0 (kA)	SAIFI (int./yr)	i_0 (kA)	SAIFI (int./yr)
1	0	1.18	3.783	1.18	3.813	1.17	5.471	1.17	8.232
2	24000	1.18	3.783	1.18	3.813	1.17	5.471	1.17	8.232
3	24000	1.18	3.783	1.18	3.813	1.17	5.471	1.17	8.232
4	48000	1.18	3.783	1.18	3.813	1.17	5.471	1.17	8.232
5	96000	1.18	3.783	1.18	3.813	1.17	5.471	1.17	8.232
6	103200	1.18	3.783	1.18	3.813	1.17	5.471	1.17	8.232
7	57097.6	90.17	0.227	23.80	2.593	2.42	3.994	0.66	5.056
8	57097.6	94.52	0.203	29.06	2.112	2.89	3.991	0.70	5.056
9	81097.6	101.09	0.172	36.84	1.519	4.12	3.978	0.81	5.056
10	129097.6	107.74	0.146	53.02	0.774	7.40	3.905	1.10	5.056
11	136297.6	106.41	0.151	48.61	0.923	6.37	3.935	1.01	5.056

j=1: No LPS; j=2: Unshielded feeder + single vertical rod; j=3: Unshielded feeder + single horizontal rod;
j=4: Unshielded feeder + two vertical rods; j=5: Unshielded feeder + straight line of 4 vertical rods;
j=6: Unshielded feeder + square array of 4 vertical rods; j=7: Shielded feeder + single vertical rod;
j=8: Shielded feeder + single horizontal rod; j=9: Shielded feeder + two vertical rods;
j=10: Shielded feeder + straight line of 4 vertical rods; j=11: Shielded feeder + square array of 4 vertical rods

In order to validate the optimisation model, 4 test cases are considered and subjected to different investment costs as described below, while the objective is the minimisation of SAIFI under these constraints.

- Case 1: Investment = US$ 10,000
- Case 2: Investment = US$ 30,000
- Case 3: Investment = US$ 50,000
- Case 4: Investment = US$ 70,000

The main concept identifies the LPS configuration plan that can result in the lowest SAIFI and cost investment when implemented in the feeder sections. The outcomes are shown in Table 6. This paper utilises the PSOGSA heuristic algorithm to obtain the best solution, which requires initialising various parameters. These parameters include a population size of 200, weighting factors with c_1' set to 1 and c_2' set to 2, a random number between 0 and 1 for the weight factor w, a descending coefficient α of 20, and an initial value of G_0 set to 100. The algorithm will iterate a maximum of 300 times, and it will terminate once this maximum iteration is reached.

The results of the cases are taken the best from 30 independent runs each. Table 6 presents the best LPS configurations for the 80-line section distribution system under various soil resistivities and investment cases. Compared to the no LPS plan for all line sections, up to 91% of line sections are unprotected (j = 1) in Case 1, up to 78%, 64%, and 50% of line sections are unprotected in Case 2, Case 3, and Case 4 respectively. As the investment increased by the cases, the selection of no LPS configuration to the line sections decreased. In contrast, the shielded feeder grounded by a square array of 4 vertical rods (j = 11) becomes more chosen with the increased investment, and up to 48% of line sections apply this LPS configuration in Case 4.

Table 6 provides the SAIFI values and their corresponding costs for different cases. It also reveals the percentage reduction in SAIFI values compared to the no LPS (j=1) base case in Table 5 under the same soil resistivities. In Case 1, a budget constraint of US$ 10,000 leads to excluding LPS installations in most line sections, resulting in reduced reliability compared to the other three cases. For Case 1, under soil resistivities of 10 Ωm and 100 Ωm, the SAIFI is reduced by 26.23% and 21.24%, respectively, compared to scenarios with no LPS. Case 2 shows 46.11% and 34.44% reductions, while Case 3 achieves 56.88% and 51.03% reductions. Case 4 attains the most substantial SAIFI reduction, with decreases of 73.34% and 56.10% for soil resistivities of 10 Ωm and 100 Ωm.

For 1 kΩm and 10 kΩm of soil resistivities, all SAIFIs under these soil resistivities have minor decreases from SAIFIs of no LPS, wherein SAIFIs in Case 1 are decreased by 0.07% and 0.09%. In contrast, 1.23% and 2.24% in Case 2, 3.38% and 4.56% in Case 3, and SAIFIs in Case 4 are decreased by 4.29% and 4.87%, respectively, because the higher the soil resistivities, the harder the lightning current discharge to the ground, therefore, there are no notable changes in SAIFIs between the cases. Since the LPSs with shielded structures are sensitive to soil resistivity, the SAIFI increases as the soil resistivity increases. Table 6 also presents that the higher the cost investment, the lower the SAIFI and the higher the reliability of the distribution system. The location of the LPS is important, and the number of customers in the line sections affects the SAIFI. Since the LPS can reduce customer interruptions, if the LPS is located at the feeder section with more customers, the SAIFI can be reduced.

For better understanding, based on Table 6, Figures 6 and 7 are graphed to show the SAIFIs for the test cases and the percentages of SAIFIs of the cases compared to the SAIFI with no LPS, respectively. Figure 6 clearly shows the drops of SAIFIs as the cost investment is increased to implement LPS for soil resistivities 10 Ωm and 100 Ωm. In contrast, there are no significant changes in SAIFIs between the cases of 1 kΩm and 10 kΩm of soil resistivities, respectively. Again, it has been proven that there is a limitation to mitigating interruptions under high soil resistivity. Among the soil resistivities, it can be seen that the SAIFIs are rising as the soil resistivity becomes higher.

Table 6
Numerical results for test cases

j	Soil Resistivity (Ωm)															
	10 Ωm				100 Ωm				1 kΩm				10 kΩm			
	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 1**	**Case 2**	**Case 3**	**Case 4**
	Percentage of Line Section Applying j (%)															
1	91.25	76.25	62.50	48.75	91.25	77.50	62.50	50	86.25	76.25	63.75	47.50	90	76.25	58.75	41.25
2	0	0	0	0	0	0	0	0	1.25	1.25	0	0	1.25	0	1.25	2.50
3	0	0	0	0	0	0	0	0	5.00	0	0	0	0	0	0	1.25
4	1.25	0	0	0	1.25	0	0	0	1.25	0	1.25	1.25	0	0	1.25	1.25
5	0	0	1.25	0	0	0	0	0	0	2.50	1.25	1.25	3.75	0	2.50	5.00
6	0	0	0	0	0	0	0	0	1.25	0	0	0	2.50	2.50	5.00	3.75
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	1.25	0	0	0	1.25	1.25	0	0	0	0	0	0	0	0	1.25
9	0	1.25	0	1.25	0	0	0	1.25	0	0	0	0	0	0	0	1.25
10	0	1.25	1.25	2.50	1.25	2.50	2.50	2.50	0	0	1.25	2.50	0	2.50	1.25	2.50
11	7.50	20.00	35.00	47.50	6.25	18.75	33.75	46.25	5.00	20.00	32.50	47.50	2.50	18.75	30	40
SAIFI (int/yr)	2.790	2.038	1.631	1.008	3.003	2.500	1.868	1.674	5.466	5.403	5.286	5.236	8.225	8.048	7.857	7.832
COST (US$)	9957.6	29949	49964	69973	9901.2	29957	49961	69910	9906.8	29982	49913	69959	9968	29934	49920	69987
SAIFI Reduct. (%)	26.23	46.11	56.88	73.34	21.24	34.44	51.03	56.10	0.07	1.23	3.38	4.29	0.09	2.24	4.56	4.87

Case 1: US$ 10,000 investment constraint; Case 2: US$ 30,000 investment constraint; Case 3: US$ 50,000 investment constraint;
Case 4: US$ 70,000 investment constraint

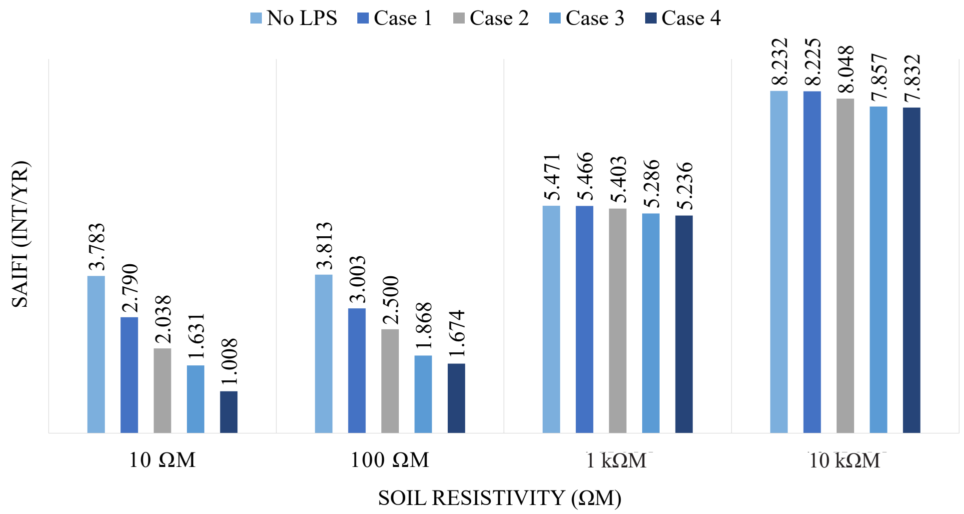

Figure 6. SAIFI against soil resistivity for test cases compared to no lightning protection system

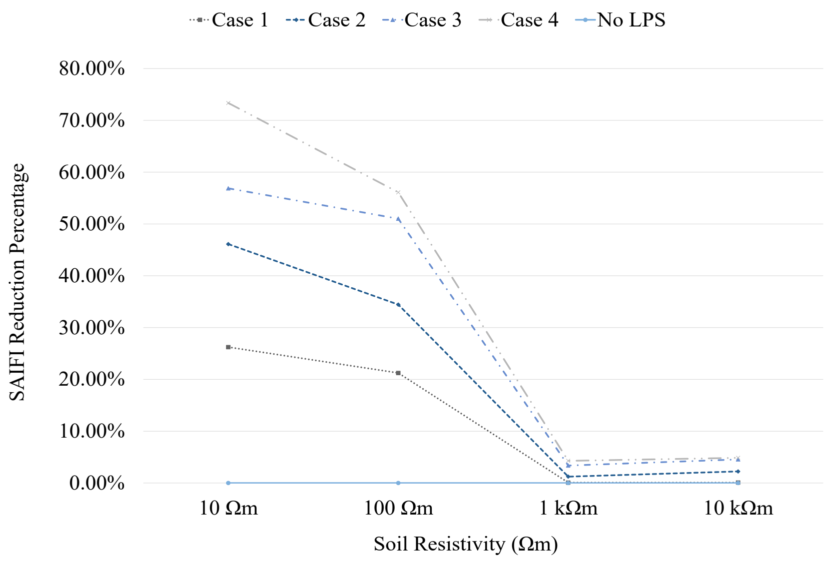

Figure 7. Percentage of SAIFI reduction against soil resistivity for test cases compared to no lightning protection system

Figure 7 demonstrates the differences in SAIFI in percentage for each case to those with no LPS under soil resistivities. SAIFIs for 10 Ωm soil resistivity drop the most. They are followed by 100 Ωm, wherein the SAIFI in Case 4 under 10 Ωm soil resistivity decreases the most by 73.34% as it has the lowest soil resistivity to discharge the lightning current and decreases the flashover rate, as well as the case of the highest cost investment to apply LPS which with lower ground resistance but higher costing. The SAIFIs for 1 kΩm and

10 kΩm soil resistivities have minor decreases from SAIFIs with no LPS, ranging from 0.07 to 4.87%.

Figures 6 and 7 show that when the soil resistivity is high, it is hard for the lightning to be discharged to the ground. Therefore, with higher soil resistivity (1 kΩm and 10 kΩm), LPS cannot help much to discharge the lightning current to the ground and mitigate the interruption to the customers.

In comparison to the previous research papers (Bretas et al., 2018; Zhang et al., 2021), a distinctive contribution of our study is the in-depth exploration of grounding schemes and soil resistivity's impact on SAIFI, which is particularly pertinent when selecting the optimal LPS configuration. By considering various soil resistivities and investment costs, our study provides valuable insights into how these factors influence SAIFI and the reduction of interruptions to customers. This consideration of diverse scenarios and soil conditions enhances the practical applicability of our findings, making them relevant to real-world distribution systems.

CONCLUSION

This paper highlights the importance of protective measures to ensure the reliability and safety of power distribution systems. Lightning protection systems, good shielding and grounding practices can help mitigate lightning's effects on power distribution systems. A grounding system is essential for lightning protection in power distribution systems, and a grounding system with lower grounding resistance means that the system is better grounded and more effective at dissipating fault currents. On the other hand, high soil resistivity means the soil does not conduct electricity as easily. As a result, the ground has a higher resistance to the current flow. This increased ground resistance can make it more challenging for a grounding system to effectively dissipate electrical faults or lightning strikes into the earth.

Among the presented grounding rod configurations, 4 grounding rods arranged in a straight line (j=10) under the soil with lower resistivity, which is 10 Ωm, results in a better grounding performance of 1.09 Ω grounding resistance. The combination with shielded feeders results in the highest withstand current of 107.74 kA, and the SAIFI was further decreased from 3.783 int./yr (no/unshielded LPS) to 0.146 int./yr. The results in Table 5 showed that shielded LPS (j=7-11) were more sensitive to the soil resistivities, as the SAIFI increases with soil resistivity for grounding topologies. At the same time, unshielded LPS (j=2-6) had no significant effect and no differences from no LPS (j=1) on the critical current for soil resistivity, as well as the SAIFIs between the grounding topologies.

The study also analysed the impact of lightning protection systems on the reliability of distribution systems for different soil resistivities and investment costs. The study validated an optimisation model using PSOGSA to minimise SAIFI under different investment cost constraints. The results showed that the higher the cost investment, the lower the SAIFI and the higher the reliability of the distribution system. However, the location of the LPS was also important, as placing the LPS at the feeder section with more customers could further reduce SAIFI. The study demonstrated the importance of considering both soil resistivity and investment cost when selecting the optimal LPS configuration for distribution systems, as well as the significance of LPS location in reducing interruptions to customers.

The study reveals that the relationship between the SAIFI and cost is inversely proportional, which means that higher investment costs can achieve lower SAIFI. Therefore, future studies plan to explore the multi-objective optimisation algorithms to find an optimal solution that simultaneously reduces cost and improves SAIFI. This approach should enable striking an optimal solution between SAIFI and cost. Lastly, obtaining comprehensive Malaysian data can be challenging. Thus, the 81-bus test system (Bretas et al., 2018) was chosen as it offered complete and accessible information for the optimisation algorithm's development and evaluation in this study. To reflect the Malaysian situation, the authors aim to validate the approach with Malaysian data in future studies to address this concern.

ACKNOWLEDGEMENTS

The authors acknowledged the Fundamental Research Grant Scheme (FRGS) support under a grant number of (Ref: FRGS/1/2022/TK08/UNIMAP/02/72) from the Ministry of Higher Education Malaysia. This work is supported by the Collaborative Research Grant (CRG), Grant No. 9023-00017 from Universiti Malaysia Perlis (UniMAP).

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