Research Article

Lightning Protection Improvement and Economic Evaluation of Thailand's 24 kV Distribution Line Based on Difference in Grounding Distance of Overhead Ground Wire

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This study determines the voltage across insulators after a direct lightning strike to an overhead ground wire on a 24 kV pole structure for different grounding distances of overhead ground wire, to calculate the maximum ground resistance required to avoid disruption of the distribution line system using ATP-EMTP software. The results show that when a 40 kA lightning current, the average lightning current in Thailand, strikes a 24 kV pole structure, the maximum ground resistance should not exceed 4 Ω for a 40 m grounding distance of overhead ground wire, based on an existing critical insulator flashover of 205 kV. However, because the average ground resistance in Thailand is approximately 10 Ω , this study proposes increasing the insulation level from 205 kV to 300 kV to reduce the likelihood of power outage. The cost-effectiveness of such an investment is assessed in terms of net present value (NPV), internal rate of return (IRR), profitability index (PI), and discounted payback period (DPP) using existing economic tools. Results show that when the critical insulator flashover is increased from 205 kV to 300 kV for a 40 m grounding distance of overhead ground wire, the project is likely to have a DPP of 15.12 years, NPV of 143,321.87 USD, IRR of 12%, and PI of 1.15. On the other hand, grounding distances greater than 40 m for overhead ground wire result in negative NPV, although the back flashover rate can be reduced by 1.51–5.71% with grounding distances of 80–200 m compared to the situation in the absence of grounding.

1. Introduction

24 kV power distribution line networks in Thailand are the most important infrastructures for sending electricity to customers. Therefore, disruptions on these distribution lines will cause significant economic losses. Lightning strikes on these distribution lines are the main reason for permanent and temporary power disruptions. Results of studies performed in Asian countries such as Malaysia, Japan, and China show that lightning is the main reason for power disruption. In Thailand, many disruptions and power outages occur because of lightning [1]. Therefore, 24 kV distribution lines should be equipped with some form of lightning protection. Many methods to decrease the disruption of distribution lines from lightning strikes to the system have been developed, and many variations in

lightning protection have been presented in literature [2–21]. For example, Yokoyama [2] indicated that there are many power failures due to lightning overvoltages that occur on the coast and in the mountainous areas of Japan. The installation of lightning arresters every 200 meters with insulation levels of 100 kV was found to greatly reduce the rate of power outages due to indirect lightning overvoltages. Additionally, it was found that the lightning protection design of a distribution system depends on the type of lightning, type of materials used, and location of the distribution system. All variables are considered to determine the appropriate lightning protection system. Zhang et al. [3] determined that ground conductivity and lightning channel position have effects on lightning-induced voltage on overhead ground wires (OHGWs). Omidiora and Lehtonen suggested that structures of

medium voltages could be protected by OHGW lines from direct lightning strikes or flashovers across trees, with the OHGW lines providing effective protection for low-ground-resistance systems [4]. Han et al. [5] demonstrated that the OHGW is an important equipment for lightning protection that functions at protection angles not exceeding 45° . Meanwhile, in another study, the voltage induced by a lightning current was reduced using two OHGWs below and above the phase conductor [6]. Paulino et al. [7] showed improvements in lightning protection by increasing the dielectric strength from 95 kV to 170 kV based on the variation of the ground resistivity in the simulations. Additionally, the lightning protection of 95 kV and 170 kV insulation systems was evaluated in a real environment. It was found that using an insulation rating of 170 kV could reduce the power outage rate by more than 50%. Michishita and Hongo [8] reported that the flashover rate is lower than 0.0001 times/year when indirect lightning strikes a distribution line in which lightning arresters are installed every 200 m, and they also found that the subsequent lightning strikes are key to the system design because their flashover rates in distribution systems are higher than those of the first lightning strokes; further, the use of vertical rods is recommended to improve the grounding system. Meanwhile, arc-extinguishing lightning protection gaps can be applied onto both ends of a 10 kV insulator to protect the insulation from burning [9]. Piantini [10] indicated that the flashovers of an insulator in a medium voltage system due to indirect lightning current are less frequent if the critical flashover (CFO) of the insulator is more than 300 kV and also found that the lightning protection level will decrease when the grounding distance of OHGW is wider and the soil resistance is higher. If the system is not equipped with OHGW, the lightning arrester may be damaged due to excessive energy power. Therefore, the best protection is to install OHGW with lightning arresters at every pole and every phase; however, the cost-effectiveness must be considered. Low-voltage systems are more sensitive than distribution systems because of their lower insulation level. The research shows that more transformers are damaged if the lightning arrester is attached to the high side; therefore, the lightning arrester on the low side can greatly reduce the damage of the transformer.

To protect against lightning overvoltages in combined underground cables and overhead lines, installation of surge arresters is required on both ends of the underground cables [11]. In places with low ground conductivities and high insulation levels of 300 kV or high ground conductivities and low insulation levels of 150 kV, the distance between arresters should be less than 400 m [12]. According to Chen et al. [13], lightning arresters are the best equipment for protecting a system from lightning. The spacing of lightning arresters is a major consideration in system protection. However, surge arresters have been shown to be unable to suppress overvoltages in cases of direct lightning strikes to the system, and OHGWs were demonstrated to be better equipment for system protection in severe-lightning areas [14].

Many factors must be considered in the provision of appropriate lightning protection, such as ground resistance, lightning current waveform, lightning current magnitude, type of lightning current, type of pole structure, and lightning current position. Meanwhile, Paulino et al. [15] showed that lightning current waveforms are affected by ground resistance. They also determined that the back flashover rate can be decreased via maintenance of the ground resistance to a minimum [16]. Meanwhile, Tossani et al. [17] reported that buildings near overhead lines in a city are expected to decrease electromagnetic lightning pulses radiated by indirect lightning strikes. Mikropoulos and Tsovilis [18] presented a statistical estimation of the surface flash rate in a distribution system in accordance with IEEE Std. 1410:2011. The conditions for a lower flashover in a distribution line system are as follows: a lower height of the distribution line structure, lower ground resistance and lightning current magnitude, and nearby objects close to the distribution system.

This paper presents a study of the effects of direct lightning to an OHGW on a 24 kV distribution system for various grounding distances of OHGW. This study considers only direct lightning strikes to the OHGW. The influence of indirect lightning strikes (lightning induced voltages) on the number of lightning outages per 100 km is not considered. The installation of an OHGW is expected to reduce the number of these outages [2]. This would affect the economic analysis presented. In this study, the flashover of insulators was obtained by simply comparing the overvoltages with the CFO of the insulators. More complex and accurate methods are available in the literature [19–21]. The investigation was performed using ATP-EMTP software. In this study, five different values of grounding distance of OHGW are tested with an existing insulator of 205 kV, to determine the permissible ground resistance and insulation that prevent power outages from occurring in the system. In addition, this study is based on the 40 kA average lightning current in Thailand striking a 24 kV distribution system with an average ground resistance of $10\ \Omega$. For this setup, the insulation level should be increased from 205 kV to 300 kV for the system to be able to withstand a 40 kA lightning current. Economic evaluations of the different grounding distances of OHGW are shown in Section 4. The paper is arranged as follows: in Section 1, the introduction is presented; in Section 2, the configuration of the system and relevant data on lightning are illustrated; in Section 3, a case study is demonstrated; and, in Section 4, the cost-effectiveness of the investment is explained. Finally, in Section 5, the conclusion is presented.

2. System Configuration and Relevant Data

2.1. Data on Lightning Current

2.1.1. Statistical Records of Lightning in Metropolis, Thailand. During 2000–2015, an average of 75.88 thunderstorm days per year (average in Thailand) were recorded [22]. This number of thunderstorm days is used to calculate the ground flash density (GFD) using the following equation [23]:

$$N_g = 0.000065T_d^{2.277}, \quad (1)$$

where N_g is ground flash density (flashes•km²/year) and T_d is the number of thunderstorms (days/year).

The probability of the peak lightning current exceeding the critical lightning-current magnitude can be calculated using the following equation [24]:

$$P(I) = \frac{1}{(1 + (I/M)^B)}, \quad (2)$$

where $P(I)$ is probability of peak lightning current exceeding critical lightning-current magnitude (%). I is critical lightning-current magnitude (kA) from the simulation in ATP-EMTP program. M is median of stroke peak current magnitude (kA), 40 kA in Thailand [23]. B is constant (3.09 for Thailand power system).

A plot of equation (2) is shown in Figure 1, where the median is 40 kA as of year 1997 [23].

The back flashover rate (BFR) [25] is calculated using equation (3), where N_L is calculated using equation (4).

$$\text{BFR} = N_L P(I), \quad (3)$$

where BFR is back flashover rate (flashes/100 km/year). $P(I)$ is probability of peak lightning current exceeding critical lightning-current magnitude (%) (from equation (2)). N_L is the number of lightning strikes (flashes/100 km/year) [26].

$$N_L = N_g \left(\frac{28h^{0.6} + b}{10} \right), \quad (4)$$

where N_g is ground flash density (flashes/km²/year), [26], h is average conductor height (m), and b is separation distance of OHGW (m). OHGW in this paper is used for single overhead ground wire; therefore, $b = 0$.

2.1.2. Model of Lightning Current. Negative lightning current is supposed to strike the OHGW. The lightning-current waveform follows a CIGRE concave shape, as shown in Figure 2 [27, 28].

The impedance of the lightning strike channel was 400 Ω parallel to the current source. The 400 Ω value of the lightning strike channel is a typical value used in literature; however, it is more appropriate for higher lightning currents as analyzed in [29]. Using a higher value, such as the 1000 Ω value proposed in [30], would considerably influence the obtained results.

Normally, the time to halve the value, or the tail time, is a stable 77.5 μ s, whereas the front time, t_f (μ s), and maximum steepness, S_m (kA/ μ s), were considered as functions of the lightning current crest, I_f (kA), where t_f and S_m are calculated using the two following equations [27, 28]:

$$t_f = \begin{cases} 1.77I^{0.188}, & 3 \leq I \leq 20 \text{ kA}, \\ 0.906I^{0.411}, & I \geq 20 \text{ kA}, \end{cases} \quad (5)$$

$$S_m = \begin{cases} 1.2I^{0.171}, & 3 \leq I \leq 20 \text{ kA}, \\ 6.5I^{0.376}, & I \geq 20 \text{ kA}, \end{cases} \quad (6)$$

where I is lightning current crest, I_f (kA).

The parameters of the lightning-current source examined in this study are outlined in Table 1.

2.2. Economic Evaluation. The economics study is performed based on calculations of the time value of the project in cash using discounting cash inflow, in terms of the following: net present value (NPV), discounted payback period (DPP), profitability index (PI), and internal rate of return (IRR) [31].

2.2.1. Net Present Value (NPV). NPV is the difference between the present values of the cash inflows and cash outflows over a period of time. NPV is applied to analyze the profitability of a projected investment. If the NPV is positive, the project is determined to be a potentially profitable investment; otherwise, the project should not proceed. NPV can be estimated using

$$\text{NPV} = -I_0 + \frac{A_1}{1+i} + \frac{A_2}{(1+i)^2} + \cdots + \frac{A_n}{(1+i)^n}, \quad (7)$$

where A_n represents cost savings per n th year, n is lifetime of project: 25 years, I_0 is investment cost at start point, and i is discount rate: 10% (mean of inflation rate of business loans in Thailand).

2.2.2. Discounted Payback Period (DPP). The DPP is used to decide the profitability of project based on the number of years required to recoup expenses from the initial investment (I_0). DPP can be calculated as follows:

$$\text{DPP} = \frac{\ln \left(\frac{1/(1 - ((I_0 \times i)/A))}{\ln(1+i)} \right)}{\ln(1+i)}, \quad (8)$$

where A represents total n year cost savings, I_0 is investment cost at start point, and i is discount rate: 10% (mean of inflation rate of business loans in Thailand).

2.2.3. Profitability Index (PI). The PI is a calculation of the potential profit of the proposed project. A PI or ratio greater than 1 indicates that the project is a potentially profitable investment, whereas a PI lower than 1 indicates that the project should be avoided. The PI can be estimated as follows:

$$\text{PI} = \frac{\text{NPV}}{I_0} + 1. \quad (9)$$

2.2.4. Internal Rate of Return (IRR). The IRR is used to estimate the profitability of a potential investment. The IRR is equivalent to the discount rate at which the NPV is equal to zero. The IRR value can be calculated from NPV equation in which the NPV value is equal to zero as follows:

$$\text{NPV} = -I_0 + \sum_{t=1}^n \frac{A_t}{(1 + \text{IRR})^t} = 0. \quad (10)$$

FIGURE 1: Probability of peak lightning current exceeding critical lightning-current magnitude.

FIGURE 2: CIGRE concave shape of lightning current waveform. I_f is lightning current crest. S_m is maximum rate of rise. t_f is equivalent front duration. t_n is time at 90% impulse amplitude or $0.9 I_f$. $t_m = I_f/S_m$, defined as the minimum equivalent front or time to crest.

TABLE 1: Lightning-current parameters in this study.

First negative stroke			
I_f (kA)	30	40	50
t_f front time (μs)	3.66	4.12	4.52
Tail time (μs)		77.5	
S_m (kA/ μs)	23.35	26.01	28.29

t_f and S_m are calculated using equations (5) and (6).

3. Simulation and Case Studies

3.1. Modeling of 24 kV Distribution Line System. ATP-EMTP was used to analyze a direct lightning strike to an OHGW on 24 kV distribution lines, as shown in Figure 3(a). The configuration and grounding system is shown in Figure 3(b) [32]. The structures are each composed of a 185 mm² three-phase all-aluminum space aerial conductor, pin post insulator used to support the three-phase conductor, 7.93-mm-diameter uniform zinc-coated steel wire as the OHGW, external ground wire connected to a 2.4 m ground rod at ground level, and 10.25 m concrete pole above ground as fixture for all equipment. The distances between conductors, phases, and the OHGW are shown in Figure 3(c).

Distribution lines are represented by JMARTI frequency-dependent models in the ATP-EMTP program with a frequency dependency of 10 Hz–3 MHz. The interval time step is less than $1/10f_{\max}$. Normally, the time step value is 1 ns.

In this project, the CIGRE type 15 model was applied, but an insulator was used instead of a capacitor. The parameters for the design are listed in Table 2.

3.2. Effects of Lightning Current on Parts of 24 kV Pole Structure. The effects of lightning current on the voltage across insulators for different grounding distances of OHGW (40, 80, 120, 160, and 200 m) are investigated using ATP-EMTP software, to determine the permissible ground

FIGURE 3: Continued.

FIGURE 3: Simulation model. (a) Simulation model in ATP-EMTP. (b) 24 kV distribution line structure in Thailand. (c) Dimension of distances among conductors.

resistance and maximum voltage across the insulators that will not cause flashovers, as shown in Figures 4–14.

For the setup shown in Figure 4, wherein the structure is grounded at every pole or every 40 m, a direct lightning strike to the structure is inferred to cause a voltage drop across the insulator up to a certain value; if this voltage is greater than the CFO of insulation, a power outage will occur. The voltage drop across the insulator is proportional to the current size and ground resistance. For example, if the ground resistance is $10\ \Omega$, the voltage drops across the insulator will be 222 kV and 310 kV at lightning currents of 30 kA and 50 kA, respectively. On the other hand, if the lightning current is 40 kA, the voltages across the insulators will be 268 kV and 350 kV at ground resistances of $10\ \Omega$ and $20\ \Omega$, respectively. For a lightning current of 40 kA (i.e., average lightning current in Thailand) and a ground resistance of $10\ \Omega$ (metropolis area), the voltage drop across the insulation is 268 kV, which is greater than the CFO of insulation of 205 kV (existing structure), resulting in a subsequent power outage. However, if we can improve the ground resistance such that it does not exceed $4\ \Omega$, the likelihood of power outage will reduce because the voltage drop across the insulator will not exceed 205 kV.

Based on the possibility of direct lightning strikes to every other pole or every 80 m, the scenario is divided into two cases. In the first case, lightning strikes the grounded pole as shown in Figure 5. The result shows that voltage across the insulator will increase consistently with increases in either lightning current or ground resistance, which is similar to the results shown in Figure 4. Moreover, for the average lightning current of 40 kA and a ground resistance of $10\ \Omega$, lightning strikes to the grounded pole will result in a

324 kV voltage across the insulation, higher than the critical insulator flashover of 205 kV, resulting in a system power outage. However, if the ground resistance is reduced to less than $2\ \Omega$, the distribution line system would be able to withstand the lightning strikes. In the second case, lightning directly strikes an ungrounded pole, as shown in Figure 6. For the average lightning current of 40 kA and a ground resistance of $10\ \Omega$, the resulting voltage across the insulation will be 793 kV, which is much higher than that in the first case because of the higher surge impedance and longer lightning-current path than those in the first case. On the other hand, reducing the ground resistance to its minimum will not improve the power system because of the lack of reflected waves from the base of the pole for reducing overvoltage at the top of the pole.

According to a simulation wherein lightning strikes directly at a structure grounded every other two poles or every 120 m, the voltage across the insulator of the grounded pole is lower than that of the ungrounded pole, which are similar to the results shown in Figures 5 and 6. For the average lightning current of 40 kA and a ground resistance of $10\ \Omega$, the voltages across the insulation will be 358 kV and 986 kV for the grounded and ungrounded poles, respectively, shown in Figures 7 and 8. Both voltages are higher than the critical insulator flashover of 205 kV, which will also result in power outages. The permissible ground resistance does not exceed $1\ \Omega$ for when lightning strikes the grounded pole, whereas there is no permissible ground resistance for when lightning strikes an ungrounded pole.

When lightning strikes a pole structure grounded every other three poles or every 160 m, for the average lightning current of 40 kA and a ground resistance of $10\ \Omega$, the voltage

TABLE 2: Parameters in ATP-EMTP modeling.

Description		Data
Lightning current	Peak value	40 kA
	Time to half value	77.5 μ s
	Time to crest value	0.936/0.411 = 4.12 μ s
Conductor (single)	Outside diameter	16 mm
	Direct current resistance	0.2 Ω /km
OHGW	Outside diameter	7.93 mm
	Direct current resistance	4.7 Ω /km
External ground wire	Outside diameter	7.93 mm
	Impedance (Z_t)	408 Ω
	Speed of lightning wave	300 m/ μ s
Concrete pole	Span of the pole	40 m
	Height	12 m
Single ground rod	Diameter of ground rod	16 mm
	Length of ground rod	2.4 m
	Ground resistance®	1–30 Ω
	Earth resistivity	40 Ω .m

FIGURE 4: Voltage across insulator after lightning strike to pole of OHGW, grounded at 40 m grounding distance or at every pole.

FIGURE 5: Voltage across insulator after lightning strike to grounded pole of OHGW, for 80 m grounding distance.

FIGURE 6: Voltage across insulator after lightning strike to ungrounded pole of OHGW, for 80 m grounding distance.

FIGURE 7: Voltage across insulator after lightning strike to grounded pole of OHGW, for 120 m grounding distance.

FIGURE 8: Voltage across insulator after lightning strike to ungrounded pole of OHGW, for 120 m grounding distance.

drops across the insulation will be 355 kV, 1,083 kV, and 1,279 kV if the lightning strikes a grounded pole, ungrounded pole near the grounded pole, and ungrounded

pole far from the grounded pole, respectively, as shown in Figures 9–11. The permissible ground resistance does not exceed $1\ \Omega$ for when lightning strikes the grounded pole,

FIGURE 9: Voltage across insulator after lightning strike to grounded pole of OHGW, for 160 m grounding distance.

FIGURE 10: Voltage across insulator after lightning strike to ungrounded pole of OHGW (near grounded pole), for 160 m grounding distance.

whereas there is no permissible ground resistance for when lightning strikes an ungrounded pole.

In a scenario wherein the structure is grounded every other four poles or every 200 m, as shown in Figures 12–14, the results are similar to those shown in Figures 9–11, that is, low voltage across the insulator when lightning strikes a grounded pole and permissible ground resistance not exceeding $1\ \Omega$ for an average lightning current of 40 kA.

The observations visualized in Figures 4–14 reveal that the voltage across the insulator changes for different grounding distances of OHGW, different ground resistances, and different lightning magnitudes. The reason for the variations is that the pole top voltage can be attenuated by reflected waves generated by nearby poles and the ground resistance of the ground rod, indicating that system reliabilities with respect to the grounding distance of OHGW and in terms of ground resistance are quite different. The main results are outlined in Tables 3 and 4.

Table 3 shows the permissible ground resistance (Ω) in the event of a lightning strike on a 30–50 kA distribution line

system that would allow the insulator to withstand the strike without flashover. The permissible ground resistance decreases either when the lightning current increases or when the grounding distance of OHGW is widened. For example, when the lightning current increases from 30 kA to 50 kA, the permissible resistance is reduced from $8\ \Omega$ to $2\ \Omega$ at a 40 m grounding distance of OHGW. On the other hand, when the grounding distance of OHGW is increased from 40 m to 120 m, the permissible resistance is reduced from $4\ \Omega$ to $1\ \Omega$ for a lightning current of 40 kA.

The results show that when lightning strikes a structure characterized by a longer grounding distance of OHGW, the acceptable ground resistance is reduced. For example, for a lightning current of 40 kA, a structure grounded at distances greater than 120 m would have a permissible ground resistance not exceeding $1\ \Omega$. However, in practice, it will be difficult for the ground resistance to attain a value as low as $1\ \Omega$. Therefore, other improvements to lightning protection, such as increasing the dielectric level of the insulator, should be considered.

FIGURE 11: Voltage across insulator after lightning strike to ungrounded pole of OHGW (far from grounded pole), for 160 m grounding distance.

FIGURE 12: Voltage across insulator after lightning strike to grounded pole of OHGW, for 200 m grounding distance.

FIGURE 13: Voltage across insulator after lightning strike to ungrounded pole of OHGW (near grounded pole), for 200 m grounding distance.

FIGURE 14: Voltage across insulator after lightning strike to ungrounded pole of OHGW (far from grounded pole), for 200 m grounding distance.

TABLE 3: Permissible ground resistance (Ω).

Lightning current (kA)	Grounding distance of OHGW (m)				
	40	80	120	160	200
30	8	4	2	2	2
40	4	2	1	1	1
50	2	1	—	—	—

In Table 4, the minimum critical impulse flashover (kV) at 10 Ω ground resistance allows the insulator to withstand lightning strikes without flashover. The minimum critical impulse flashover increases either when the lightning current increases or when the grounding distance of OHGW is widened. For example, when the lightning current increases from 30 kA to 50 kA, the minimum critical impulse flashover is increased from 222 kV to 310 kV. On the other hand, when the grounding distance of OHGW is increased from 40 m to 200 m, the minimum critical impulse flashover is increased from 268 kV to 360 kV when the lightning current is 40 kA.

4. Increase in CFO of Existing Insulator

According to Table 4, the CFO of the insulator should be 268–360 kV to reduce the likelihood of power outage for an average lightning current of 40 kA (as in Thailand) and an average ground resistance of 10 Ω (as in a metropolis setting) in case direct lightning strikes the OHGW. The influence of indirect lightning strikes (lightning induced voltages) on the number of lightning outages is not considered. Moreover, the grounding distance of OHGW has an effect on suitable CFO; wider grounding distances of OHGW require corresponding increases in CFO. Therefore, the objective of this section is to increase the CFO of an existing insulator from 205 kV to 300 kV for a variety of grounding distances of OHGW. Afterward, the cost-effectiveness is evaluated according to economic principles to determine which projects are probable good investments.

First, the critical lightning current, which causes the voltage across the insulator to be equal to a CFO voltage of 300 kV, is determined. This step is performed manually via increases in current in the ATP-EMTP software. Second, the critical current is used to calculate the probability of peak lightning current exceeding the critical lightning-current magnitude (%) from equation (2). Third, the back flashover rate is calculated using equation (3) in Microsoft Excel software.

Fourth, the BFR is multiplied with the outage cost in column (e) to determine the damage cost in column (f) and reduction or savings cost in column (g) of each grounding structure. The project periods and discount rates used for economic evaluation are 25 years and 10%, respectively.

In this study, increasing the CFO from 205 kV to 300 kV and varying the grounding distance of OHGW from 40 m to 200 m are both analyzed in order to find cost reductions. The results are outlined in Table 5.

Finally, the cost-effectiveness of the investment is determined using economic tools, in terms of measures such as DPP, NPV, IRR, and PI. The project periods and discount rates used for economic evaluation are 25 years and 10%, respectively.

The total breakdown of investment cost is equal value of 302.27 USD/pole, comprising materials and services used on the pole, which include the new insulator, zinc-coated steel wire for OHGW and external ground wire, and labor cost and work control, as shown in Table 6.

The total investment cost for 100 km distribution lines can be calculated using the data in Table 7.

TABLE 4: Minimum critical impulse flashover (kV) at 10 Ω ground resistance (average in Thailand).

Lightning current (kA)	Grounding distance of OHGW (m)				
	40	80	120	160	200
30	222	267	292	292	300
40	268	324	358	359	360
50	310	377	416	418	420

TABLE 5: Reduction cost (savings cost).

Grounding distance	I^* (kA) (a)	P (Ip) (b)	N_L (flashes/100 km/year) (c)	BFR (flashes/100 km/year) (d) = (b) $\times$ (c)
No G	3.30	0.9996		15.250
40 m	29.27	0.7242		11.048
80 m	12.84	0.9429	15.257	14.386
120 m	9.17	0.9747		14.870
160 m	7.90	0.9820		14.982
200 m	7.38	0.9843		15.017
Grounding distance	Outage cost (USD/event) (e)*	Damage (USD) PV of 25 years (f) = (d) $\times$ (e)	Reduction (USD) PV of 25 years (g)	Reduction (%)
No G		4,005,228.37	0	0.00
40 m		2,900,463.301	1,104,765.07	27.58
80 m	28,921.70	3,776,671.06	228,557.31	5.71
120 m		3,903,712.55	101,515.82	2.53
160 m		3,933,034.95	72,193.43	1.80
200 m		3,942,202.24	63,026.13	1.57

*Outage cost per event in distribution line service area in Thailand is 28,921.70 USD/event in the year 2020 [1], where PV is the present value.

TABLE 6: Breakdown of investment cost.

Item	Investment cost (USD/pole)
Material	227.76
Labor	42.44
Work control	32.06
Total	302.27

TABLE 7: Total investment cost for 100 km distribution lines.

Parameters	Description				
Grounding distance of OHGW (m)	40	80	120	160	200
Number of concrete poles per 100 km	2,500	1,250	833	625	500
Investment cost per pole (USD per pole)			302.27 (Table 6)		
Total cost (USD) per 100 km	755,666.70	377,833.35	251,888.90	188,916.67	151,133.34

TABLE 8: Economic feasibility.

Grounding distance (m)	Total investment cost (USD) (h)	O&M cost (USD) 3% of column h (i)	DPP (year)	NPV (USD)	IRR (%)	PI	Conclusion
40	755,666.70	22,670	15.12	143,321.87	12	1.15	Accepted
80	377,833.35	11,335	>25	-252,164.29	2	0.48	No
120	251,888.90	7,556.67	>25	-218,965.25	-1	0.32	No
160	188,916.67	5,667.50	>25	-168,167.37	-1	0.30	No
200	151,133.34	4,534	>25	-129,262.51	-1	0.33	No

The annual costs of operation and maintenance (O&M) for both increase in CFO from 205 kV to 300 kV and installation of grounding distance of OHGW, which is estimated to be at 3% of the total investment cost, are shown in Table 8, column (i).

With regard to the economic results, summation of the total investment cost and annual cost of O&M according to Table 8 in columns (h) and (i), compared with the damage reduction or cost savings in Table 5, column (g), demonstrates that purchases of new or replacement insulators for 40 m grounding distance of OHGW should be considered important investments that require high installation costs but result in greater reductions with better economic results, that is, DPP of 15.12 years, NPV of 143,321.87 USD, greater IRR of 12%, and superior PI of 1.15.

5. Conclusions

This study investigated the effects of direct lightning strikes to an OHGW on a 24 kV distribution system in Thailand. The statistics of power outages have identified large numbers of unknown power outages occurring in urban areas of Thailand. Therefore, a method for improving lightning protection, via installation of OHGW at various grounding distances, was proposed, to distribute lightning current to the ground level and to account for increases in the critical insulator flashover from 205 kV to 300 kV. The purpose of the study was to reduce power outages among distribution systems. ATP-EMTP software was used for analysis. The study determined that increasing the insulation level via installation of OHGW at every pole or every 40 m can greatly reduce the back flashover rate, thereby causing reductions in power outages by 27.58% compared to when the system is unprotected by OHGW. Although calculations showed that increasing insulation levels to 300 kV with installation of OHGW at every pole has the highest installation costs, the payback period will be fast, at 15.12 years. On the other hand, other grounding distances or wider grounding of OHGW would at least be able to help reduce back flashover rate by 1.51%–5.71% for grounding distances of 80–200 m. If the ground resistance is significantly distinct from 10 Ω , the results of cost analysis of the investment may change, that is, lower ground resistance causes a lower back flashover rate. Therefore, a grounding system is imperative for the design of lightning protection in distribution systems, which should be a first priority. Furthermore, another method should be considered if the grounding system is not enough for lightning protection, such as increasing the insulation level of insulator or using a lightning arrester to reduce overvoltage, to enhance the lightning protection performance. All results of this study could serve as a guideline for the design of distribution lines and improvement of power systems.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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