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Back Flashover Analysis Induced by Lightning Strikes on the 150 kV Sawahan–Krembangan HV Transmission Line

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Abstrak—HV Transmission Lines play a crucial role in the electrical power transmission system but are highly vulnerable to external disturbances, particularly lightning strikes. One common consequence is back flashover, which occurs when lightning-induced overvoltages exceed the insulation strength, causing a flashover from the tower or ground to the phase conductor. This study aims to analyze the potential occurrence of back flashover and evaluate the protection zone of the overhead ground wire on the 150 kV Sawahan–Krembangan transmission line, specifically at towers number 8, 9, and 10. The methodology involves collecting data on tower and insulator specifications, grounding resistance, and lightning strike parameters. Calculations of transient overvoltages and protection zones were conducted using a trigonometric approach. The analysis results indicate that the lightning-induced overvoltages on all three towers remain below the Basic Impulse Insulation Level (BIL) of the insulators, suggesting that back flashover is unlikely to occur. Furthermore, the protection zone evaluation demonstrates that the overhead ground wire sufficiently covers the phase conductors, with protection angles conforming to established standards. Therefore, the lightning protection system on this transmission line is considered effective. This study is expected to provide technical recommendations for PT. PLN (Persero) and contribute to the development of knowledge in the field of electrical engineering.

***Keywords*—Back Flashover, Ground Wire, HV Transmission Lines, Lightning Strikes, Protection Zone**

I. INTRODUCTION

Electric energy is a critical necessity across all sectors, including households, industries, and transportation. To maintain continuity and reliability of electricity supply, transmission systems play an essential role in delivering power from generating stations to load centers. In Indonesia, high voltage transmission lines commonly use overhead configurations (SUTT), which, due to their exposed structure, are highly vulnerable to external disturbances such as lightning strikes, particularly in tropical regions with high lightning density [1], [2]. Among the various disturbances, back flashover is one of the most common and damaging events, occurring when the lightning-induced overvoltage exceeds the insulator's dielectric strength, causing a flash from the tower or ground to the phase conductor [3]–[5].

This phenomenon can lead to equipment failures, service interruptions, and even cascading faults in power systems. To mitigate such risks, ground wires are installed to create a protective zone above the conductors. The effectiveness of these ground wires depends significantly on their geometric configuration, especially the protection angle and height, which define the safe zone beneath the wire using methods such as the rolling sphere or electrogeometric model [6]–[9]. Several studies have analyzed the lightning performance of transmission lines using simulation-based approaches and empirical data, confirming the critical role of tower footing resistance, insulator characteristics, and line configuration in determining lightning withstand capability [10]–[12]. Recent research has also highlighted the importance of optimizing the shielding angle and improving grounding systems to minimize back flashover probability [13]–[15]. In this study, a comprehensive analysis is conducted on towers 8, 9, and 10 of the 150 kV Sawahan–Krembangan transmission line. In addition, localized environmental conditions such as soil resistivity, terrain elevation, and lightning strike density also influence the overall effectiveness of lightning protection systems. These factors must be considered alongside structural parameters during the design and evaluation of overhead transmission lines to ensure comprehensive protection and reduce the likelihood of back flashover events in high-risk areas.

The research includes protection zone evaluation and overvoltage calculation due to lightning strikes, incorporating local lightning density, tower geometry, grounding resistance, and insulator specifications. The goal is to determine whether the existing configuration provides sufficient protection and to offer technical recommendations for enhancing the reliability of the transmission system under lightning exposure.

II. METHODS

The methodology of this research began with the preparation of all necessary resources to ensure the smooth execution of the study. The initial stage involved a comprehensive literature review, which entailed collecting and examining various scholarly references from journals and books to strengthen the theoretical foundation and deepen the understanding of the research problem. Following this, a field observation was conducted at the Sawahan–Krembangan Transmission Substation to gain a practical overview of the site conditions. This observation included both direct visual assessments and interviews with relevant personnel to gather supporting information.

After completing the literature review and field investigation, the next step was data collection. The data gathered encompassed several technical aspects, including tower specifications (such as type, height, phase spacing, and operating voltage), insulator specifications (type, brand, and number of discs), and grounding system data, particularly the measured grounding resistance. Additionally, lightning-related data were collected, including the frequency of lightning strikes, lightning impulse steepness, and the Basic Insulation Level (BIL) or Critical Flashover Voltage (TID) of the insulators, which indicate the maximum voltage they can withstand before flashover occurs. These datasets formed the basis for analyzing the lightning-induced overvoltages within the transmission system.

A. Protection Zone on 150 kV Transmission Tower

Substations located inside buildings, open fields, or switch-yard areas are highly susceptible to lightning strikes. Therefore, specialized lightning protection systems are required, involving the installation of various protective devices. Copper rods or overhead ground wires function as lightning arresters by directly intercepting lightning strikes. These devices are typically made from conductive materials such as copper, aluminum, or steel, and are installed vertically above or around structures, or in the form of shielding wires. A protection system is considered effective if, out of 1.000 lightning strikes, 999 are intercepted by the protection system and only one strike reaches the substation equipment representing a protection level of 0,1% [2].

In general, overhead transmission lines are protected using ground wires. This method provides a high level of effectiveness against direct lightning strikes to the phase conductors. Alternatively, in low-voltage systems (typically below 30 kV), overhead lines without ground wires may use protective devices such as *protector tubes*; however, this technology is rarely applied today due to its limitations and obsolescence [2]. Protection using ground wires is a widely adopted method in transmission and distribution systems to safeguard against lightning-induced surges or overvoltages. In this system, the ground wire is installed along the transmission line or on top of the towers to divert the lightning current safely to the ground, thereby preventing damage to critical electrical components such as insulators and phase conductors. One or more ground wires may be used depending on the required level of protection. Key considerations in selecting ground wires include:

1. Mechanical properties take precedence over electrical properties. The ground wire must have high tensile strength and corrosion resistance.
2. Based on laboratory testing and field experience, an effective protection angle for shielding against lightning is generally limited to a maximum of 30 degrees.

The protection zone of High Voltage Overhead Transmission Lines can be determined using trigonometric relationships and the Pythagorean theorem. Trigonometry is applied to calculate the protection angle (θ), which is formed between the overhead ground wire and the protected phase conductor. The basic equation used is:

$$\tan\theta = \frac{h}{d} \tag{1}$$

where h is the vertical distance from the ground wire to the conductor, and d is the horizontal distance between the ground wire and the conductor. In addition, the Pythagorean theorem is used to determine the total protection reach or the radius of the protection zone, based on the tower height and horizontal distance. This is calculated using the following formula:

$$r = \sqrt{h^2 + d^2} \tag{2}$$

Where r represents the protection radius, defining the effective area considered safe from direct lightning strikes. By combining these two equations, it is possible to evaluate and calculate an optimal protection zone, ensuring that the phase conductors remain within the shielding coverage of the ground wire. This approach is essential for minimizing the risk of lightning-related disturbances and improving the reliability of the transmission system. Figure 1 and Figure 2 are the determination of the protection angle for each phase wire by modeling single and double ground wires installed at the top of the transmission tower.

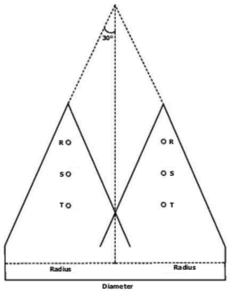

Figure 1. Protection Zone Configuration for One Ground Wire

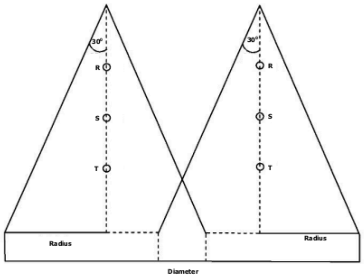

Figure 2. Protection Zone Configuration for Two Ground Wire

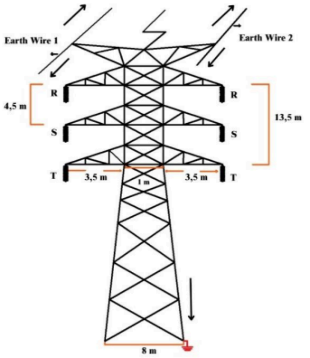

Figure 3. Direct Strike On Tower

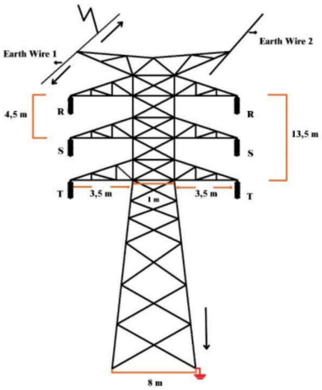

Figure 4. Direct Strike on Ground Wire

B. *Lightning Strikes on 150 kV Transmission Towers*

Lightning strikes on 150 kV transmission towers occur primarily due to their elevated and exposed position, making them highly susceptible to direct lightning discharges. Such events can generate voltage surges capable of damaging critical components such as insulators, transformers, and circuit breakers. In addition to equipment damage, lightning strikes can also trigger flashover or back flashover, potentially compromising the stability and reliability of the power system. To mitigate these risks, protective devices such as surge arresters and grounding systems are employed. These components serve to divert the lightning current safely into the ground while enhancing insulation performance to maintain the integrity and safety of the transmission system.

A direct lightning strike on a transmission tower can induce a significant voltage rise on the tower structure, potentially leading to a backflashover. This phenomenon occurs when the resulting overvoltage exceeds the insulation strength, causing a reverse breakdown across the insulation gap between the tower and the phase conductor, as illustrated in Figure 3. The induced voltage at the tower, denoted as V_m, can be calculated using the following equation:

$$V_M = (i_s \times R_E) + L\frac{di}{dt} \tag{3}$$

V_M : Voltage rise at the tower (kV)
i_s : Lightning current (kA)
R_E : Earth Resistance (Ω)
L : Tower Inductance (mH)
$\frac{di}{dt}$: Impulse rate of rise (kA/µs)

This equation reflects the contribution of both resistive and inductive components to the total overvoltage at the tower during a lightning event. Accurate estimation of these parameters is essential for evaluating the risk of back flashover and designing effective lightning protection systems for high-voltage transmission lines.

C. *Lightning Strike on the Earth Wire*

A lightning strike on a transmission line with a ground wire results in the distribution of current into three distinct paths through the conductor, the tower structure, and the ground depending on the impedance of each path, as illustrated in Figure 4. A portion of this current flows through the tower inductance L. If the transmission line utilizes two phase conductors, the lightning current will be split into five paths, and so on. Although the peak current flowing through the tower tends to decrease with an increasing number of conductors, the rate of current change $\left(\frac{di}{dt}\right)$ remains constant. Consequently, the induced voltage on the tower can be expressed by the equation:

$$V_m = L\frac{di}{dt} \tag{4}$$

Where,

V_m : Induced voltage on the tower (kV)

L : Tower Inductance (mH)

$\frac{di}{dt}$: Rate of change of lightning current (kA/µs)

D. Lightning Impulse Steepness

Lightning impulse steepness refers to the rate at which voltage or current changes over a very short time during a lightning strike. It is typically expressed in units of kV/µs or kA/µs. This value indicates how rapidly the impulse reaches its peak, which significantly influences the dielectric performance of insulators and their ability to withstand flashover. Standardized lightning waveforms are usually represented by a front time (t_1) ranging from 1 to 10 microseconds, and a tail time (t_2) from 10 to 100 microseconds. The steepness of the impulse current can be calculated using the following formula:

$$\frac{di}{dt} = \frac{I_2 - I_1}{t_2 - t_1} \quad (5)$$

Where,

I_2 : Minimum lightning current (kA)

I_1 : Peak lightning current (kA)

t_2 : Time after peak (µs)

t_1 : Time to peak (µs)

Understanding and quantifying impulse steepness is crucial for evaluating insulation coordination and designing reliable lightning protection systems for HV transmission lines.

III. RESULT AND ANALYSIS

This chapter presents the analysis and discussion of back flashover phenomena occurring on the 150 kV transmission line. The focus is on evaluating the risk and impact of lightning-induced overvoltages, particularly those resulting from direct strikes on towers and earth wires. By using technical parameters such as tower geometry, grounding resistance, lightning current characteristics, and insulation levels, the analysis aims to assess whether back flashover conditions are likely to occur and to determine the effectiveness of the existing lightning protection system.

A. Protection Zone on HV Transmission Tower

The analysis of the protection zone aims to assess the extent to which the ground wire can shield the phase conductors from direct lightning strikes along the 150 kV Sawahan–Krembangan transmission line. The data used in the protection zone calculation are presented in Table 1.

TABLE 1. TRANSMISSION TOWER CHARACTERISTICS

Tower Characteristics	**Information**
Voltage Nominal	150 kV
Tower Type	Suspension
Isolator Type	Porcelain
Cross Arm Length	8 m
Height	33 m
Zone Protection	30^0

TABEL 2. RADIUS OF LIGHTNING PROTECTION ZONE

Tower Number	One Ground Wire		Two Ground Wire	
	Height	Radius	Height	Radius
Tower 8	33,3 m	18,9 m	58,9 m	22,9 m

Based on Table 1, the protection zone calculation was carried out using the shielding angle approach in accordance with the electrogeometric method. Equation (1) was employed to determine the radius of the protection zone. Using the specified parameters, the protection zone calculation for a tower equipped with a single ground wire is presented as follows:

C : 33,3 m

θ : 30°

Determining the Protection Radius

$$\text{Tan } 30^\circ = \frac{r}{33{,}3}$$

$$0{,}57 = \frac{r}{33{,}3}$$

$$r_1 = 0{,}57 \times 33{,}3 = 18{,}9 \text{ m}$$

Calculation with a Two Ground Wire Configuration

r_1 : 18,9 m

Cross Arm : $\frac{8}{2} = 4$ m

θ : 30°

Determining the Protection Radius

$$\text{Tan } 30^\circ = \frac{22{,}9}{r_2}$$

$$0{,}57 = \frac{22{,}9}{c}$$

$$r_2 = \frac{22{,}4}{0{,}57} = 25{,}9 \text{ m}$$

Table 2 presents the results of the protection zone calculations for the 150 kV transmission tower, illustrating the coverage area provided by the ground wire and tower structure against lightning strikes based on the tower height.

B. Lightning Impulse Stepness Analysis

Lightning strike data from the year 2024 were used to analyze potential disturbances that could trigger back flashover on the 150 kV transmission line. This information was obtained from the annual disturbance report. The detailed lightning strike data recorded are presented in Table 3.

TABLE 3. TRANSMISSION TOWER CHARACTERISTICS

Tower Number	**Count**	**Count (-)**	**Count (+)**	**Current Strikes**	
				min	**max**
Tower 8	52	44	8	-149	71
Tower 9	27	19	8	-149	71
Tower 10	28	21	7	-149	71

Based on Table 3, which presents the lightning impulse steepness data for Towers 8, 9, and 10, calculations were performed using Equation (5) as follows:

$I_2 = 71$ kA

$I_1 = -149$ kA

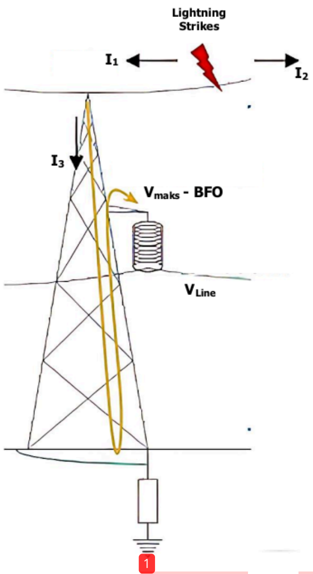

Figure 5. Backflashover when a Lightning Strike occurs on the Ground Wire

$t_2 = 10\ \mu s$

$t_1 = 1\ \mu s$

By substituting the parameters above into the equation, the lightning impulse steepness values were obtained as follows:

$$\frac{di}{dt} = \frac{71 - (-149)}{10 - 1} = 24\ kA/\mu s$$

C. Back Flashover Due to Direct Strikes on the Tower

In this analysis, calculations were performed to determine the magnitude of the back flashover voltage on the 150 kV HV Overhead Transmission Line. When a lightning strike hits the SUTT tower and two earth wires are present, the lightning current is divided into five paths. Several parameters from Tower 8 used in the calculation are as follows:

Lightning Current	: -149 kA
Earth Resistance	: 1.8 Ω
Tower Inductance	: 30 μH
Lightning Impulse	: 24 kA

Based on the aforementioned data, the voltage at the tower as illustrated in Figure 3 can be calculated using Equation (3), resulting in the following value:

$$V_M = (29{,}8 \times 1.8) + 30 \times 24$$
$$= 53{,}6 + 720 = 773{,}7 \text{ kV}$$

D. Back Flashover Due to Direct Strikes on the Ground Wire

In this analysis, calculations were conducted to determine the magnitude of the back flashover voltage on the 150 kV High Voltage Overhead Transmission Line. When a lightning strike hits the earth wire, the current is divided into three paths. Based on the previously presented data for Tower 8, the voltage at the tower illustrated in Figure 4 can be calculated using Equation (3) as follows:

$$V_M = (49{,}6 \times 1.8) + 30 \times 24$$
$$= 89{,}4 + 720 = 809{,}4 \text{ kV}$$

Table 4 presents the results of the back flashover voltage calculations and provides data on the voltage levels induced on the transmission line due to lightning strikes.

TABLE 3. THE MAGNITUDE OF BACK FLASHOVER THAT OCCURRED

Tower Number	Back Flashover (kV)	
	Ground Wire	Direct Tower
Tower 8	773,7	854
Tower 9	761,7	824
Tower 10	734,9	757,3

E. Discussion

High-voltage transmission systems serve as the backbone of long-distance electric power delivery. One of the main challenges in operating such systems is lightning-induced disturbances, which can lead to temporary faults or even widespread blackouts across the network.

Figure 5 illustrates the backflashover phenomenon that occurs when a lightning strike hits the ground wire of a transmission tower. In this situation, the lightning current (I_1) enters the ground wire, with a significant portion flowing down through the tower structure to the ground (I_3), while the remaining current propagates along the ground wire in both directions (I_2). If the magnitude of the lightning current is high and the tower grounding impedance is not sufficiently low, a substantial potential rise occurs across the tower structure. The resulting potential difference between the tower and the phase conductor generates an overvoltage (V_{BFO}) that may trigger a flashover across the insulator string, as indicated by the yellow path in the diagram. This overvoltage, known as backflashover voltage, is highly dependent on the grounding impedance, the magnitude of the lightning current, and the length and electrical characteristics of the insulators. Such an event causes a phase-to-ground fault, posing a serious threat to system reliability.

This phenomenon highlights that even though the ground line is designed to shield phase conductors from direct lightning strikes, a strike to the ground wire itself can still induce severe disturbances via the backflashover mechanism particularly when the grounding system is inadequate to safely dissipate the surge current. Therefore, lightning protection system design for transmission lines must account not only for direct strike shielding but also for transient phenomena such as backflashover [16].

IV. CONCLUSION

Based on the analysis and discussion presented in this study, several conclusions can be drawn. First, the use of two earth wires provides a more optimal level of protection compared to a single earth wire. This is evidenced by the increased installation height from 33.3 meters to 58.9 meters, resulting in a wider protection zone radius from 18.9 meters to 22.9 meters. Therefore, the dual ground wire configuration is more effective in expanding the lightning protection coverage for high-voltage transmission towers. Second, the calculated back flashover voltages due to lightning strikes on the earth wire were 854 kV (Tower 8), 824 kV (Tower 9), and 757.3 kV (Tower 10). For direct strikes to the tower, the resulting voltages were 773.7 kV (Tower 8), 761.7 kV (Tower 9), and 734.9 kV (Tower 10). All these values remain below the Basic Insulation Level (BIL) of the insulators, indicating that the insulation system is not exceeded under lightning stress. Hence, the lightning protection system using earth wires is proven to be effective in mitigating the risk of disturbances caused by lightning strikes and in maintaining insulation reliability on the 150 kV HV transmission network.

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