Analysis of lightning disturbance at 150 kV high voltage power lines

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Abstract. The power transmission line channels electrical energy from power plants to consumers through diverse natural conditions. East Java is an area with a unique topography, where clouds causing rain and lightning are frequently formed. Such clouds strongly interfere with the 500 kV Extra High Voltage Line (SUTET), causing a lightning strike. Therefore, the lightning strikes along the channel needed to be analyzed. The random method used in this research measured the lightning safety at the tower, within a quarter of the distance from the tower and half the distance from the tower (Lightning disturbance due to back flashover) Based on the calculation, the highest number of disturbances in the phase wire per 100 km² of conductor per year has obtained and (SFO) was $1.07399 \times 10^{-3}$ while tower impedance has found at 273.6219 Ohms.

1. Introduction
The development of science and technology affects the national energy demand and the need for electrical energy for daily life to supply both households and businesses. Unfortunately, the current national energy demand is not followed by adequate growth of quality and highly reliable generators [1]. Perusahaan Listrik Negara or the State Electricity Company contributes to developing the national economy by supporting energy independence through active contribution for reliable and quality electricity supply. Electric power's reliability is defined as the opportunity for equipment to operate by its procedures and functions within certain intervals and under certain conditions to fulfill the electricity needs [2]. An electric power system is a complex unit that consists of a generator center, distribution channel & transmission line to distribute power from the power plant to the consumer. The electric power system is named based on the coverage area, for example, Sistem Tenaga listrik Jawa Bali (STLJB) or Java Bali Electric Power System (STLJB), covering Java, Bali, and Madura [3].

The state electricity company (PLN) has an extra high voltage 500 kV power line with bundling two performance conductors. Some combine two, three, or more conductors to distribute electrical power [4]. V-String insulation is also applied to provide stability against wind and rainwater exposure. Every tower has equipped with a static cable in the transmission line tower. This cable does not have an insulator. Instead, it has directly connected to the ground. Such a system protects the conductor from direct lightning strikes.

Disruptions in the electric power system often occur in distribution areas, namely transmission disruption and distribution disruption. Internal and external factors can also trigger disruptions. The lightning strike is an external factor that often occurs due to Indonesia's geographical location, which
is in the equatorial region with a tropical climate and high humidity [5]. Such characteristics make the lightning density in Indonesia higher than in other countries [6].

| No | Country       | Lightning Day / Year |
|----|---------------|-----------------------|
| 1  | European Countries | 30                    |
| 2  | America       | 100                   |
| 3  | Japan         | 80                    |
| 4  | Korea         | 80                    |
| 5  | Australia     | 80                    |
| 6  | Indonesia     | 200                   |

The dominant use of an overhead electricity transmission system in Indonesia rather than an underground transmission system makes it more vulnerable to lightning strikes. The use of an overhead power line and tall construction also increases the vulnerability of lightning strikes. Mountainous areas are more susceptible since the transmitters are closer to the clouds. Two types of lightning strikes disrupt the transmission system, namely direct lightning strikes and indirect lightning strikes. A direct lightning strike occurs when the strike hits the phase wires or ground wires in the transmission system, while an indirect lightning strike occurs when the strike hits the area around the transmission system [7][8].

1.1. The distribution of surge voltage at transmission tower
When lightning strikes the ground wire, the lightning surge voltage waves will propagate to the left and right from the strike point. The surge voltage waves propagate through the ground wire towards the transmission tower. Due to the different impedance of the ground wire and the tower's resistance, there will be a voltage reflection from the bottom of the tower to the top of the tower. In this case, a large difference between the tower's impedances and the ground wire will create voltage reflections from the top of the tower to the bottom of the tower. In other words, voltage reflections will create more substantial lightning surge voltage on the tower insulator. The amount of the maximum voltage capacity in each tower differs, depending on the point of strike, tower surge impedance, and tower resistance [9],[10].

1.2 The distribution of surge current
A lightning strike on a tower followed by a high lightning current flow within a short time will cause damages determined by several parameters as follows [11].

- The peak current of the lightning impulse, which is the maximum lightning impulse that can cause overvoltage at the strike point.
- The lightning current's steepness, which is the rate of increase over time, can cause the electromagnetically induced voltage on metal objects near the lightning strike point.
- Electric charge of lightning current, which is the amount of lightning current that can cause fusion at the end of the object getting struck by lightning.
- Integral Square of the impulse current, referring to the thermal effect that arises and results in an overheated conductor.
Figure 1. Surge current distribution

\[ V_A = \text{Surge voltage of the ground wire} \]
\[ V_r = \text{Surge voltage reflected from the branch point} \]
\[ V_g = \text{Surge voltage passed through the following ground wire} \]
\[ V_t = \text{Surge voltage passed to the tower from the branch point} \]
\[ I_S = \text{Surge current of the ground wire} \]
\[ I_g = \text{Surge current passed to the following ground wire} \]
\[ I_t = \text{Surge current passed to the tower from the branch point} \]

The current flowing to the wire

\[ I_r = -\frac{Z_g}{Z_g+2Z_t}I_g = g\cdot I_g \]  \hspace{1cm} (1)\]
\[ g = -\frac{Z_g}{Z_g+2Z_t} \]  \hspace{1cm} (2)

where:
\[ Z_g = \text{Surge impedance of the ground wire} \]
\[ Z_t = \text{Surge impedance of the tower} \]

Lightning density per unit area per year
\[ D = 8,875.10^{-8} \cdot \text{IKL} \]  \hspace{1cm} (3)

where:
\[ D = \text{Lightning density per year} \]
\[ \text{IKL} = \text{Isokeraunic level} \]

The average height of ground wire (hg)
\[ H_g = H_t - \frac{2}{3} \cdot \text{Sag Average} \]  \hspace{1cm} (4)

where:
\[ H_t = \text{Tower height (m)} \]

Total area covered by the ground wire (A)
\[ A = (2 \cdot \pi + 1) \cdot h_t^2 + 4 \cdot hg \cdot (S - h_t) \]  \hspace{1cm} (5)

where:
\[ h_g = \text{Average height of ground wire (m)} \]
\[ S = \text{Average wicket length (m)} \]

The number of possible lightning strikes per 100 km conductor per year (L)
\[ L = 100 \cdot \frac{1000}{S} \cdot A \cdot D \]  \hspace{1cm} (6)

Probability of ground wire protection failure (Pφ)
\[ \log P_\phi = \frac{\sqrt{H_t}}{90} - 4 \]  \hspace{1cm} (7)

If their lightning strikes the transmission tower, overvoltage will propagate through the tower. Due to the insulation resistance of the insulator, fire sparks will occur to the phase wire, and a short circuit
to the ground will appear. This disturbance is known as back flashover interference. If the strike does not hit the ground wire or transmission tower yet directly hits the phase wire, a very high overvoltage will arise at the strike point, propagating along the phase wire to reach the insulator. When the insulator cannot withstand this overvoltage, fire sparks will arise, causing a short circuit to the ground.

The voltage that occurs on the transmission isolator depends on the peak, steepness, and lightning or lightning wavefront time. Table 2 describes the relationship between peak lightning flows and lightning strike frequency, while Table 3 describes the relationship between peak times and the lightning frequency [12]. The peak of the lightning current above 80 kA usually creates a flashover.

| Peak Current (kA) | Probability(%) |
|------------------|----------------|
| Up to 60         | 90             |
| 80               | 8              |
| 100              | 1.2            |
| 160              | 0.5            |
| More than 200    | 0.3            |

### Table 3. The relationship between lightning wavefront and lightning strike occurrence probability

| Lightning Wavefront (ms) | Probability(%) |
|--------------------------|----------------|
| Up to 0.5                | 7              |
| 1                        | 23             |
| 1.5                      | 22             |
| 2.0                      | 18             |

### 2. Method

This research was conducted through several steps as follows. Protection failure is calculated based on lightning density per unit area, the average height of ground wire, the total area covered by ground wire, the probability of ground wire failure, and the number of lightning disturbances in-phase wire. The back flashover sparks are calculated based on ground wire impedance, the transmission tower's impedance, the radius of the tower, the critical time of the lightning impulse, the spire reflection coefficient, the clutch-related factor, and the total number of lightning disturbance.

![Research methodology flowchart](image-url)
3. Results and Discussions
The following calculations have been made:

Lightning density per unit area per year (D):
\[ D = 8.875 \times 10^8 \times \text{IKL} \]
\[ = 8.875 \times 10^8 \times 102 \]
\[ = 9.0525 \times 10^6 \text{ Lightning strikes per meter square per year} \]

The average height of the ground wire (\( h_g \)):
\[ h_g = H_t - \left( \frac{2}{3} \times \text{Sag Average} \right) \]
\[ = 62.76024 \text{ m} \]

The total area covered by ground wire (A):
\[ A = (2 \times \pi + 1) \times h_t^2 + 4 \times h_g (S - h_t) \]
\[ = 109650.0812 \text{ m}^2 \]

Total lightning strikes that can occur in a 100 km conductor per year (L):
\[ L = 100 \times \frac{1000}{S} \times A \times D \]
\[ = 271.05015 \text{ lightning per 100 km conductor per year} \]

Probability of Ground Wire Protection Failure (\( P_\phi \)):
\[ \log P_\phi = \frac{\theta \sqrt{H_t}}{90} - 4 \]
\[ = -2.33327 \]
\[ P_\phi = 0.004648 \]

Number of lightning disturbance per phase wire per 100 km conductor per year (SFO):
\[ SFO = P_\theta \times L \times (\text{length of line} / 100 \text{ km}) \]
\[ = 1.073399 \times 10^{-3} \]

![Figure 3. Tower Dimension](image)

Transmission tower impendence (\( Z_t \)):

Tower height
\[ H_t = 228,018 \text{ kaki} \]

Phase wire height \( R \) (\( h_0 \))
\[ H_0 = 103.346 \text{ feet} \]
\[ X_b = 20.8743 \text{ feet} \]
\[ X_u = 4.3963 \text{ feet} \]

Calculating the ln rt equivalent radius of the tower
\[ \ln rt = \frac{h_0}{h_t \cdot (X_b - X_u)} \left[ X_b \cdot (\ln X_b - 0.87) - X_u \cdot (\ln X_u - 0.87) \right] + \frac{h_t - h_0}{h_t} \ln (1.14 \cdot X_u) \]

\[ = 0.9088 \text{ feet} \]

\[ Rt = 2.4814 \cdot 0.3048 \text{ (feet unit is converted to meter)} = 0.7563 \]

Tower impedance \( (Z_t) \)

\[ Z_t = 60 \cdot \ln \left( \sqrt{2} \cdot \frac{2 \cdot h_l}{r_t} \right) - 60 \]

\[ = 273.6219 \Omega \]

Critical period \( (T_c) \)

\[ T_c = T + \frac{X_1}{c} \]

Where

\( T = \) time required to reach the top of the tower

\( X_1 = \) vertical distance from the top of the tower to the bottom phase line of the tower (m)

\( C = \) light speed \( (3.10^8 \text{ m/det}) \)

At \( T = 0.5 \)

\[ T_c = T + \frac{X_1}{c} \]

\[ = 0.5 + \frac{11}{300} \]

\[ = 0.5366 \]

Where \( t_c = \) critical period

The time required to reach the peak and the critical period are summarized in Table 4.

| The time required to reach the peak | Critical period \( (T_c) \) |
|-----------------------------------|--------------------------|
| 0.5                              | 0.5366                   |
| 1                                | 1.0366                   |
| 1.5                              | 1.5366                   |
| 2                                | 2.0366                   |

Calculations and facts regarding lightning disturbances in the field showed a relatively similar outcome with a margin of error of 9.26%. The test was carried out by calculating IKL value for the last six years, resulting in the following outcomes.

| Number | Year | Number of Lightning Disturbance Calculation | Data from PLN |
|--------|------|--------------------------------------------|---------------|
| 1      | 2014 | 0.1235                                     | 0             |
| 2      | 2015 | 0.2769                                     | 0             |
| 3      | 2016 | 0.5432                                     | 1             |
| 4      | 2017 | 0.4276                                     | 1             |
| 5      | 2018 | 0.3214                                     | 0             |
| 6      | 2019 | 0.1222                                     | 0             |
| Total  |      | 1.8148                                     | 2             |
\[ Error = \frac{\text{Calculation Outcome} - \text{data from PLN}}{\text{Data From PLN}} \times 100\% \]  
\[ Error = \frac{1.8148 - 2}{2} \times 100\% \]
\[ Error = 9.26\% \]

4. Conclusions
Measurement of extra-high voltage overhead line against lightning disturbance is influenced by several factors affecting the output figure. Some of these factors include the number of lightning strike days in an area, the height of a tower, the angle of protection, and the tower resistance.

Tower resistance tested using a soil moisture sensor has a gap in humidity up to 20% from the measuring instrument. The resistance of a tower is affected by several factors, namely temperature, current, water content, chemicals, humidity, and weather.

Some aspects are worth developing in future research as follows. Software refinement is needed, and advanced research using other methods is worth conducting to determine the lightning disturbance extra-high voltage overhead lines to obtain a more precise outcome. It is necessary to develop the use of soil moisture sensors to determine the resistance of a tower further.

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