Lightning Strikes Mitigation Plan on Transmission Line Tower at Kedah Paddy Field

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Abstract. This paper presents a mitigation plan for lightning strikes towards the transmission line tower at Kedah paddy field area. The ATP Draw software produces a schematic diagram of an incoming main intake sub-station and a transmission tower struck by lightning. Simulation on multiple soil resistance values and multiple soil conditions are then plot into graphs. A static eliminator reduces the electrostatic force between negatively charged thunder clouds with a positively charged steel transmission tower. It shows that a static eliminator makes the transmission line act invisibly in the lightning pathway. This protection level avoids surge current from transmitting in the transmission line reduces the possibility to damage surge arrestor.

1. Introduction

Located at the equator line, Malaysia experiences dry and wet climates throughout the year. Published by [1] in 2017, Figure 1 shown the monsoon season starts from May until October while the drought season starts from November until April. During the monsoon season, the increased rainfall and thunderstorm activity are detected and recorded by different techniques [2]. This phenomenon creates an active lightning strike to the ground.

![Figure 1: Malaysia Rainfall Record 2017.](image)

A transmission tower made from galvanized steel has positively charged ions. These positively charged ions are called a cation and contain free valence electrons in the s-orbital. At the outermost ions shell, a free electron needs to loosen up to achieve a stable octet. The transmission tower with a positive charge attracts a negative charge from thunderstorm clouds. The lightning strike carries 15 Coulombs of electric charge and 30 kA electric current, and 1 Gigajoule of energy. A high current in the skyline was dismissed by two protection schemes, first by lightning arrestor and second by direct grounding to the earth. This leads to distortion in voltage sags, overcurrent, and overvoltage to power quality.
2. Types of grounding

A low-frequency grounding resistance is different from impulsive grounding impedance refers to Visacro [3] and Verma [4]. Different type parameters are used for response characteristics of electrodes subjected to lightning currents. These findings changed the conventional way to prevent flashover, as previous practices are to reduce tower footing resistance and installation of surge arrester to reduce back flashover frequency. Mazetti [5] concludes that transient behavior current under impulse current of a horizontally buried wire has a decisive influence on its behavior in length, soil resistivity, and wave-shape and intensity of the impulse. Then Visacro [6] proposed the effect of decreasing grounding resistance underbuilt wires helps in reducing the development of overvoltage across insulator strings of the existing line during direct strike events.

2.1. Soil Permittivity and Resistivity

Silverio [7] recommended accurate lightning performance calculations on transmission lines installed in regions of moderate and high soil resistivity. The frequency dependence of soil permittivity and resistivity is taken into account. This brings to their next research [8] that shows decreasing on tower footing grounding resistances yields continuous reduction of the overvoltage experienced across insulator strings in response to first-stroke current strikes, but it is not effective to decrease over-voltages of subsequent strokes. As tower-footing grounding resistance decreased, the subsequent-stroke contribution increased. For almost all back flashover by subsequent strokes, the distribution with prevailing low grounding resistance value is responsible. Many research papers find the low frequency at the line, the characteristic of grounding systems subject to high impulse current has dramatically differed. The surrounding of the grounding conductor generates large current complicated soil ionization. This makes transient characteristics typically non-linear.

Oettle [9] advises to consider power frequency fault current conditions and the desired impulse impedance for tower earthing. For non-linear characteristics, Geri [10] developed a simulation code to verify the impulsive response on the ground system using a horizontally buried steel bar and vertically buried steel rod. The effectiveness of the code was being compared between the simulation code and the experimental. Meanwhile, Xiong [11] studies the electrical field on the earth's surface by proposing a square ground grid (60m x 60m x 10m) mesh buried at 0.5m depth. The scalar potential and electric field are significantly dependent on frequency, while the magnetic field is heavily influenced by the current injection location at all frequencies. However, at low frequency, both scalar potentials and electric fields are not affected.

2.2. Soil Ionization

The incorporation of a complex grounding structure computed using a rigorous electromagnetic modeled in transient analysis proposed by Markus [12] provides large grounding grid accuracy improvement for sub-station. Liu [13] presented a nonuniform transmission line by simulating transient behaviors on horizontal grounding conductors and the grounding grids of different sizes. He compared the result to the electromagnetic field approach and circuit theory approach. Liu advice to include soil ionization in the future by increase the radius of the grounding conductor when the electric field on the surface of the conductor exceeds the critical value of soil ionization.

The ionization phenomenon around the ground conductor in the soil in the transient models of grounding systems is considered by Zeng [14]. The soil turned out to have conductor behavior when its breakdown
around the conductor rod when electrical field strength in the soil surrounding the conductor exceeds the critical value due to high lightning current strikes. This inductive effect of the grounding conductor will obstruct the transient current from flowing toward the conductor’s end terminal. The ionized zone of the soil around the conductor is pyramidal instead of columniform.

3. Related Theory

To model and represent the soil ionization phenomenon in grounding system, the mathematical formula is shown in equation (1) and equation (2) [15]:

\[
R_T = \frac{R_0}{\sqrt{1 + \frac{l}{Ig}}} \quad (1)
\]

\[
I_g = \frac{E_{cr} \rho_s}{2\pi R_0^2} \quad (2)
\]

Where \( R_T \) is the nonlinear tower footing resistance (\( \Omega \)), \( I \) is the lightning current (A), \( I_g \) is the lightning current from which the soil ionization initiates (A), \( \rho_s \) (\( \Omega \)m) is the soil resistivity, \( R_0 \) is the static grounding resistance (\( \Omega \)) and \( E_{cr} \) is the critical electric field (kV/m).

With this concept, it can be stated that the soil disruption can be better represented, if the increase in the conductance \( G \) is considered in the model. Therefore, based on equation (1), the nonlinear conductance in time \( G(t) \) can be estimated using equation (3) for a horizontal electrode and equation (4) for a vertical rod, where \( a \) is the electrode radius (m), \( l \) is the electrode length (m), \( h \) is the depth of the buried conductor (m), and \( \Delta x \) is the segment length (m).

\[
G(t) = \frac{2\pi \Delta x}{\rho_s \cdot \ln \left( \frac{2l}{\sqrt{2}h} \right) - 1} \cdot \sqrt{1 + \frac{l(t)}{I_g}} \quad (3)
\]

\[
G(t) = \frac{2\pi \Delta x}{\rho_s \cdot \ln \left( \frac{2l}{a} \right)} \cdot \sqrt{1 + \frac{l(t)}{I_g}} \quad (4)
\]

A test performs by Chandima [16] with various backfill materials for earthing improvement concluded that metal oxide powder, granite powder, limestone powder, and cock breeze are the best performing material for earth resistance and corrosive characteristic. On the other hand, Huangfu [17] study on the upper high of composite transmission line under overvoltage impact as explained in figure 2 and figure 3 below.
Figure 1: Equivalent radius calculation for (a) ground-wire cross arms and (b) metal tower main body.

The standard expressions for horizontal lines can be applied as below:

\[ L_{AG} = \left( \frac{\mu}{2\pi} \right) \ln \left( \frac{2h}{r_{Aeq}} \right) \]  \hspace{1cm} (5)

\[ C_{AG} = \frac{2\pi\varepsilon}{\ln \left( \frac{2h}{r_{Aeq}} \right)} \]  \hspace{1cm} (6)

The geometrical and earth impedance \( Z_{BG} \) and \( Z_{BE} \) are:

\[ Z_{BG} = \frac{1}{2\pi} \sqrt{\frac{\mu}{\varepsilon} \ln \left[ \frac{\sqrt{h^2 + r_{Beq}^2} + h}{r_{Beq}} \right]} \]  \hspace{1cm} (7)

\[ Z_{BG} = \frac{1}{2\pi} \sqrt{\frac{\mu}{\varepsilon} \ln \left[ \frac{\sqrt{(h+p)^2 + r_{Beq}^2} + h + p}{\sqrt{h^2 + r_{Beq}^2} + h} \right]} \]  \hspace{1cm} (8)

Figure 2: Vertical lines above a lossy earth plane (a) Single conical line and image, (b) Two conical lines and images.

From the above equations, we can calculate overvoltage and electric potential from the composite tower insulation performance. Lumped capacitances caused some fluctuations in transient voltage wave. Flashover will not occur between the upper phase wire based on the intersection method and the grounding ladder. We can avoid the flashover between the ground wire and upper phase wire by fixing the insulator string. The minimum insulation distance between the grounding ladder and tower body ascertains the electric field distribution around the composite at the upper phase cross arm.
Since the low-frequency grounding resistance and impulsive grounding impedance were always in focus, it is often forgotten that avoiding the lightning strike may reduce the possibilities of overcurrent flow in the transmission line. The percentage of lightning strikes depends on an understanding of build-up material the transmission tower material. Towards the end of the '90s, George [18] introduced steel utility poles to replace the wood pole. He has discovered the high current passes steel tower is grounded effectively to the ground with or without a parallel ground rod. The test revealed that the steel pole provided a low resistance connection to earth even in dry soil conditions and rock fill.

In the next research conducted by Yang [19], the cold-formed steel material is lightweight compared to hot-rolled steel and shows a higher degree of corrosion-resistant due to the weathering phenomenon. Furthermore, research by Lodwig [20] proposed to increase insulator string length due to the higher insulator critical flashover value capability to mitigate lightning outage. He proposed overhead ground wire and installation of surge arrestors to limit the voltage produced on the insulators from transient and overvoltage on the line.

Therefore, this paper focus on an additional static eliminator to the tower. The project concept flowchart is shown in figure 4. The soil resistance is low during the monsoon season that provides a good grounding for the lightning strike to discharged. Meanwhile, the soil resistance is high in the drought season. There is a greater possibility of lightning striking the transmission tower when the negatively charged ions inside rainy clouds have passed this dry area. A static eliminator attached to the tower discharges the negative ions from rainy clouds and positive ions at the steel transmission tower, resulting in always naturally charged transmission tower.

![Figure 3: Project Flowchart.](image)
4. Methodology

This is the example of a 400kV main intake sub-station one-line diagrams shown in figure 5. The ATP Draw software simulates a single-phase back flashover caused by a lightning strike to tower 900m away from the main intake. 120kVA amplitude and 4/50 μs front/tail times represent severe lightning parameters. In the investigation, only Bus 1 and Bus 2 are connected with the transformer bus. The conventional Silicon Carbide Arrestor (SiC) act as transformer protection.

Next, the ATP Draw models figure 6 circuit with a condition the lightning strike is near to the main intake sub-station. Meanwhile, 4-phase JMarti LCC Object (which includes phase conductor and sky wire) presents as the line spans. The single-phase constant parameter transmission lines are a Vertical pylon section. The R-L branches below the tower represent tower grounding impedance. The FLASH modeled flashover characteristics on the insulators line. It plays a significant role in the back-flashover study. The Thevenin 3-phase source is connected to the remote end of Bus 2 to simulate the back-flashover since the influence of the power frequency voltage on the back-flashover probability cannot be neglected.
5. Result and Discussion

The first example is run and plotted as shown in Figure 7, Figure 8, and Figure 9. The red line in figure 9 shows incoming surge at the main intake sub-station entrance, while the blue line indicates voltage stress at the transformer terminal, the green line indicates arrester discharge current, and the purple line indicates the lightning strike voltage at the transmission tower.

Figure 7: RLC Ohm equivalent to 13Ω.

Figure 8: Resistor Ohm Value is 40Ω.

Figure 9: ATP Simulation First Test Results.

The second test with a different value of resistance in tower grounding is shown in figure 10, figure 11, and figure 12. From the second simulation test, figure 12 shows when a tower grounding has a high resistance value, lightning strikes increase significantly. It means when the tower resistance is too high (dry soil condition during drought season), the lightning is most likely to strike the tower if the rainy clouds contain mist happen to pass by the dry area, but not raining at that area. In this graph, the green line of arrester discharge current should be showing some arisen and fallen line characteristic that indicates the arrester is discharging the current propagate from transmission line to the transformer to protect the transformer.
Figure 10: RLC Ohm equivalent to 100Ω.

Figure 41: Resistor Ohm Value is 400Ω.

Figure 12: ATP Simulation Second Test Results.

Figure 13 shows the proposal 3 numbers of 5-meter height static eliminator at the top of the transmission tower. At the positively charged static eliminator, negatively charged ions are attracted and passed thru it and flown out into the air. In the end, the transmission tower maintains a natural charge and does not attract lightning to the tower.

The electrostatic forces causing attraction and repulsion can be explained by Coulomb's Law in equation 9. It stated that a force of attraction or repulsion between two-point charges is directly proportional to
the product of the magnitude of each charge but inversely proportional to the square of the distance between them.

\[ F_c = \frac{kq_1q_2}{r^2} \]  

(9)

Where \( F_c \) is Electrostatic Force, \( k \) is Coulomb's Constant, \( q_1 \) is charge of point 1, \( q_2 \) is charge of point 2 and \( r \) is distance between charges. When \( q_1 \) and \( q_2 \) is equal to zero, thus there is no electrostatic force between transmission tower and rainy clouds.

![Figure 64: ATP Simulation Third Test Results.](image)

The third simulation is mimicking natural charges around the transmission tower. The purple line indicates the intensity of lightning voltage has loosened as the result of weakening electrostatic forces. In summary, the below Table 0.1 shows the result of three simulations of three different conditions. In condition 1, the lightning strike voltage intensity is 2.21MV in low soil resistance. For high soil resistance (during dry soil condition), the lightning strike voltage intensity increase double to 4.85MV. When the soil resistance value is high, lightning is more likely to strike the transmission tower. At the third condition, when static grounding resistance is zero while the soil resistance is high, lightning strike intensity is lessened to 2.10MV.

| Simulation | Condition | tower grounding impedance (Ω | R | L | C) | Soil Resistance ohm value (Ω m) | Lightning strike voltage (MV) (PURPLE) | Incoming surge at substation (RED) | Voltage stress at the transformer terminal (MV) (BLUE) | Arrester discharge current (kA) (GREEN) |
|------------|-----------|----------------------------|-----|---|----|-----------------|-----------------------------------|--------------------------------|--------------------------------|--------------------------------|
| 1          | Low tower grounding impedance, low soil resistance | 13 | 40 | | 2.21 | 1.46 | 1.3 | +0.00 | |
| 2          | High tower grounding impedance, High soil resistance | 100 | 400 | | 4.85 | 3.0 | 1.8 | +0.00 | |
| 3          | Natural tower grounding impedance (zero static), | 0 | 400 | | 2.10 | 0.9 | 0.8 | +0.00 | |
6. Conclusion

The proposal of static eliminator to transmission tower mimicking static eliminator installed at aircraft. As aircraft fly high in the sky, any lightning strike to the aircraft body shall be fatal to the electronics devices. But the aircraft survive the lightning strike thanks to engineers’ understanding of electrostatic force generated between the aircraft body with thunder cloud and how to get rid of this problem in the first place. Prevention is the best than treatment nor cure. Therefore, when this electrostatic theory is applied to the electrical system like the transmission tower, it acts invisibly in a lightning pathway. In the worst case, even it was strike by lightning, the static eliminator can discharge the electrostatic charge immediately to the air instead of trying to go for a grounding system. This protection level avoids surge current from transmitting in the transmission line and damaging the surge arrestor.

7. References

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