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Evaluation of Lightning Induced Voltage due to the Effect of Design Parameters on Medium Voltage Distribution Line

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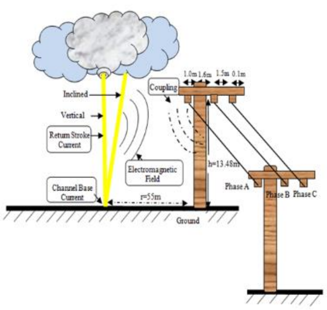
Graphical abstract



Abstract

This paper investigates the effect of design parameters on the induced voltages on a distribution power line. This investigation is based on perfect ground conductivity, single stroke lightning and lightning without branches. The design of the parameters includes, d, the striking distance of the lightning, h, the height of the conductor, and r, the diameter of the conductor, all of which are elements that produce the variations in the induced voltage on a distribution power line with respect to a vertical or an inclined lightning channel. Thus, the outcome of this investigation can act as a guide for utility companies or other power engineers in order to plan an appropriate protection scheme for a distribution power line.

Keywords: Lightning; induced overvoltage; striking distance; vertical lightning channel; inclined lightning channel.

Abstrak

Kertas kerja ini mengkaji kesan reka bentuk parameter pada voltan teraruh pada talian kuasa pembahagian. Penyiasatan ini adalah berdasarkan pada kekonduksian tanah yang sempurna, satu panahan kilat dan kilat tanpa cabang. Reka bentuk parameter termasuklah, jarak panahan kilat, m, ketinggian konduktor, h dan diameter konduktor,d di mana semua parameter ini menghasilkan kepelbagaian nilai voltan teraruh pada pembahagian talian kuasa dengan merujuk pada saluran kilat menegak dan condong. Oleh itu, hasil penyiasatan ini boleh digunakan sebagai panduan bagi pihak utiliti atau jurutera kuasa lain dalam usaha untuk merancang satu skim perlindungan yang sesuai bagi talian kuasa pembahagian.

Kata kunci: Lebihan voltan teraruh; jarak panahan kilat; saluran kilat menegak; saluran kilat condong

■1.0 INTRODUCTION

Lightning is a natural discharge phenomenon. The discharge of lightning from cloud to ground with a negative discharge occurs more frequently than positive discharges and accounts for 90 % of the lightning strikes. A negative discharge contributes to the most damage, serious injuries and possibly even death [1-4].

This is because the negative discharge gives rise to a higher peak current for the first stroke as compared to the subsequent lightning strokes [5-6]. Moreover, backflashover, shielding failure and induced overvoltage in nearby power lines are the main result when lightning strikes the ground [7-8]. The induced overvoltage in power lines is usually due to an indirect strike (striking to the ground or a nearby object) which has a greater effect on a distribution power line [9-10].

Apart from that, the induced voltages on distribution power lines are also affected by the design parameter [11-15]. This includes the lightning parameters such as the velocity of the lightning, the height of the lightning channel, crest current, front time, maximum current steepness, and duration. Further, the line parameters also have to be considered when determining the affecting factors that give rise to induced voltages on a power line. The line parameters include the height of the conductor line, the diameter size of the conductor, the gap distance between the three-phase conductor and the associated matching impedance.

The other design parameters such as the substation, tower and lightning protection are the main parameters which should be considered when studying induced voltages. However, most of design parameters evaluate the induced voltage with respect to a vertical lightning channel only [9-15]. It should be noted that in reality, lightning channels are usually not vertical but strike at a certain inclined angle to the surface of the ground [16-19].

Therefore, for the evaluation of the lightning induced overvoltage (LIOV) should be evaluated using an inclined lightning channel with specific inclined angles. These inclined angles produce differences of a few percent the effect of the parameters on the induced voltage as compared to a vertical lightning channel [16-21].

Thus, this paper will provide information concerning induced voltages which are affected by the design parameters with respect to vertical and inclined lightning channels by using a fast and simple determination method.

2.0 METHOD

In order to investigate the effect of design parameters on the induced voltage on distribution power lines in Malaysia, the work is divided into two parts, namely the determination of the design parameters and the determination of induced voltages on the distribution power lines. Both of these determinations are implemented through programming. An injected lightning current of 10 kA with an inclined angle set at 10 degrees is used in this work.

2.1 Determination of Design Parameters

The striking distance of the lightning, d, is selected to be in the range 36 m to 59 m by considering the Electro-geometric Model (EGM) as suggested by IEEE 1410 [23,24] through Equations (1)-(3).

$$r_s = \alpha \times I_0^{\beta} \tag{1}$$

$$r_g = k \times r_s \tag{2}$$

$$y_{min} = \sqrt{{r_s}^2 - (r_g - h)^2} \tag{3}$$

Where; r_s is the striking distance to the conductor (m), r_g is the striking distance to the ground (m), I_0 is the lightning peak current (kA), y_{min} is the minimum distance for lightning will not be attracted by the line (m) and h is the height of the line. While, the coefficient of α is 10, β is 0.65 and k is 0.9. Also, in order to determine the Y_{max} , Equation (4) is applied in which the variable of y should be solved by assuming that V_{max}=1.5 × CFO.

$$V_{max} = \frac{Z_0 I_0 h}{y}\left[1 + \frac{1}{\sqrt{2}}\frac{v}{v_0}\frac{1}{\sqrt{1-\frac{1}{2}(\frac{v}{v_0})^2}}\right] \tag{4}$$

Where; Z_0 is $1/(4\pi)\sqrt{\mu_0/\varepsilon_0}$, I_0 is the lightning peak current, h is the average height of the distribution line over the ground level, y is the closet distance between the lightning strike and the line, v is the return stroke velocity and v_o is the velocity of light in free space.

Further, the height of the conductor, h, is selected to be in the range of 9 m to 15 m based on the height of 33kV overhead lines in Malaysia. Lastly, the diameter of the conductor, r, is selected based on the type of conductors that are used for 33kV lines [25, 26].

2.2 Determination of Induced Voltages on Distribution Power Lines

Evaluating the induced voltages on a distribution power line involves several steps as depicted in Figure 1. The figure shows that there are two types of lightning channel, which are the vertical and an inclined lightning channel. The phenomena of a lightning channel is referred to as 'neutralization' which occurs when the negative charges inside a cloud are travelling down and at the same time positive charges from the ground are trying to attach to these negative charges. This phenomenon is completed in around 20 ms [1, 27-28]. Therefore, the steps for evaluating induced voltages begin when the lightning channel strikes the surface of the ground.

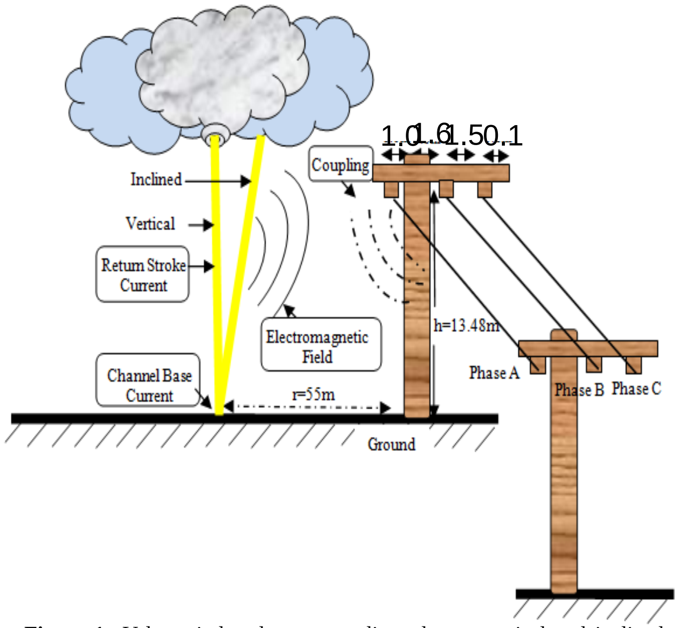


Figure 1 Voltage induced on power lines due to vertical and inclined lightning channels [22]

The first step is the evaluation of the channel base current which is when the lightning channel strikes the surface of the ground. According to the literature [16, 29-30], this current is a parameter that is derived as the first input in evaluating the induced voltage.

The second step is the evaluation of the return stroke current which depends on the behaviour of the current and the height of the lightning channel [31-35]. There are several models available for this evaluation such as the Bruce-Golde model (BG), Transmission Line model (TL), Travelling Current Source model (TCS), Modified Transmission Line Exponential decay model (MTLE) and the Modified Transmission Line Linear model (MTLL) [36-37].

The third step is the evaluation of the electromagnetic field, which arises from the propagation of the field from the lightning to a power line. There are several numerical methods involved in this evaluation [38-40] such as the Monopole, the Dipole, the Finite Difference Time Domain (FDTD) and the Hybrid method.

The last step is the evaluation of the coupling. This last evaluation step produces the total effect of the distribution line field together with the lightning channel field. Both of these fields can be represented through a few models such as the Rusck model, the Taylor model, the Rachidi model and the Agrawal model [41-44].

In this paper, the step current is selected to be the channel base current and the TL model is employed for the return stroke current. The Hybrid method is selected to serve as the numerical evaluation of the electromagnetic field by using Figure 2 to describe the geometry problem. According to Figure 2 [33], the lightning channel is located between the Z-Y planes at an inclined angle of θ. Further, an observation point is located at a height of Z with respect to the surface of the ground in the X-Y plane with a radial distance equal to r from the channel base to the image of the point on the X-Y plane. Also, the other geometric parameters are described in Equations (5) to (7) as given by;

$$r = \sqrt{x^2 + y^2} \qquad (5)$$

$$x = r sin\emptyset \qquad (6)$$

$$y = r cos\emptyset \qquad (7)$$

Whereby;
r is the radial distance from the channel base to the image of the observation point on the surface of the ground
x is the position of the observation point on the x-axis
y is the position of the observation point on the y-axis
r' is the temporary channel length along the lightning channel which can be defined through Equation (8):

$$\vec{r'} = r' \sin\theta\vec{y} + r' cos\theta\vec{z} \qquad (8)$$

And R(r') is the radial distance from the temporary channel length lightning channel to the observation point which is defined in Equation (9):

$$R(r') = \sqrt{x^2 + (y - r' sin\theta)^2 + (z - r' cos\theta)^2} \qquad (9)$$

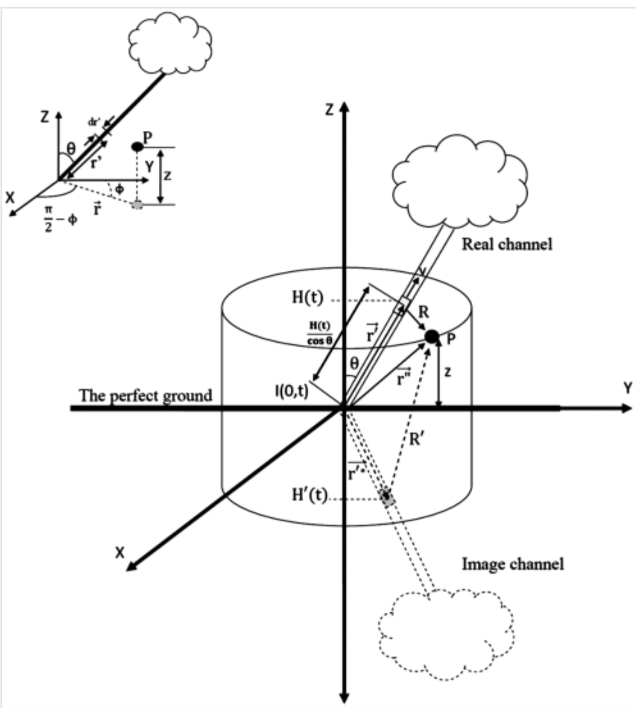


Figure 2 Geometry problem for an inclined lightning channel [33]

Finally, for the coupling model evaluation, the Agrawal model is selected. The selection of these models should provide a fast calculation of the induced voltage.

3.0 RESULTS AND DISCUSSION

Figure 3 shows the differences in the peak induced voltage with respect to the vertical and inclined lightning channels. It can be clearly seen that there is at least a 4 % difference in the peak voltages. The percentage differences very much depend on the selected method used to determine the induced voltage, the inclined angle and the characteristic impedance matching [19, 20, 45].

Further, the percentage differences of the induced voltage between the vertical and inclined lightning channel increase with increasing time until 8 µs. Thus, this may have an influence on the selection of suitable lightning protection devices in terms of the operation time of such devices.

Moreover, the variation in the peak induced voltage at different striking distances of the lightning to a power line can be seen in Figure 4. The maximum peak induced voltage which results in an over voltage occurs at a minimum striking distance of 36 m from the power line. Further, the peak induced voltage decreases as the striking distance moves further away from the power line. These results are in agreement with the work undertaken by other researchers [19, 20, 24]. Also, as stated in [24], a distance less than the minimum striking distance is considered to be a direct strike in which the lightning effect is fully absorbed by the object that is struck, while a distance more than the maximum striking distance is assumed to be so far away from the power line that only the normal induced voltages occur [46, 47].

In addition, there is at least a 3 % difference between the peak induced voltage arising from the vertical and inclined lightning channels.

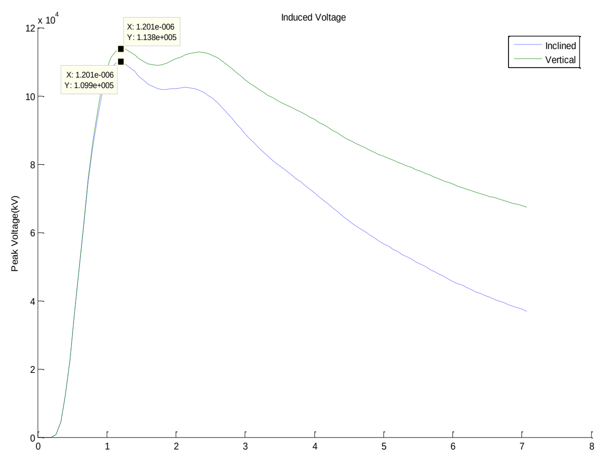


Figure 3 The differences of peak induced voltage with respect to a vertical and an inclined lightning channel

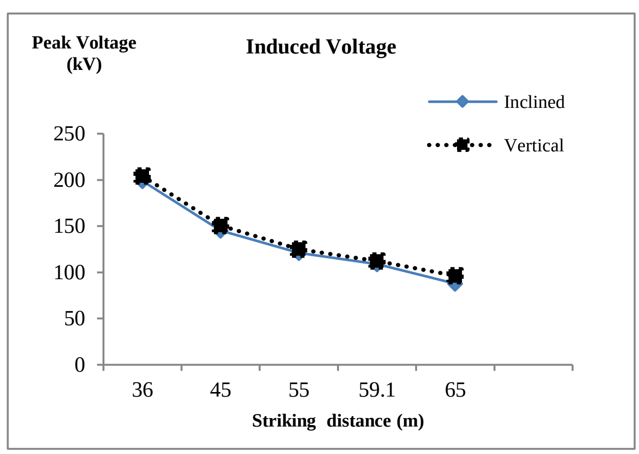


Figure 4 The variation of peak induced voltage affected by striking distance

Furthermore, in Figure 5, the effect of the height of the conductor also gives rise to a variation in the peak induced voltage. The increase in the height of the distribution power line conductor, which may be due to the geographical area, contributes to the increase in the peak induced voltage for both types of lightning channel.

On the other hand, in Table 1 the peak induced voltage is seen to decrease as the diameter size of the conductor increases. The effect of the diameter of the conductor is influenced by the determination of the inductance and capacitance per length. These determinations are used in the evaluation of the induced voltages in the evaluation of coupling. Further, there is at least a 3 % difference between the peak induced voltage of the vertical and the inclined lightning channels. However, the vertical lightning channel does not give any reflection induced voltage for different diameter conductors.

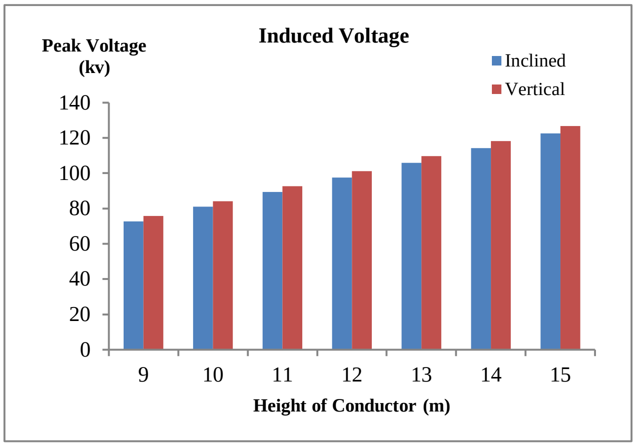


Figure 5 The variation of peak induced voltage affected by the height of the conductor

Table 1 The peak induced voltage affected by the diameter size of the conductor

Type of Conductor	Manufacturer	Diameter Size of Conductor (mm)	Induced Voltage (kV)	
			Inclined	Vertical
Simalec Condcuctor (AAAC)	Universal Company (UC)	14.3	97.52	101.20
Aerial Bundle Cable (ABC)	Tenaga Cable Industri (TCI)	14.4	97.52	101.20
XLPE	Tenaga Cable Industri (TCI)	28.3	97.35	101.20

4.0 CONCLUSION

In this paper, the effects of design parameters have been successfully investigated. Results show that the percentage differences between the two lightning channels are small for the front time of the lightning induced voltage, but that this also increases with the passage of time. Thus, these results need to be considered when dealing with the selection of a protection scheme such as the selection of line arresters i.e. the peak current value and maximum continuous operating voltage (MCOV).

In addition, the results show that the striking distance is the most influential parameter on the induced overvoltage on a power line which exceeds at least 14% and 20% of the Basic Insulation Lightning Level (BIL) i.e. estimated around 150kV, for inclined and vertical lightning channels, respectively. The other parameters are less significant in the induced overvoltage evaluation when compared to the BIL. Full consideration should be given when setting up an appropriate protection scheme for the distribution line, particularly related to the BIL and the Critical Flashover voltage (CFO) of the line, where the striking distance may influence the induced overvoltage of the line. In this case, perhaps the Lightning System Detection Network (LSDN) can be used to map the lightning occurrence with respect to the distribution line which can help a utility to plan for a proper protection scheme of the line.

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