# Behaviour of Lightning Induced Voltage due to Inclined Lightning Channel

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***Abstract-*** **Lightning can cause serious damage to various type of equipment through the lightning induced voltage (LIV) on power line. Previous research have been carried out on the evaluation of the LIV with respect to inclined lightning channel. However, a little consideration has been done on evaluating the behaviour of LIV with respect to the inclined channel (sometimes referred as angle), line and lightning parameters. Therefore, the aim of this paper is to evaluate the behaviour of LIV due to these variations by taking into account the height of the conductor and the striking distance. The guideline for calculating the LIV as recommended by IEEE 1410-2010 has been considered. Results indicate that the behaviours of LIV at different heights of conductor and striking distances are non linear and the peak of LIV due to these parameters shows the decreasing trend with the increment of the inclined angle. Whilst another results show the linear relationship obtained between the heights of conductor and the variation of return stroke velocity, which in contrast between the striking distance and return stroke velocity. These results will be beneficial to the utility and electrical power engineer for designing a proper and an appropriate lightning protection system for iproving lightning performance of the distribution lines.**

***Keywords-***Lightning induced voltage, inclined lightning channel, return stroke velocity, striking distance, lightning performance

## I. INTRODUCTION

Nowadays, mostly modern electronic equipment is used to control the power system equipment on a distribution power line. However, the modern electronic equipment is thus exposed to transient lightning phenomena on the power line [1] either as a direct lightning strike or as indirect lightning. In references [2, 3], the modern electronic equipment will suffer malfunction and damage if exposed to voltage transients that are mainly caused by indirect lightning strikes. Therefore, it very important to evaluate the effects of indirect lightning which is able to create lightning induced voltages on a power line. According to references [4, 5], the lightning induced voltage on a distribution power line can be created through experimental work and numerical calculation. In this paper, numerical calculation of the induced voltage was applied. In previous work to calculate the lightning induced voltage [6-8] it was mostly assumed that the lightning channel struck the surface of the ground vertically. However, according to references [9, 10], the lightning channel is typically not vertical but is in fact an inclined channel which can be seen for a few hundred metres from the surface of the ground. It is noted that the peak of the electromagnetic field and induced voltage is effective for a few hundred metres to be calculated a few microseconds. In addition, several studies have been undertaken to calculate and evaluate the induced voltage caused by an inclined lightning channel [10-15]. However, less attention has been given to evaluate the influence of the inclined angle with respect to other parameters such the line and lightning parameters. Therefore, this study is concerned with evaluating the behaviour of the lightning induced voltage arising from the effect of the inclined angle. The inclined angles were varied at different conductor heights and striking distances. Also, at specific inclined angles, the height of the conductor and striking distance were varied for different return stroke velocities. Thus, by the result of the lightning induced voltage with respect to the effect of the inclined angle, the protection level of a power line can be considered for each effect of the inclined angle.

## II. METHODOLOGY

The parameters modelled of an overhead 33 kV distribution power line included the height of the conductor line and the striking distance of the lightning to the power line. The height of the conductor line was assumed to be in the range of 9 m to 15 m. This range was considered based on the type of overhead distribution line in Malaysia such as the Lattice pole. This type of pole is mostly located in rural fields which have a non-flat ground surface [16]. Also, the striking distance applied was in the range of 20 m to 100 m from the power line. The selection of this range depended on the determination effect of the indirect lightning strike through the EGM model [17,18]. The velocity of the return stroke was in the range of c/2 to 2c/3 where c is speed of light [19, 20].

Moreover, in order to calculate the lightning induced voltage, the block diagram as shown in Fig.1 was considered so as to take into account the guides provided by IEEE Standard 1410-2010. A current was applied at the channel base, $i(0,t)$ with the step current function as an input to calculate the return stroke current model, $i\,(z',t)$. The return stroke current was calculated for different times and heights along the lightning channel by considering the Transmission Line (TL) model. Then, the lightning electromagnetic field was calculated by applying a numerical calculation method, namely the dipole and Finite Difference Time Domain (FDTD) method. The calculation was based on an observation point with respect to the temporary changes in the lightning channel by considering the vertical electric field, $E_Z$ and horizontal electric field, $E_h$. The derivative of the vertical electric field has been described in detail in reference [21] and the derivative of the horizontal electric field can be expressed by Equation (1) [22]. Further, both of these derivative fields are effective for use in the Agrawal model. Then, the induced voltage was calculated by applying a coupling model such as the Agrawal model in order to describe the interaction between the lightning electromagnetic field with the power line [23,24].

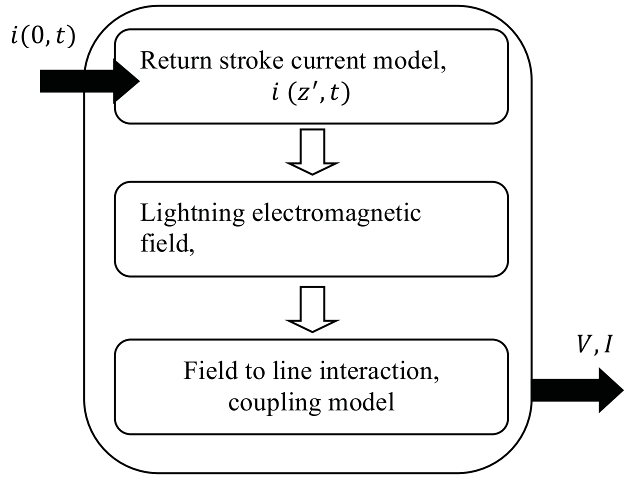


Fig.1 Block diagram for calculating the lightning induced voltage.[25]

$$\frac{d\overrightarrow{E_y}(x,y,z,\theta,t,r')}{dr'dt} = F_{i,5}(x,y,z,\theta,t,r') = \frac{1}{4\pi\varepsilon_0}\times\Bigg[\Big\{\frac{3}{4}\times$$

$$\frac{A_1(r')A_2(r')\cos\theta-A_1(r')^2 sin\theta}{R(r')^5}+\frac{sin\theta}{R(r')^3}\Big\}\times i\left(r',t-\frac{R(r')}{c}\right)-$$

$$\frac{1}{2}\Big\{\left(\frac{-A_2(r')\cos\theta+A_1(r')sin\theta}{2cR(r')^4}\right)A_1(r')\Big\}\times\frac{\partial i\left(r',t-\frac{R(r')}{c}\right)}{\partial t}+$$

$$\Big\{\frac{A_1(r')A_2(r')\cos\theta-A_1(r')^2 sin\theta}{2cR(r')^4}+\frac{sin\theta}{cR(r')^2}\Big\}\times\frac{\partial i\left(r',t-\frac{R(r')}{c}\right)}{\partial t}-$$

$$\frac{1}{2}\Big\{\left(\frac{-A_2(r')\cos\theta+A_1(r')sin\theta}{2c^2R(r')^3}\right)A_1(r')\Big\}\times\frac{\partial^2 i\left(r',t-\frac{R(r')}{c}\right)}{\partial t^2}-$$

$$\Big\{\frac{3x^2 sin\theta}{R(r')^5}-\frac{sin\theta}{R(r')^3}\Big\}\times i\left(r',t-\frac{R(r')}{c}\right)-$$

$$\frac{x^2 sin\theta}{cR(r')^4}\times\frac{\partial i\left(r',t-\frac{R(r')}{c}\right)}{\partial t}-$$

$$\Big\{\frac{2x^2 sin\theta}{cR(r')^4}-\frac{sin\theta}{cR(r')^2}\Big\}\times\frac{\partial i\left(r',t-\frac{R(r')}{c}\right)}{\partial t}-$$

$$\frac{x^2 sin\theta}{cR(r')^3}\times\frac{\partial^2 i\left(r',t-\frac{R(r')}{c}\right)}{\partial t^2}\Bigg] \qquad (1)$$

where;
x is the position of the observation point on the x-axis
$(x = rsin\emptyset)$
y is the position of the observation point on the y-axis
$(y = rcos\emptyset)$
r is the radial distance from the channel base to the image of the observation point on the surface of the ground
r' is the temporary channel length along the lightning channel
$\theta$ isthe inclined angle
$\emptyset$ is the observation point angle
c is the speed of light $(3\times10^8 m/s)$
$A_1(r')$ is $2z - 2r'cos\theta$
$A_2(r')$ is $2y - 2r'sin\theta$
R(r') is a radial distance from the temporary channel length lightning channel to the observation point where:

Fig. 2 shows the geometry problem, which is used to calculate the electromagnetic field [22, 26]. Note that the lightning channel was considered to be an inclined lightning channel. The inclined angle, θ was located between the z-axis and the inclined lightning channel. Also, the height of conductor line, z was considered as a point observation. The small inserted figure in Fig. 2 shows the location of the observation point angle, ϕ which in this paper is assumed to be a constant value of 70°. Note that the power line was parallel with the y-axis.

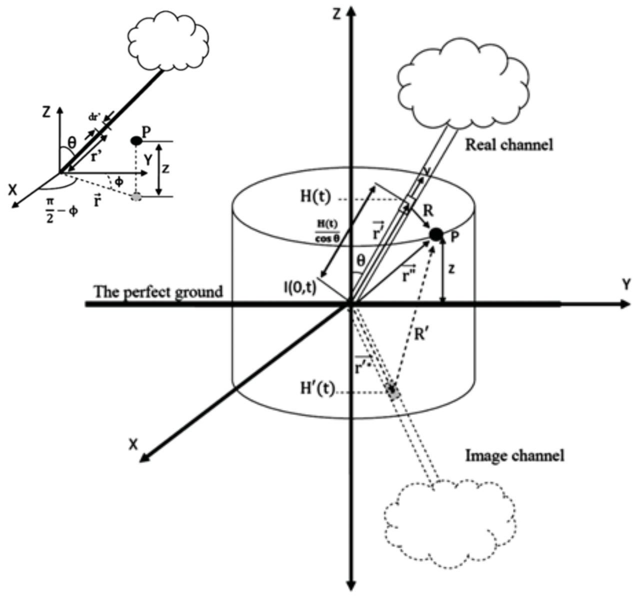


Fig 2. Problem geometry for evaluating the electromagnetic field due to an inclined lightning channel [22, 26].

## III. RESULTS AND DISCUSSION

The results that were generated were based on the typical parameters of an overhead 33kVdistribution line in Malaysia. The behaviour of the LIV was observed based on the variation of the inclined angle with respect to:

1. The height of conductor, $h$
2. The striking distance, $d$
3. The return stroke velocity, $v$

Fig. 3 shows the peak of LIV against inclined angle,θ for different conductor heights was indirect and had a non-linear relationship. The peaks of the LIV increased for an increase in height of the conductor line and decreases with respect to the inclined angle. In addition, the peak of the LIV is seen to be the highest value for the highest conductor line at 15m. This is due to the influence of the radial distance, **R** between the temporary charges in the lightning channel with the height of the conductor line as shown in Fig. 2. As the height of the conductor line increases, the radial distance becomes very close and thus produces more current. At the BIL of 110 kV, an inclined angle of less than 40° caused an excess voltage of the peak LIV for a conductor line height of more than 11m.

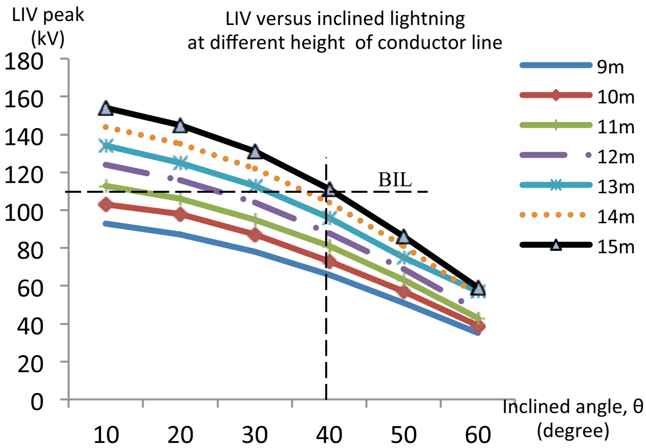


Fig 3. The behaviour of the LIV for variation of inclined angle and height of conductor (at ϕ=70°,$v = 1.5{\times}10^8\ m/s$,$d$=50m)

Fig. 4 represents the peak of the LIV against the inclined angle with respect to the increase in striking distance at a conductor height of 15 m. This shows that the peaks of the LIV have an indirect and non-linear relationship. The relationship reveals that the peak of the LIV increases for a decrease in striking distance and shows a declining trend with respect to the increase in inclined angle. In addition, the peak of the LIV is seen to be the highest value for a very close striking distance to the power line at 50m which generates an overvoltage. This situation is influenced by the implemented of the EGM model. An increase of at least 60 % of the LIV peak was observed with a time delay for decreasing striking distance. Also, at an inclined angle of less than 40°, the peak LIV exceeded the BIL for a very close striking distance of 50m.

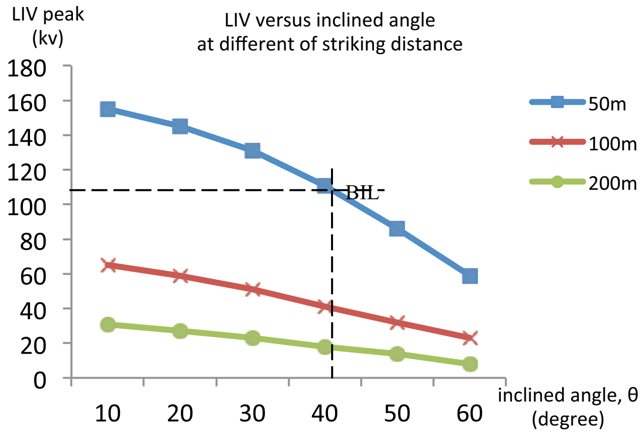


Fig 4. The behaviour of the LIV for variation of inclined angle and striking distance at specific of height of conductor (at ϕ=70°,$v = 1.5{\times}10^8\ m/s$, h=13.48m)

In addition, Fig. 5 shows the behaviour of the LIV versus the height of the conductor at a specific effect of theinclined angle at 40°. The results indicate the peak of the LIV has a direct and linear relationship with the variations of height of the conductor and the velocity of the return stoke. The LIV peak increases for a decrease in the velocity of the return stroke and increases for an increase in the height of the conductor. It can be seen that the highest value peak of the LIV is generated at a velocity return stroke of $1.2{\times}10^8\ \mathrm{m/s}$ as well as due to the influenced of the radial distance. A height of the conductor of more than 14 m and avelocity range for thereturn stroke of $1.2{\times}10^8\ \mathrm{m/s}$ to $1.5{\times}10^8\ \mathrm{m/s}$, should be noted since the LIV generated exceeds the BIL of the system.

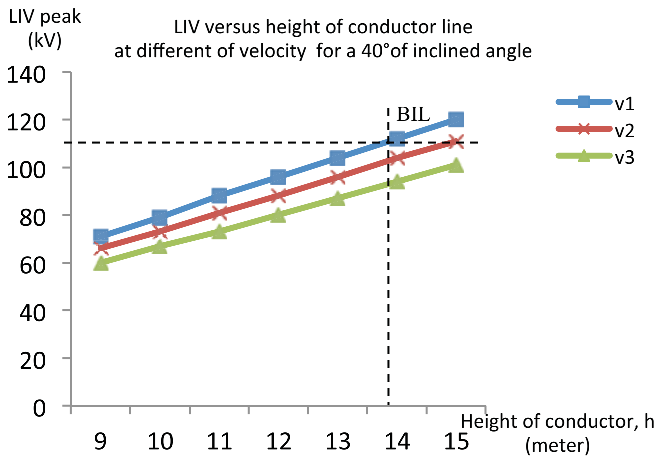


Fig.5 The behaviour of the LIV for variation of height of conductor and velocity of return stroke at specific inclined angles (at ϕ=70°, θ= 40° ,$d$=50m, v1=$1.2{\times}10^8\ \mathrm{m/s}$, v2=$1.5{\times}10^8\ \mathrm{m/s}$, v3=$1.9{\times}10^8\ \mathrm{m/s}$)

Lastly, Fig. 6 shows the behaviour of the LIV for different striking distances with a variation in the velocity of the return stroke for a specific inclined angle of 40°. Results represent the non-linear relationship between them. The peak of LIV increased for a reducing velocity of the return stroke. However, there is a declining trend for the increase in striking distance. Also, at a striking distance ofless than 50 m for a velocity in the range $1.2\times10^8$ m/s to $1.5\times10^8$ m/s the LIV peak exceeds the BIL voltage.

Thus, the peaks of the LIV for the height of the conductor line parameter and the radial distance show a declining trend for an increase in the inclined angle. However, for the specific inclined angle with a decreasing return stroke velocity, the peak of the LIV for both of these parameters indicated an increasing trend.

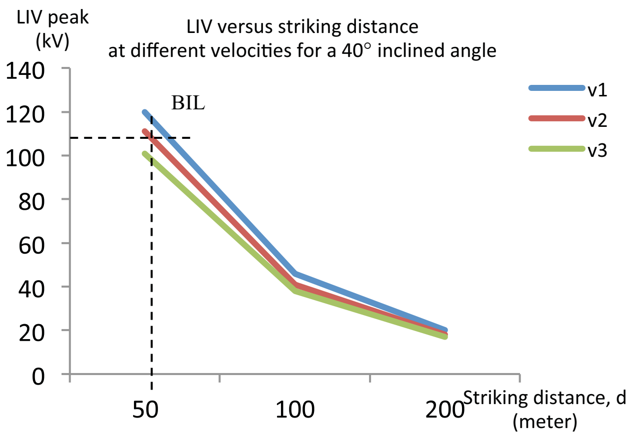


Fig. 7 The behaviour of the LIV on variation of striking distance and velocity return stroke at a specific inclined angle (at ϕ=70°, θ= 40°, $h$ =15m, v1=$1.2\times10^8$ m/s, v2=$1.5\times10^8$ m/s, v3=$1.9\times10^8$ m/s))

## IV. CONCLUSION

In this paper, the findings show that the behaviour of the LIV with respect to the inclined angle of the lightning channel are a non-linear relationship with consideration of the conductor line height and the striking distance parameters. However, at a specific inclined angle, a linear relationship can be determined between the height of the conductor line and the return stroke velocity, which contrasts with the non-linear relationship between the radial distance and the return stroke velocity. This findings provide great benefit to the electrical engineers to consider the appropriate level of protection scheme to be implemented, when taking into account the BIL for that system.

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