VOT 78273

ELEMENTARY STUDIES OF ELECTROMAGNETIC EFFECTS FROM TRANSIENTS IN THE HIGH VOLTAGE TRANSMISSION SYSTEM ONTO ITS VICINITY AND SURROUNDING SYSTEMS.

KAJIAN DASAR KESAN ELEKTROMAGNET DARI TRANSIEN PADA SISTEM PENGHANTARAN VOLTAN TINGGI KE ATAS KAWASAN BERDEKATAN DAN SISTEM-SISTEM DI PERSEKITARANNYA

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DEDICATION

The researcher would mainly wish to express gratitude and many votes of thanks to the bodies and personal acquaintance while conducting this research, listed generally as before

1, Ministry of Higher Education

2, Universiti Teknologi Malaysia

3. My colleagues at IVAT

4. My colleagues at FKE

5. My colleagues in UTM.

Thanks a million.

Regards

ABSTRACT

Due to the economic advantages, it is expected that other future resource and information transmission/delivery (such as gas pipes, water pipes, telephone cables, mobile repeaters, TV/radio transmitters) will be integrated to the existing High Voltage Transmission line Networks (HVTN) route according to its suitability. It is also well known that, being one of the tallest structures around and spanning across regions and states, HVTNs are prone to direct lightning strikes. However, even if the HVTN may be a shield, it may also be a threat to them.The research concentrates on assessing the threat which is electromagnetic field environment when the 275/315kV quad circuit transmission line is struck by lightning. A thorough ElectroMagnetic Interference (EMI) environment obtained can be used as a guideline to integrate other electrical systems into the right of way of HVTNs, Thus the decision of where to place the accompanying systems with ElectroMagnetic Compatibility (EMC) concerns can be inferred. The aim is to model this scenario with the attention of estimating the intensity of the interference to other electrical systems from the 275/315kV quad circuit transmission line struck by lightning since the electromagnetic waves from the power line (50 Hz), is deemed safe for electrical systems with minimal protection devices. The result would help the design of other electrical systems that would be integrated (especially near the towers) to the HTVN in an effort to be cost efficient.

ABSTRAK

Oleh kerana faktor ekonomi, dijangkakan sumber-sumber dan sistem penghantaran lain (seperti paip air, paip gas, kabel telefon, pemancar) akan digabungkan kepada laluan Talian Penghantaran Voltan Tinggi (High Voltage Transmission Network-HVTN) yang sedia ada mengikut kesesuaiannya. Namun memandangkan HVTN adalah struktur yang tinggi dan merentasi daerah dan negeri, ia terdedah kepada panahan kilat secara langsung. Selagi sistem tambahan lain lebih rendah dari HVTN, ia dipercayai boleh menjadi perisai dan juga menjadi ancaman kepada sistem yang ingin digabungkan. Kajian ini tertumpu kepada penilaian ancaman ini, dimana medan elektromagnet dekat (near electromagetic field) yang terhasil apabila talian penghantaran empat litar 275/315kV (275/315kV quad circuit transmission line)dipanah kilat secara langsung. Gangguan elektromagnetik persekitaran yang diperolehi boleh digunakan sebagai panduan untuk menggabungkan sistem elektrik lain kepada Laluan Hak (Right of Way) HVTN. Maka keputusan untuk menempatkan sistem lain dengan mengambil kira hal-hal Keserasian Elektromagnetik (EMC) boleh dirujuk. Kehadiran sistem elektrik lain boleh 'terpasang' (coupled) dan meresap tenaga yang sepatutnya dibekalkan kepada gelombang yang merambat. Objektif kajian ini adalah untuk memodelkan senario ini dengan tujuan untuk menilai tahap gangguan kepada sistem elektrik lain dari talian penghantaran empat litar 275/315kV yang dipanah secara langsung oleh kilat memandangkan gelombang elektromagnet dari talian kuasa (50Hz) adalah selamat untuk sistem elektrik dengan hanya sistem perlindungan litar yang mudah. Keputusan kajian akan membantu dalam merekabentuk sistem elektrik lain yang ingin diserapkan kepada TPVT (terutamanya berdekatan menara) dalam usaha untuk menjadikannya lebih berkesan dari segi kos.

CONTENT

RESEARCH REPORT

CHAPTER 1

2.1 INTRODUCTION

Electric transmission line's right-of-way (R.O.W.) is a strip of land meant solely for construction, operation, maintenance and repair works of transmission line facilities. The width of a R.O.W. depends on the voltage of the line and the height of the structures, but can be 7 to 85 meters depending on the type of facilities (i.e. voltage system) planned for on the right-of-way [1]. Table 1 lays out the width of R.O.W. for forests according to the voltage system. Depending on the lowest voltage system, a substantial clearance is also available underneath the cables.

The idea of integrating other transmission of delivery system such fiber optic cables are already in use for the energy provider's information and control data line. Meanwhile gas pipes are already installed and in use along the R.O.W. of transmission lines with their own R.O.W. and research on the transient effects from the High Voltage Transmission Network (HVTN) to the pipelines are ongoing [2].

Energy providers prefer good clearance at the HVTN's R.O.W. as this ensures no flashover to the surroundings thus promising reliability of the transmission. As for health reasons, studies generally could not conclude the existence of health hazards from the HVTN, even below the transmission line itself.

Transmission Voltage (KV) Width of	Right of Way (Mts)
11	7
33	**15**
66	18
110	**22**
132	27
220	**35**
400	52
800	85

Table 1. R.O.W for HVTN across forests area [1].

Due to economic reasons, it is only logical to make use of this vacant space with the integration of other systems such as communication lines, repeaters for mobile network and even mass rail transportation as the HVTN spans across the region and further they are interconnected between countries of the same continent. To achieve this however, an elementary study of the transient electromagnetic field is required in concern with lightning. This does not mean that the power line faults and other transients such as back flashover are not a concern, but the intensity of lightning current surpasses the other transients in this study.

Electromagnetic fields excited by the lightning current propagate to the surroundings. Further these fields can be simply classified according to the distance from the source as near-field and far-field. This is further shown on Figure 1, whereby distances shorter than one wavelength of the dominant frequency a near-field, whilst distances further than two wavelengths are considered as far-field.

This near field or evanescent standing waves (as termed in the antenna field) are very different that the propagating waves in a sense that

i) any absorption of the evanescent waves will affect how the lightning current flows through the stricken HVTN,

ii) The waves are not in the TEM (transverse electromagnetic mode, whereby the electric field and magnetic field propagate transversely and the wave impedance is around 377Ω i.e. impedance of free space), but rather in an exponentially decaying intensity.

iii) the wave impedance can be highly capacitive or inductive (imaginary component), depending on how near is the point of observation to the source.

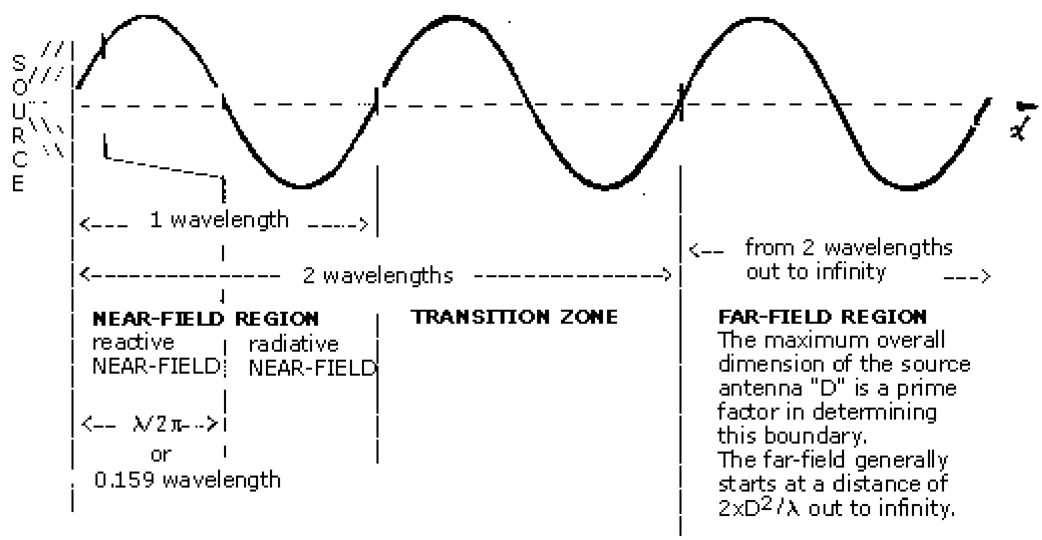


Figure 1 The near and far field in the antenna radiation distances

The presence of any electrical in the near field region may couple to source circuitry and absorb most of the energy that is meant to be radiated to the surroundings (analogous to the coupling of a transformer between primary coil and secondary coil). The study of this near-field waves require the solution of the wave equation

$$\mathbf{k} = k_y \hat{\mathbf{y}} + k_x \hat{\mathbf{x}} = i\alpha \hat{\mathbf{y}} + \beta \hat{\mathbf{x}}, \qquad (1)$$

which is a complex equation, but with regions of reactive near-field and radiative near-field, where the relationship of the E and H are not predictable (reactive near-field) and complex (radiative).

Solution of the above equation leaves us with an exponentially decaying electric field or magnetic field, depending on the type of receptor, which can be represented as

$$E(\mathbf{r}) = E_o e^{-i(i\alpha y + \beta x)} = E_o e^{\alpha y - i\beta x} \qquad (2)$$

where α is the attenuation constant and β is the propagation constant.

This also means that at distances really close to the source (or very close to the tower legs) may experience an unpredictably high electric field that it may couple to the source and thus alter the current reflections between the top and bottom of the HVTN tower.

1.2 Problem Statement

Lightning current that attaches to the tower of a HVTN will make its way to ground or vice versa depending on the type of charge being transferred by the lightning. It is shown in many studies [3-5] that tall structures with moderate grounding properties will cause reflection from the ground up or vice versa. This current will in fact cause an electromagnetic field by electrostatic, induction and radiation from the lightning currents [6].

One might think that to utilize the space under the HVTN, near-fields are the main concern due to the broad spectrum of the lightning current. However, further discretion will show that the far-fields will be a concern if we consider distances in parallel with the HVTN.

1.3 Objective

A detailed assessment of the electromagnetic fields emanating from the lightning current flowing through towers will be done through mathematical modeling. Electric fields and magnetic fields at the far-field and near-field region will be presented.

1.4 Research Scope

The assessment is limited to far-field transients from lightning. Other transients and the power line electromagnetic fields will be studied according to their threat level in future works. Due to limited resources, the near-field is explained in detail in the introduction but modeling which requires solution of the evanescent waves is reserved for further works.

CHAPTER 2

2.1 TITLE

Modeling Lightning Induced Voltages on nearby Overhead Conductor's Ends

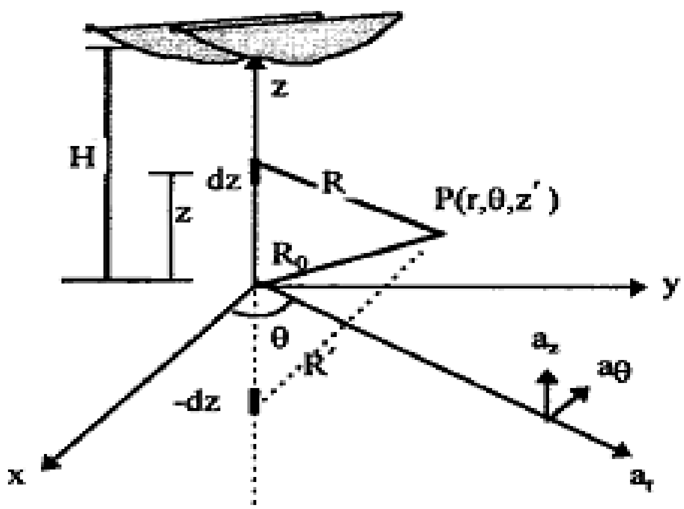
2.2 ABSTRACT

Lightning return stroke carries an amount of charge either from the clouds to ground or vice versa. Within this process, the transfer of charges at certain rates and current wave-shapes thus alter the surrounding electric and magnetic field. These changing fields might not influence human or small scale systems. However when a particular system becomes comparatively large, the changing fields (though small in magnitude) may affect since the changes are experienced at all points of the large system. A simple example of such a system is a long overhead communication or transmission wire or conductor. The above situation is mathematically modeled and the results for a particular situation are presented. The results are analyzed and the parameter difference between induced voltages at both ends due to nearby ground lightning strike is discussed. A proposed method of obtaining parameters of the ground lightning return stroke form the induced voltages at both ends of an overhead conductor with matched impedance is presented.

2.3 INTRODUCTION

Ground lightning strikes induce voltage to ungrounded conductors above and below ground by electrostatic coupling, electromagnetic induction and radiation from the current that flows through the lightning channel. From the development of the staggered stepped leaders to the subsequent strokes, this current generally flow the most during the return stroke process.

Voltages induced on an overhead power distribution line by lightning strokes to nearby ground are the most frequent causes of outage on these lines [1]. Many instances have been noted and published regarding induced potential from lightning to telecommunication lines [2], data lines [3] and power lines [4-5]. While many research on induced voltages focus on its effect to insulation across the conductor and ground, this work concentrates on the determination of the parameters of the lightning return stroke (specifically location and the peak current). Some field study on the same idea has been done by Aulia [6]. This paper will discuss and tabulate the results of the mathematical modeling.



2 Fig. 1. Model geometry of a nearby lightning [7]

2.4 MODELING

2.4.1 The geometry of the model

The horizontal and vertical electric fields (including the magnetic fields) produced by the ground lightning return stroke are determined at points in consideration via the geometry shown in Fig. 1. The calculation is based on Equations (1) & (2) as presented by Uman [11]. These time domain calculations ease the computation in particular the processing speed and storage.

$$d\overline{E_z} = \frac{dz}{4\pi\varepsilon_0} x$$

$$[\frac{2(z-z')^2 - r^2}{R^5} \int_0^t i(z', t - R/c) dt$$

$$+ \frac{2(z-z')^2 - r^2}{cR^4} i(z', t - R/c) \tag{1}$$

$$- \frac{r^2}{c^2 R^3} \frac{\partial i(z', t - R/c)}{\partial t}] \overline{a_z}$$

$$d\overline{E_r} = \frac{dz}{4\pi\varepsilon_0} x$$

$$[\frac{3r(z-z')^2}{cR^5} \int_0^t i(z', t - R/c) dt$$

$$+ \frac{3r(z-z')^2}{cR^4} i(z', t - R/c) \tag{2}$$

$$- \frac{r(z-z')}{c^2 R^3} \frac{\partial i(z', t - R/c)}{\partial t}] \overline{a_r}$$

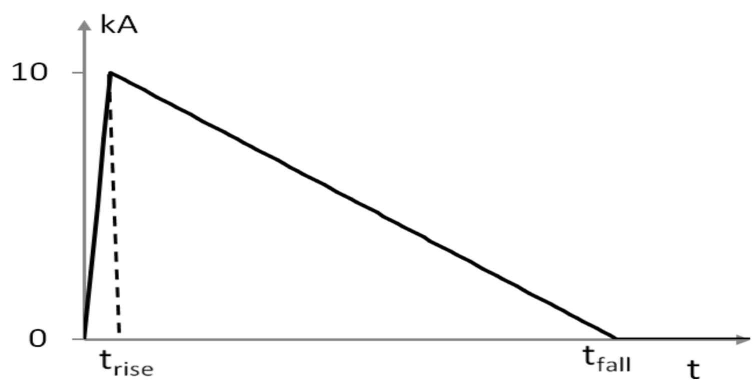


Fig. 2. Ramp type return stroke current

2.4.2 Ground lightning return stroke current

To ease computation and storage capability, the lightning return stroke current is modeled as a ramp function with the time to peak (trise) and time to zero (tfall) adopted as shown in Fig. 2. This assumption shows acceptable results as presented by Sorwar [7]. Further the return stroke current is assumed to flow along the lightning channel at a constant speed of a third of the speed of light. The 0.8 meter dipoles from the return stroke current are then utilized to calculate the electric fields at points along the overhead conductor.

2.4.3 Vertical and Horizontal Electric Fields

The vertical and horizontal electric fields at points along the overhead conductor are calculated using the dipole charges and in time domain expressions. These fields are among the forcing functions that energize the free electrons within the conductor. The same result would be achieved if the magnetic field is used as the forcing functions [10] on an overhead conductor looped through ground. In this work, the overhead conductor is divided into 32 equal segments, requiring the calculation of the electric fields at 33 points along the line.

2.4.4 Coupling Fields to the Overhead Conductor

The time domain expressions adopted from Agrawal [9] listed as Equations. (3) to (6), is applied to determine the voltage at equally spaced points on the overhead conductor. This partial differential equation needs to be digitized for every segment on the overhead conductor, whereby scattered voltages are determined at both sides of each segment and the current determined at the middle of every segment.

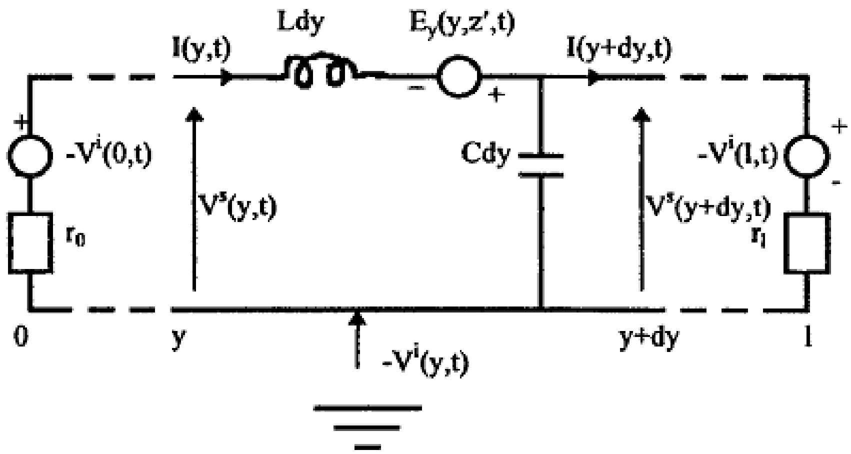


Fig. 3. Differential equivalent coupling circuit for a single-wire lossless overhead conductor

$$\frac{\partial}{\partial y}V^s(y,t)+L\frac{\partial}{\partial t}I(y,t)=E_y(y,h,t) \qquad (3)$$

$$\frac{\partial I(y,t)}{\partial y}+C\frac{\partial}{\partial t}V^s(y,t)=0 \qquad (4)$$

Where $I(y,t)$ is the current, $V^s(y,t)$ the scattered voltage, $E_y(y,h,t)$ is the horizontal component of the electric field at height, h in absence of the overhead conductor, directed positive from left to right along the conductor. L and C are the per-unit length inductance and capacitance of overhead conductor respectively.

Equations (3) & (4) above are for any point on the overhead conductor in general. It does not contain the total voltage at the overhead conductor's ends which includes the component of the vertical electric field from the ground up to its ends. The voltages at the ends will be solved by the equations (5) & (6).

$$V^T(y,t)=V^s(y,t)+V^i(y,t) \qquad (5)$$

$$\mathit{where}$$

$$V^i(y,t)=-\int_0^h E_z(y,z,t)dz \qquad (6)$$

$$\approx -hE_z(y,h=0,t)$$

Where $E_z(y,z,t)$ is the incident or the inducing vertical component of the electric field directed towards the ground.

The equivalent circuit for the overhead conductor above a perfectly conducting ground, excited by a non-uniform incident vertical and horizontal electric field, follows the model given in equations (3) through (6) as shown in Fig. 3. It can be seen that the parameters of distributed line inductance and capacitance are incorporated as to accumulate the voltages experienced at other segments, and included at the ends of the overhead conductor.

2.4.5 Overhead conductor's terminations

The matched termination of the overhead conductor is a function of the conductor's distributed inductance and capacitance. The expression below defines the overhead conductor's impedance neglecting the distributed resistance and conductance of the conductor.

$$Z_0 = \sqrt{\frac{L}{C}} \qquad (7)$$

Where, L and C are the conductor's distributed inductance and capacitance respectively

With the above expression in Equation (7), the matched impedance for the conductor's distributed inductance of 0.5µH/m and distributed capacitance of 22.2pF/m is approximately 150Ω. The termination impedance is also critical in contributing to the induced voltage at the ends whereby mismatched impedance would cause reflections to the other end's induced voltage.

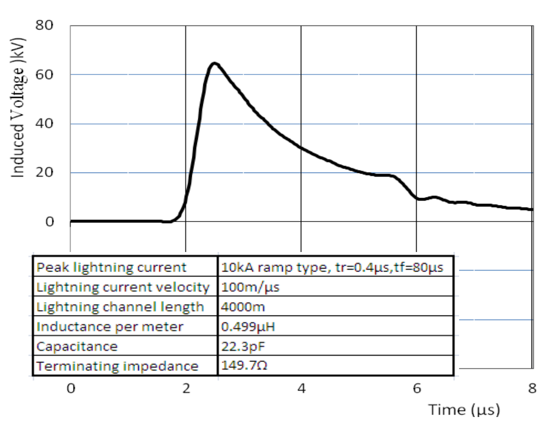


Fig. 4. Induced voltages at both ends of an impedance matched 1km overhead conductor

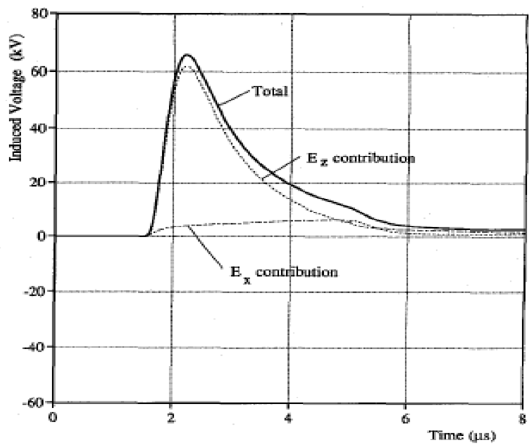


Fig. 5. Induced voltages calculated using electric fields with similar parameters to Fig. 4, adopted from Figure 2(b) in [10].

2.4.6 Validation

The resulting induced voltages (to ground) at both ends of a 1 km overhead conductor, suspended at a height of 10m above ground are shown in Fig 4. The impedance of the ends of the conductor is matched and the ground is assumed lossless. The ground lightning return stroke is assumed vertical and striking ground at 50m from the overhead's center (i.e. equidistant to the line terminations). The induced voltages for both ends are similar and if further compared to the modeling result from [10] shows the applicability of the mathematical model.

2.5 Results

Induced voltages on a 210m overhead conductor

Further the model is extended to calculate the induced voltages on the ends of a 210m overhead conductor simulating the situation in field measurements by Aulia [6]. However in the modeling, the terminations

are matched to cancel out reflections from one end to the other.

Figures 7 to 13 displays the induced voltages at the ends of the overhead conductor termed as V0 and V210 as indicated in the plan view coordinate of Figure 6. The cross-marks in Figure 6 denote the location of the ground lightning return stroke being modeled. They are at coordinates (x=50, y=0), (x=50, y=63), (x=50, y=105), (x=50, y=147), (x=50, y=210) in meters for Figures 7 to 13 respectively. Figure 9 shows similar induced voltages for both ends as the ground lightning strike location is 50m away equidistant to both ends of the overhead conductor.

3.2 Preliminary analysis of results

As the location of the ground lightning strike is shifted alongside the x=50m axis, the difference between the three parameters of the induced voltages at both ends namely the start time, the peak time and the peak amplitude shows a somewhat linear trend. They are then termed as time taken for induced voltages start to appear from lightning instance (tS0 and tS210), time taken for induced voltages to peak from lightning instance (tP0 and tP210) and peak amplitudes of induced voltages at both ends (VP0 and VP210).

These values are then tabulated as differences, ΔVP = VP210 - VP0 (refer Fig. 8), ΔtP = tP210 - tP0 (refer Fig. 11) and ΔtS = tS210 - tS0 (refer Fig. 7) between both ends and plotted in Fig. 12 and 13. These plots show their linearity and their zero crossings at the equidistant point between the ends of the overhead line (i.e. at y=105m). Further ΔtS spans linearly across the 5 coordinates due to the retarded time for the fields to reach the ends of the overhead conductor is fully dependent on the speed of propagation of the fields. It is noted that the plot for ΔtP does not completely overlap the plot for ΔtS and further investigation is ongoing.

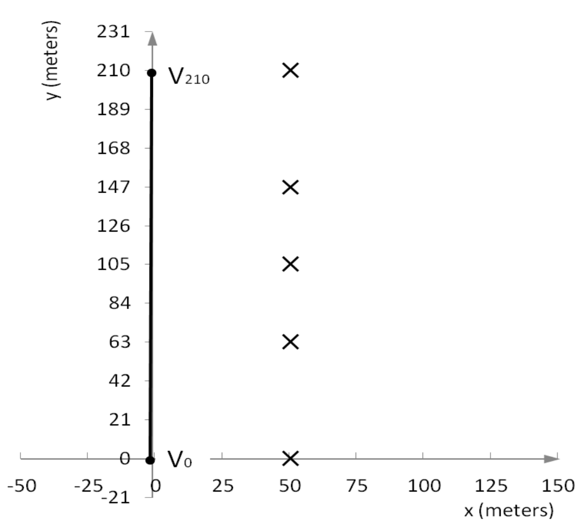


Fig. 6. Plan view of the 10-meter above ground overhead conductor and coordinates of nearby ground lightning strikes

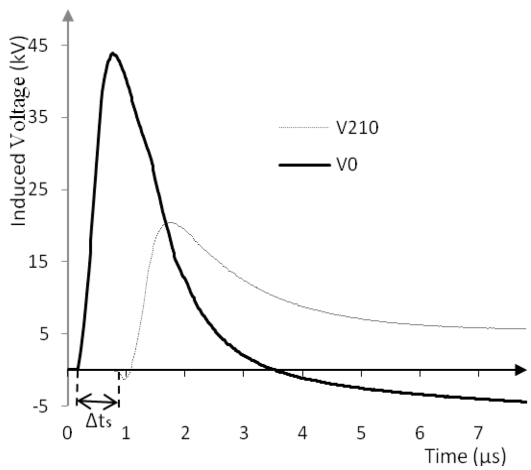


Fig. 7 Induced voltages at both ends with ground lightning strike coordinates of (x=50, y=0) m.

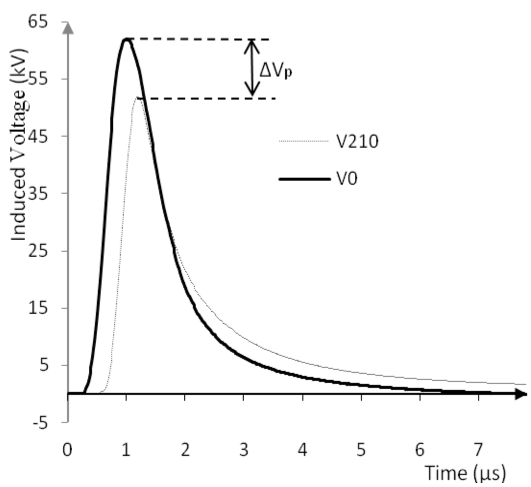


Fig. 8 Induced voltages at both ends with ground lightning strike coordinates of (x=50, y=63) m.

Further analysis

To strengthen the finding, further analysis is done on the time to peak (tp) variation with varying current peak of the return stroke current with ground lightning stroke coordinates of x=50 & y=105. Figure 14 shows that with increasing ground lightning return stroke currents and same location, the peak time remains unchanged. Further investigation leads to testing the same property with varying time to peak (t_{rise}) and time to zero (t_{fall}). Initial investigation reveals that the time to peak remains unchanged with varying t_{fall} but changes proportionally to t_{rise}. However the results are not presented in this paper and would be included in future publication.

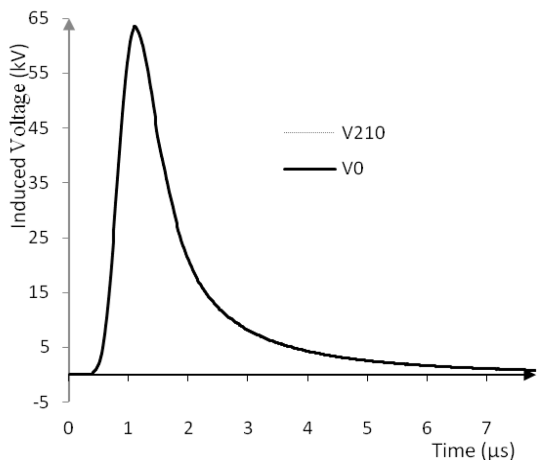


Fig. 9 Induced voltages at both ends with ground lightning strike coordinates of (x=50, y=105)m.

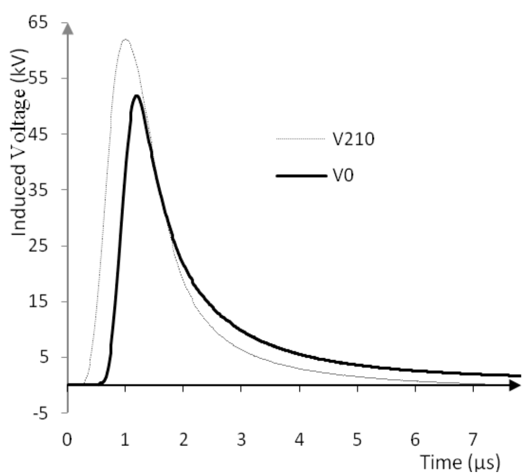


Fig. 10 Induced voltages at both ends with ground lightning strike coordinates of (x=50, y=147) m.

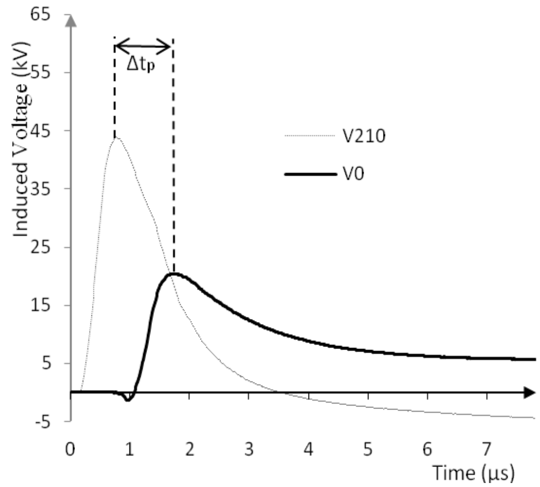


Fig. 11 Induced voltages at both ends with ground lightning strike coordinates of (x=50, y=210) m.

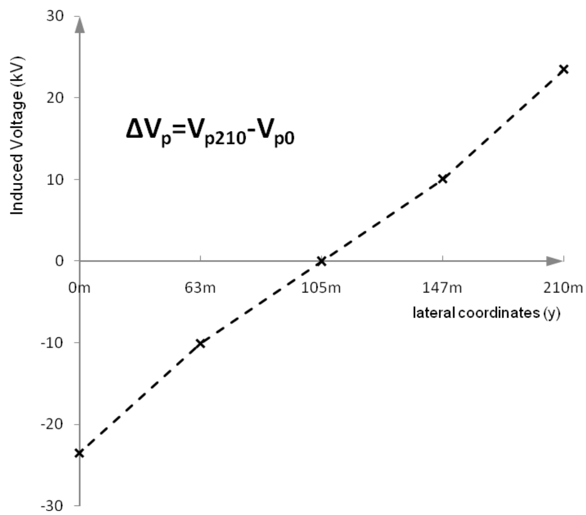


Fig. 12 Difference of peak amplitudes between both ends for the 5 ground lightning strike coordinates.

2.6 CONCLUSION

The results of the modeling presented show the possibility of extracting the location of nearby ground lightning strikes from the induced voltages measured at both ends of an overhead conductor. The linearity with zero crossings at y=105m may enable the determination of the ground lightning strike location alongside the overhead conductor. Further analysis is done and shows that finding requires more investigation. Nonetheless results presented here would give some evidence of that possibility.

Another issue to be solved in this possibility is to determine on which side of the overhead conductor does the ground lightning strike. From the results presented, generally this issue cannot be solved by measuring voltages on the ends of a single overhead conductor.

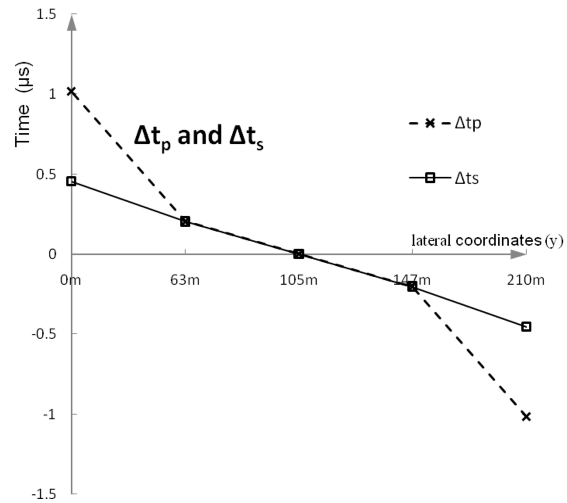


Fig. 13. Difference of start and peak times between both ends for the 5 ground lightning strike coordinates.

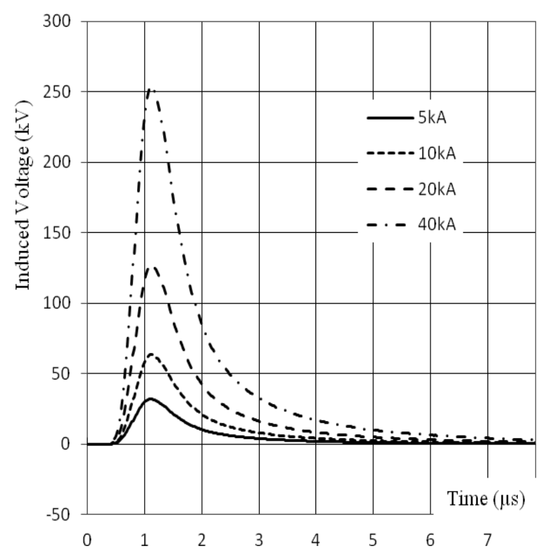


Fig. 14. Calculated induced voltages with varying peak lightning base current

2.7 Acknowledgments

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CHAPTER 3

3.1 TITLE

Modeling induced voltages on ends of suspended conductor to locate nearby lightning

3.2 ABSTRACT

Lightning induces voltage on a horizontally suspended conductor due to electromagnetic field coupling. If the induced voltage is measured across a matched impedance at both ends, it may be possible to locate the distance and angle of incidence of the lightning. Researches on lightning induced voltages mainly focus on its effect to insulation across the conductor and ground. The situation is modeled in time domain, to plot the lightning distribution of a specific area of particular size. From the results, the relationship of induced voltages to the distance and angle of incidence of the cloud to ground lightning is to be presented. A thorough study on extracting information of each lightning incident parameters (i.e. distance and angle) from expected induced voltages is discussed. The model will be tested on a physical mock setup for its concept and applicability. The parameters obtained and actual parameters are to be compared and discussed.

3.3 INTRODUCTION

Voltages induced on an overhead power distribution line by lightning strokes to nearby ground are the most frequent cause of outages on these lines [1]. Further, many instances have been noted and published regarding induced potential from lightning to telecommunication lines [2], data lines [3] and power lines [4-5]. While many research on induced voltages focus on its effect to insulation across the conductor and ground, this work concentrates on the determination of the parameters of the Ground Lightning Return Stroke (GLRS). Some field study on the same idea has been done by Aulia[6]. This paper discusses and tabulates the results of the mathematical modeling.

3.4 MODELING

Input parameters of the mathematical modeling

The input parameters in the modeling exercise are listed below,

i) x-axis and y-axis distance of the GLRS terminating at the ground
ii) intensity of the GLRS current
iii) rise and fall time of the GLRS current

speed of the GLRS as it traverses the channel length

iv) length of the GLRS channel
v) length and height of the overhead conductor
vi) distributed inductance and capacitance of the overhead conductor.

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Generalized assumptions adopted

Listed below are the assumptions used in the modeling exercise to facilitate capable computation time and storage.

i) The GLRS is vertical and straight from the base of the cloud to the ground
ii) Constant speed of the GLRS current throughout the channel
iii) Simple triangular waveshape of the GLRS current
iv) Infinite ground conductivity from the source to the overhead conductor

Mode of the mathematical modeling

GLRS currents travel throughout the lightning channel in order to transfer accumulated charges from the cloud to ground and vice versa. These moving charges cause electric and magnetic field changes throughout its surroundings. The modeling uses the geometry described in Fig. 1 and the corresponding equations are presented in Sorwar et.al.[7]. The vertical and horizontal electric fields at points along the overhead conductor are calculated using the dipole charges and time domain expressions. These fields are the forcing functions that energize the free electrons within the conductor. The induced voltages are calculated by applying Finite Difference method on the Telegrapher's Equation [8].

This coupling mode relates the electrical pressure experienced by the unperturbed free electrons within the overhead conductor. The horizontal electric fields are calculated at equal spacing points along the overhead conductor, whilst the vertical electric fields are determined at the terminating ends of the conductor. It is worth noting that other than the electric fields, magnetic fields can be forcing functions as well [9].

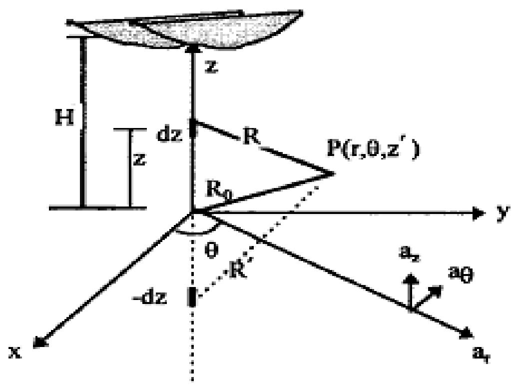


Figure 1: Geometry of a model nearby lightning used in the vertical and horizontal electric fields computation at a point above ground

3.5 RESULTS

Figure 2 below shows the result of the mathematical modeling on a stretch of wire with matched terminations for a 1km of overhead conductor. The stroke location is at 50 m from the line center and equidistant from the line terminations.

Comparison to other works

The results are comparable to the induced waveform from [9] shown in Figure 3. A slight difference is the bump at 5.5µs which is due to some minimal reflection of the induced voltage at the other end of the overhead conductor.

Plotting nearby GLRS locations

Then the same situation is modelled but with variations of the GLRS location from the ends to the side of the overhead conductors.

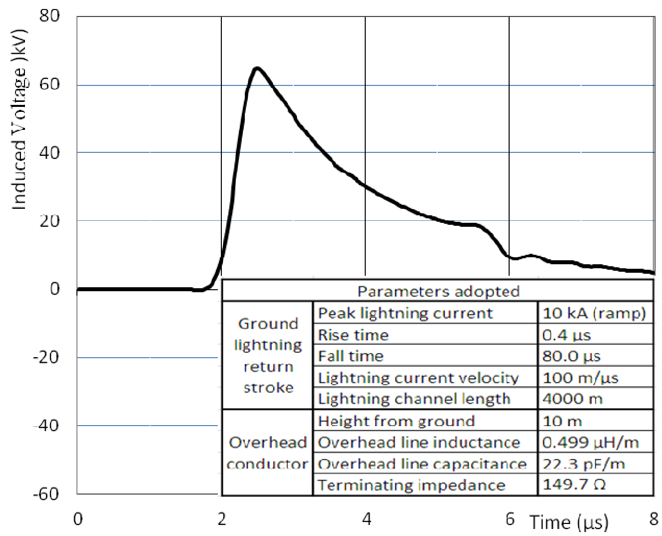
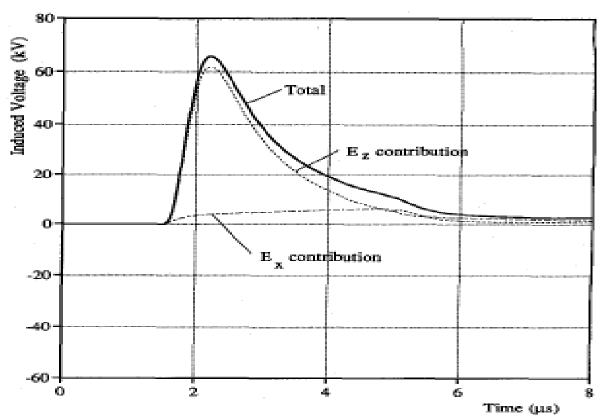


Figure 2: Induced voltages at both ends of an impedance matched 1km overhead conductor due to 10kA peak current ground lightning 50 meters away equidistant to both ends



(b)

Figure 3: Induced voltages calculated using vertical and horizontal electric fields with similar parameters to Fig. 2, Figure 2(b) in [9]

The coordinates applied is shown in the plan view below (Fig. 4) whereby the overhead conductor is placed exactly on the y-axis. The first end of the conductor is at coordinates (0,0) and the other end is at (0,210). (1 axial unit is equivalent to 1meter). The ’x’ marks the vertical ground lightning location in reference to the overhead conductor location.

Varying the lightning current intensity

The peak GLRS current does vary the induced voltages amplitudes but the start time, peak time and their difference remain constant throughout as shown in Fig. 5.

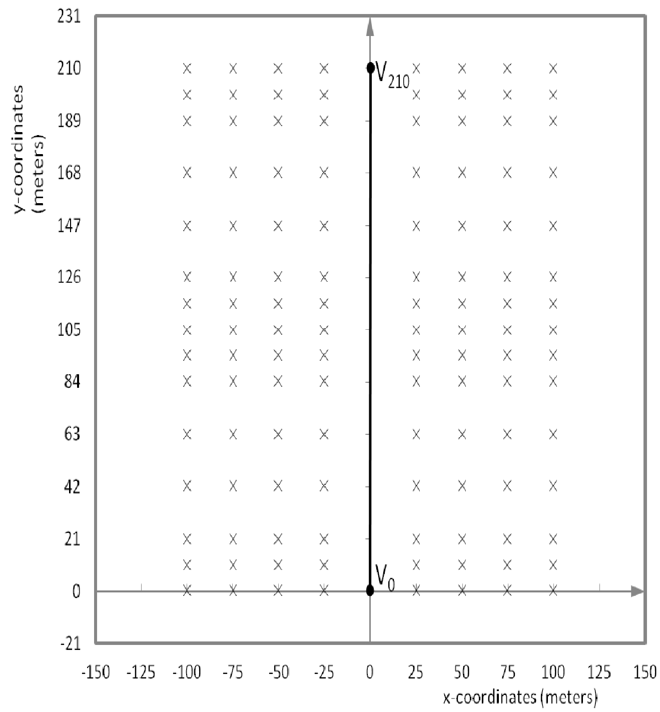


Figure 4: Coordinates of GLRS nearby the 10-meter overhead conductor being modeled

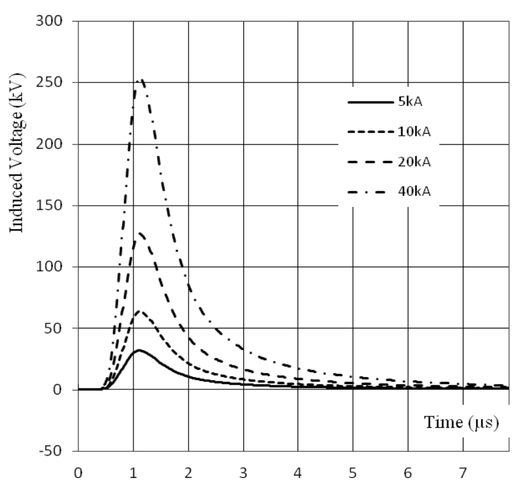


Figure 5: Induced voltages with varying peak GLRS channel base current

Modeling a real measured induced voltage

From the analysis below, an attempt to infer the location of the ground lightning from a measured waveform (at the line ends across a 50Ω unmatched termination) with the same modeling configuration is done by producing similar calculated induced voltages. The mismatched load partially reflects the voltage to the other end. From Fig. 6, the result from actual field measurement from Aulia's [6] is compared to the mathematical modeling **with** estimated coordinates. However, this estimation may be of a large error due to the assumption of infinite ground conductivity. In the figure, the voltage from the other end is inverted to avoid overlapping.

3.6 DISCUSSION AND ANALYSIS

The modeling results in calculated induced voltages on both ends of the overhead conductor. The data are tabulated to include the peak amplitudes of induced voltages at both ends (VP0 and VP210), time taken for induced voltages to peak from lightning instance (tP0 and tP210), time taken for induced voltages start to appear from lightning instance (tS0 and tS210), and their difference in values namely ΔVP = VP210 - VP0, ΔtP = tP0 - tP210 and ΔtS = tS210 - tS0. The results are shown in the following graphs in Figures **7-11.**

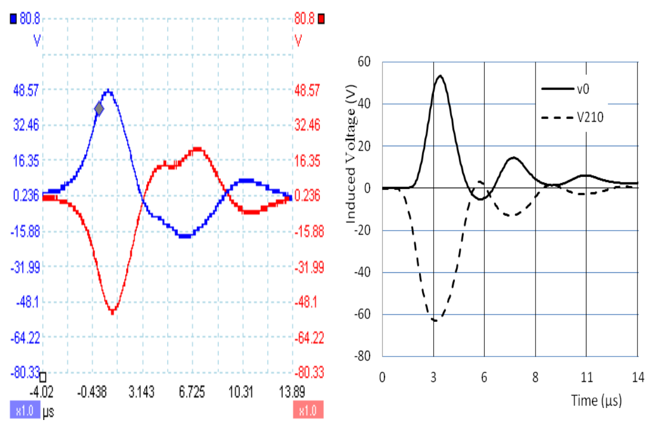


Figure 6: Induced voltages measured (left) and estimated x=50m, y=137m by calculation (right). (Coordinates based on Fig. 4)

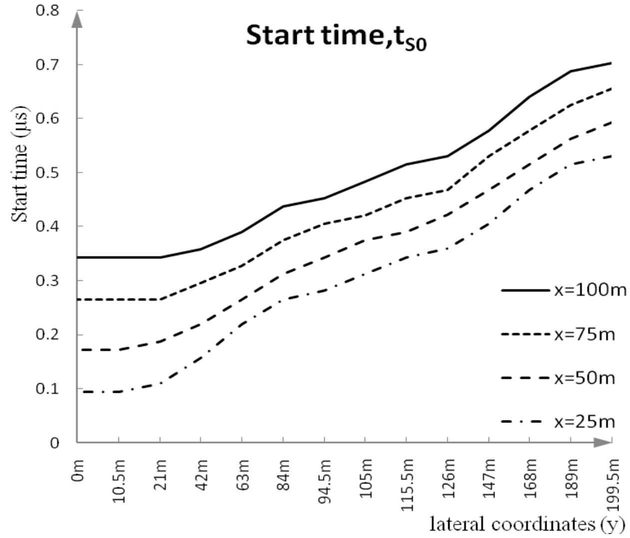


Figure 7: Time taken for induced voltage to appear from lightning instance

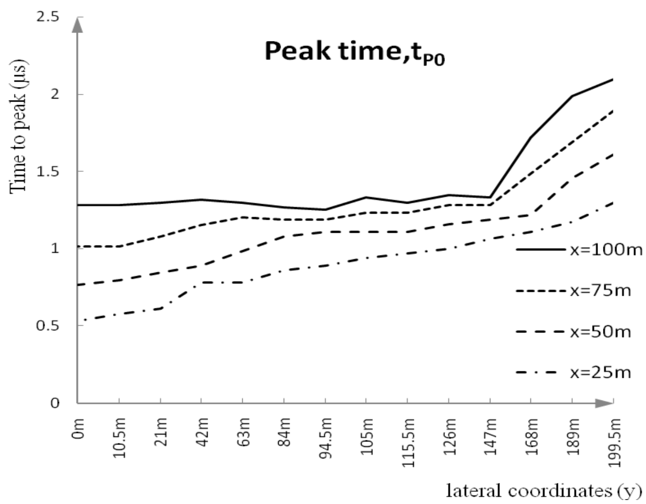


Figure 8: Time taken for induced voltage to peak from lightning instance

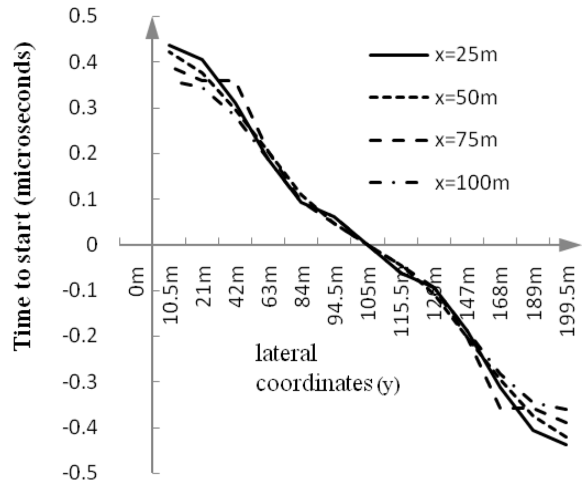


Figure 9: Difference of start times, $\Delta t_S = t_{S210} - t_{S0}$

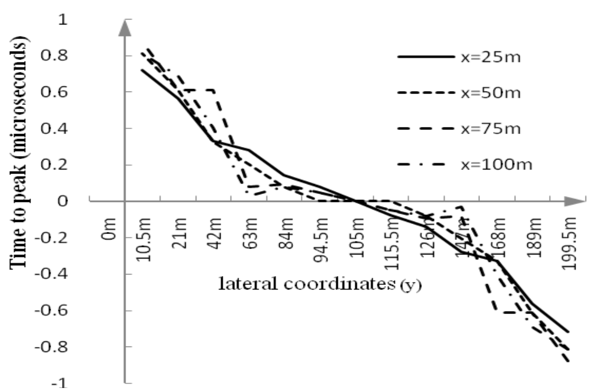


Figure 10: Difference of peak times, $\Delta t_P = t_{P210} - t_{P0}$

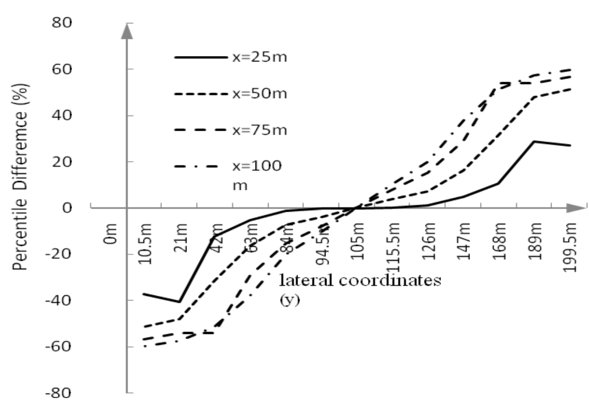


Figure 11: Difference of peak voltages in percentage $\Delta V_P = (V_{P210} - V_{P0})$ %

The induced voltages at both ends of a matched impedance overhead conductor, VP0 and VP210 varies accordingly from being equal from the centre of the conductor length and having different peak amplitudes VP, time of peak amplitudes tP, start times tS, and their differences ΔVP , ΔtP, and ΔtS as the location of the GLRS is shifted to either side. GLRS striking the equidistant point between both ends of the overhead conductor will result in similar induced voltages. As the location is shifted in the y-axis (as in Fig. 4), the peak amplitudes, times to peak, start times and the difference of the same parameters between both ends is analyzed.

The similarity of the trending between the ΔtS and ΔtP suggests the agreement in using the peak times, tP as reference from real measured waveforms as applied in [6] (as the start time, tS cannot be predetermined). The calculated waveform shows reasonable agreement with the measured waveform. However the peak current value cannot be estimated as some reference to known and exact real lightning parameter is required. The relationship between ΔtS, ΔtP and ΔVP(%) tends to be a straight line. Fig. 9-11 respectively exhibits this with some minor deviations. Equations below characterizes this

$\Delta tS = m(y) + 0.45\mu\text{second},$ (1)

where $m \approx -4.8$ (nanoseconds/meter).

$\Delta tP = n(y) + 0.9\mu\text{second},$ (2)

where $n \approx -8.6$ (nanoseconds/meter).

$\Delta VP(\%) = p(y) - 60\%,$ (3)

where $p \approx 0.57$ (%/meter).

3.7 CONCLUSION

The results of the mathematical modelling has been presented partially and the parameters discussed are ΔtS, ΔtP and ΔVP(%) with respect to the lateral coordinates of the estimated lightning strike location. The estimation of the location of lightning based on the induced voltage on both ends of an overhead conductor is partially presented.

To reduce the large estimated error, the effect of finite ground conductivity is to be considered as the distances in consideration are small. Initial further investigations suggest the possibility to resolve the subsequent strokes in a typical multi-stroke lightning flash since the source current is still flowing through the same return stroke channel but only with different amplitudes and durations (between the subsequent strokes and the continuing currents). To evaluate the whole lightning flash, the critical issue in measurement is sampling rate, size & time resolution. Whilst in modeling, the resolution of time step is a limitation.

3.8 ACKNOWLEDGMENT

The authors wish to thank the Ministry of Science, Technology and Innovation, Malaysia, Ministry of Higher Education, and Universiti Teknologi Malaysia, in which the research votes 78273 & 79032 have been a substantial part of the source to finance this research.

CHAPTER 4

4.1 TITLE

Modeling Lightning Induced Voltages on Nearby Overhead Conductor's Ends

4.2 ABSTRACT

Lightning return stroke carries an amount of charge either from the clouds to ground or vice versa. Within this process, the transfer of charges at certain rates and current wave-shapes thus alter the surrounding electric and magnetic field. These changing fields might not influence human or small scale systems. However when a particular system becomes comparatively large, the changing fields (though small in magnitude) may affect since the changes are experienced at all points of the large system. A simple example of such system is a long overhead communication or transmission wire or conductor. The aim of this paper is to mathematically model this physical occurrence in order to determine the voltages induced on the ends of an overhead wire due to nearby lightning. The main inputs of this model are the lightning return stroke parameters and the orientation of the lightning strike to the system.

4.3 INTRODUCTION

Voltages induced on an overhead power distribution line by lightning strokes to nearby ground are the most frequent causes of outage on these lines [1]. Further, many instances have been published regarding induced potential from lightning to telecommunication lines [2], data lines [3] and power lines [4-5]. While many research on induced voltages focus on its effect to insulation across the conductor and ground, this work concentrates on the determination of the lightning return stroke parameters, particularly the location of the ground lightning strike with respect to the overhead conductor. Some field study on the same idea has been done by Aulia[6] and the results have been encouraging. This paper will discuss and tabulate the results of the mathematical modeling, and the resultant induced waveform parameters compared from both ends of the overhead conductor. The relationship between the parameters of the induced waveforms, to the location of the ground lightning strike occurring at the sides of the overhead conductor is discussed.

4.4 MODELING

Input parameters of the mathematical modeling

The input parameters in the modeling exercise are as below

x-axis and y-axis distance of the lightning return stroke terminating at the ground

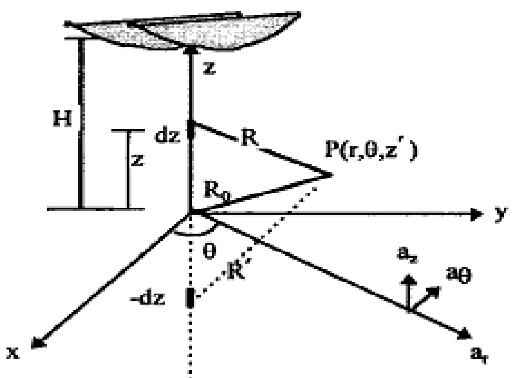


Fig. 1. Geometry of a model nearby lightning used in the vertical and horizontal electric fields computation at a point above ground [7].

intensity of the return stroke current

rise and fall time of the return stroke current

speed of the return stroke as it traverses the channel length

length of the return stroke channel

length and height of the overhead conductor

the distributed inductance and capacitance of the overhead conductor.

Assumptions

Listed below are the assumptions used in the modeling exercise to facilitate capable computation time and storage.

The return stroke is vertical and straight from the base of the cloud to the ground

Constant speed of the return stroke current throughout the channel

Simple triangular waveshape of the return stroke current

Infinite ground conductivity from the source to the overhead conductor

The effect of ground finite conductance will be included in future work.

Mode of the mathematical modeling

Lightning return stroke currents travels throughout the lightning channel. These moving charges cause electric and magnetic field changes throughout its surroundings. The modeling uses the geometry described in Fig. 1 and the corresponding equations are presented in Sorwar et.al. [7].

The vertical and horizontal electric fields at points along the overhead conductor are calculated using the dipole charges and time domain expressions as in [8]. These fields are the forcing functions that energize the free electrons within the conductor. The induced voltages are calculated by applying Finite Difference method on the Telegrapher's Equation [9].

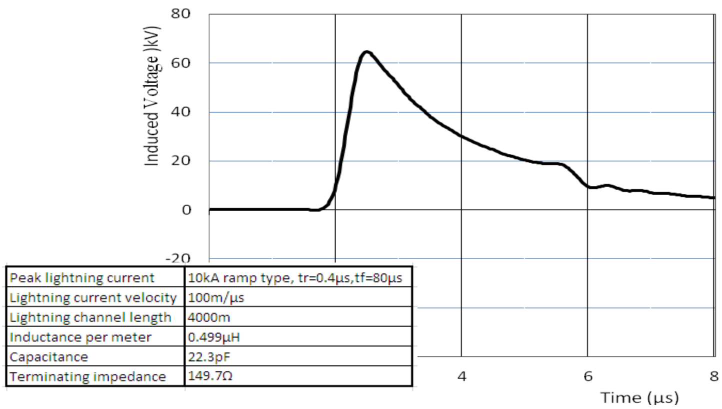
This coupling mode relates the electrical pressure experienced by the unperturbed free electrons within the overhead conductor. The horizontal electric fields are calculated at equal spacing points along the overhead conductor, whilst the vertical electric fields are determined at the terminating ends of the conductor. It is worth noting that other than the electric fields, magnetic fields can be forcing functions as well, as explained in [10].

4.5 RESULTS

Fig. 2 shows the result of the mathematical modeling on a stretch of wire with matched terminations for a 1km of overhead. The stroke location is at 50 m from the line center and equidistant from the line terminations.

Validation of results

The results are comparable to the induced waveform from [9] pictured in Fig. 3. A slight difference is the bump at 5.5µs which is due to induced voltage at the other end of the conductor since the modeled conductor is assumed lossless.



Peak lightning current	10kA ramp type, tr=0.4µs,tf=80µs
Lightning current velocity	100m/µs
Lightning channel length	4000m
Inductance per meter	0.499µH
Capacitance	22.3pF
Terminating impedance	149.7Ω

Fig. 2. Induced voltages at both ends of an impedance matched 1km overhead conductor due to 10kA peak current ground lightning 50 meters away equidistant to both ends with input parameters included.

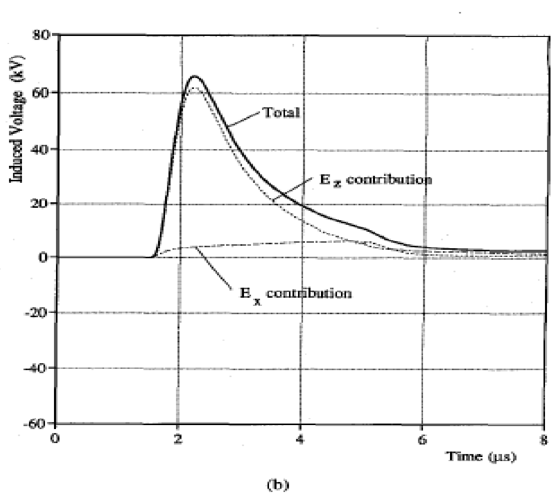


Fig. 3. Induced voltages calculated using vertical and horizontal electric fields with similar parameters to Fig. 2, from Figure 2(b) in [9].

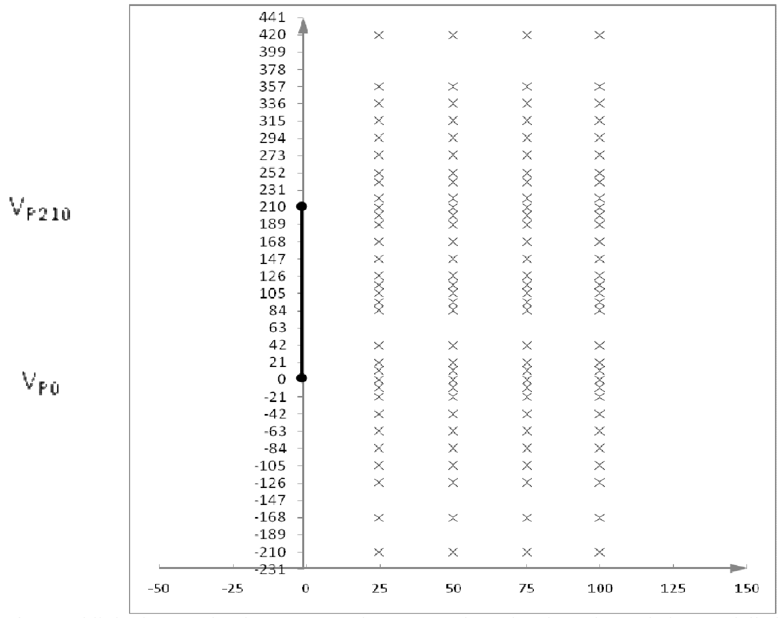


Fig. 4. Coordinates of ground lightning nearby the 10-meter above ground overhead conductor being modelled.

Then the same situation is modelled but with variations of the ground lightning return stroke location from the side of the overhead conductors are presented. The coordinates applied is shown in the plan view above (Fig. 4), whereby the overhead conductor is placed exactly on the y-axis. The first end of the conductor is at coordinates (0,0) and the other end is at (0,210). (1 axial unit is equivalent to 1meter). The 'x' marks the vertical ground lightning location being modelled in reference to the overhead conductor location.

Varying the ramp lightning current rise time

The result of varying the peak current has been presented [11], including comparison of the modelling result with real measured waveform from a 210m suspended overhead conductor. Herewith, variation of the rise time of the lightning is presented in Fig.5, of the induced voltages on both ends and the tabulated peak time and peak voltage difference, namely ΔVP = VP210 - VP0, ΔtP = tP210- tP0 laid on Table 1. Take note of the much smaller variations of the difference in the voltage peaks and peak times compared to actual corresponding value of voltage peak and time peak. This minimizes the error but demands an error analysis of this method.

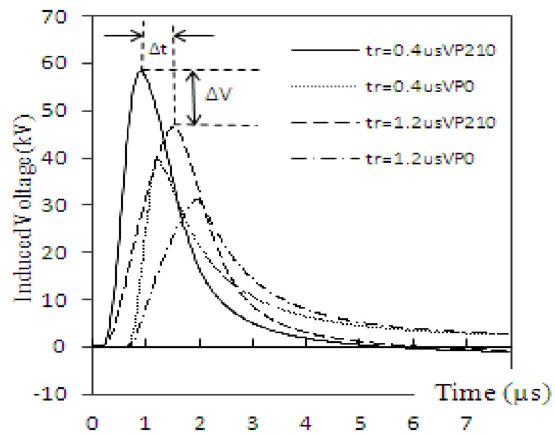


Fig. 5. Induced voltages at both ends with different rise times, indicating the difference of voltage peaks and time to peak.

TABLE I RESULTS OF DIFFERENT LIGHTNING RAMP RISE TIME

Rise time (μs)	0.2	0.4	0.6	0.8	1	1.2	1.4
V_{P210} (kV)	41.20	39.82	37.62	35.26	33.08	30.98	29.13
V_{P0} (kV)	59.97	58.24	56.03	53.38	49.97	46.55	43.11
t_{P210} (μs)	1.05	1.22	1.40	1.58	1.76	1.95	2.14
t_{P0} (μs)	0.78	0.89	1.06	1.22	1.34	1.53	1.69
ΔV_P (kV)	-18.77	-18.42	-18.41	-18.11	-16.89	-15.57	-13.98
Δt_P(μs)	0.27	0.33	0.34	0.36	0.42	0.42	0.45

Induced voltages at both ends

The modelling results in the calculated induced voltages on both ends of the overhead conductor. The data are tabulated to include the peak amplitudes of induced voltages at both ends (VP0 and VP210), time taken for induced voltages to peak from lightning instance (tP0 and tP210), time taken for induced voltages start to appear from lightning instance (tS0 and tS210) and shown in Figures 6 to9 below. Lightning instance is at exactly 0.0μs in these results.

4.6 DISCUSSION

The difference in the calculated values of the modeling namely ΔVP = VP210 - VP0, ΔtP = tP210- tP0, and ΔtS = tS210- tS0 are tabulated to see its variation as the ground lightning strike location shifts. The results are shown in the following Figures 10 to 12.

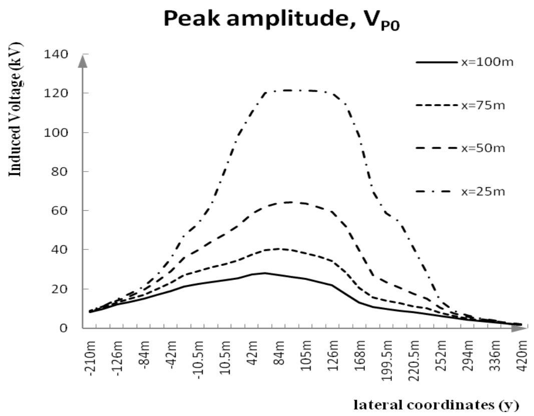


Fig. 6. Peak induced voltages calculated for the first end of the overhead conductor

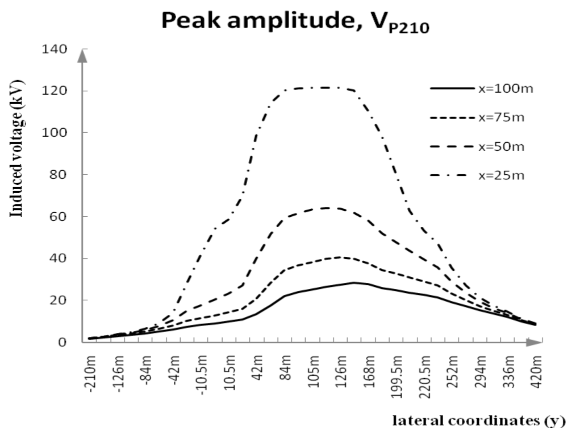


Fig. 7. Peak induced voltages calculated for the other end of the overhead conductor

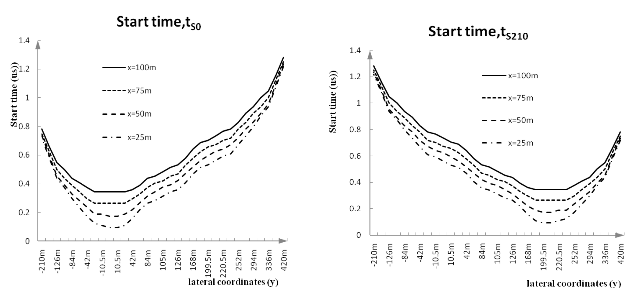


Figure 8: Time taken for induced voltage at the first end of the overhead conductor, (left) and the other end, (right) to appear from lightning instance

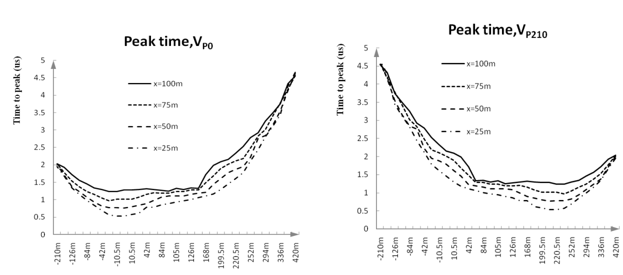


Figure 9: Time taken for induced voltage to peak at the first end of the overhead conductor, (left) and the other end, (right) from lightning instance

The induced voltages at both ends of a matched impedance overhead conductor, VP0 and VP210 varies accordingly from being equal from the centre of the conductor length and having different peak amplitudes VP, time of peak amplitudes tP, start times tS, and their differences ΔVP , ΔtP, and ΔtS as the location of the ground lightning is shifted to either side.

In Fig.10, ΔVP is presented in percentage and combined with ΔtP to estimate the x and y coordinates of the measured waveform. The calculated waveform shows reasonable agreement with the measured waveform [11]. However the peak current value cannot be estimated as some referencing to known and exact real lightning parameters is required.

The similarity of the trend between the ΔtS and ΔtP suggests the agreement in using the peak times, tP, as a reference quantity from real measured waveforms as applied in [6]. The relationship between ΔtS, ΔtP and ΔVP(%) tends to be a straight line at lateral coordinates within the length of the overhead conductor (i.e. 210m<y<0m, or just alongside the overhead conductor).

Fig. 10 describes the relationship between the difference of peak induced voltages at both ends of the overhead conductor. With ground lightning striking points at the sides of the overhead conductor, a rough estimation can be deduced as follows

$$\Delta VP(\%) = m(y) - 60\% \tag{1}$$

where $m \approx 0.57$ (%/meter),

Fig. 11 exhibits this relationship with some minor deviations at lateral coordinates within the overhead conductor length. Equation below characterizes them as

$$\Delta tS = n(y) + 0.45\mu\text{second} \tag{2}$$

where $n \approx -4.8$ (nanoseconds/meter),

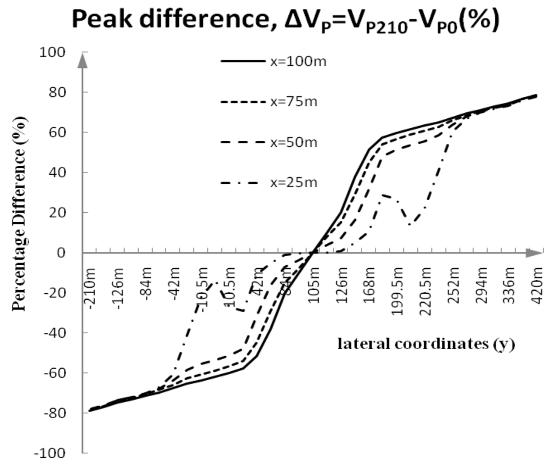


Figure 10: Difference of peak voltages in percentage

Fig. 12 shows the relationship between ΔtP and the lateral coordinates, and is consistent throughout from -210m ≤ y ≤ 420m. They can be coarsely estimated as

$$\Delta tP = p(y) + 0.9\mu\text{second}, \qquad (3)$$

where p ≈ -8.6 (nanoseconds/meter) .

In the above equations, x-axis represents the lateral coordinates with the origin referring to the first end of the overhead conductor, where y= 0 meter as depicted in Fig. 4.

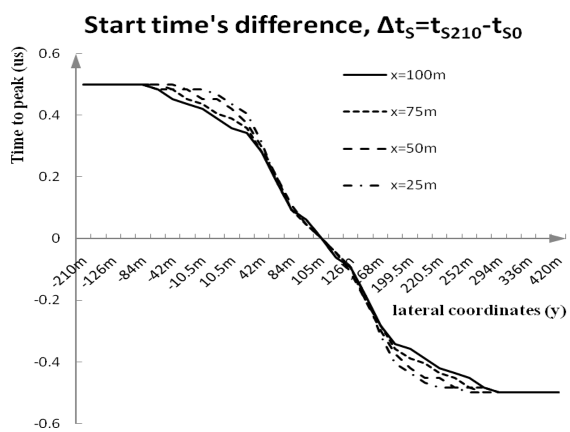


Fig.11. Difference of start times, $\Delta t_S = t_{S210} - t_{S0}$

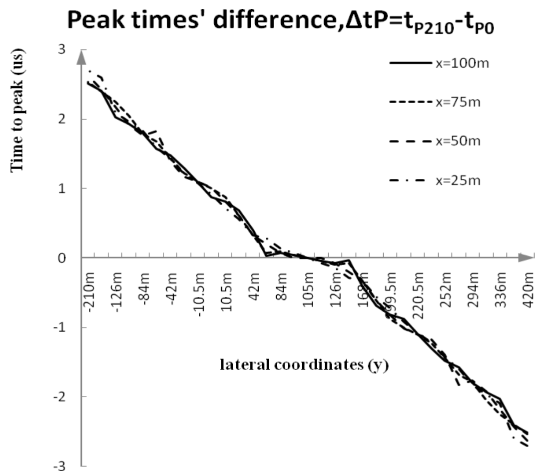


Fig.12. Difference of peak times, $\Delta t_P = t_{P210} - t_{P0}$

4.7 CONCLUSION

The results of the mathematical modelling have been presented with the modelled waveforms produced being compared to other work. The parameters discussed are ΔtS, ΔtP and ΔVP(%) with respect to the lateral coordinates of the estimated lightning strike location. The estimation of the location of lightning based on the induced voltage on both ends of an overhead conductor is presented. However, the estimation may be further improved. This will involve more parameters to be considered and fewer assumptions to be adopted in the modelling work.

From the results, it is not possible to ascertain on which side did the lightning strike from the induced voltage waveforms as they will be symmetrical along both sides of the overhead conductor length.

4.8 ACKNOWLEDGMENT

The authors wish to thank the Ministry of Science, Technology and Innovation, Malaysia, Ministry of Higher Education, and Universiti Teknologi Malaysia, in which the research votes 78273, 77300 & 79032 have been a substantial part of the source to finance this research.

Conclusion

In the research,

i) the far-field electric field has been modeled mathematically using the Finite Difference Tine Domain (FDTD) and

ii) coupled with Agrawal's coupling equation to find the field to wire induced voltage between two ends of a 210m overhead wire 10m above ground level.

The results are presented and from analysis and tabulation, the research shifted its focus to the ability of estimating the location of the lightning strike from simple analysis of the induced voltages. The parameters analyzed are the difference between the peak voltages induced ΔV_P and the difference between the time it reaches peak, Δt_P.

Further recommended work

Since it is found that the far-fields are not a hazard to small electrical systems, a focus to assess the near field effects is necessary to complete this research. It is suggested to perform

i) an assessment of the near field to

    a. a highly capacitive load (conductive structure that erects parallel to the tower) or

    b. inductive load (conductive structure that forms a loop nearby the tower.

ii) A detailed study that would enable us to design

    a. protective shield for the towers that would ‘couple’ to the lightning current flowing in the tower and

    b. thus shield its near-field and far-field electromagnetic field as well

However, a thorough review on the complex and unpredictable E-H relationship needs to be generalized for better manipulation and solution of the wave equation (1) & (2). This requires good comprehension of the wave equation and at the same time manipulation of the many mathematical softwares available.

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From Paper No. 1 (APSAEM2010, UPM, Malaysia)

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