UNIVERSITI PUTRA MALAYSIA

LIGHTNING INDUCED VOLTAGE ON DISTRIBUTION LINE DUE TO INCLINED LIGHTNING CHANNEL

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By

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May 2013

Chairman : Mohd.Zainal Abidin Ab.Kadir,PhD

Faculty : Engineering

Cloud to ground discharge lightning is the most common type of lightning discharge to the ground. It contributes to at least 90 % of all negative charge discharges and demonstrates a higher value of peak current for the first stroke of the lightning. Thus, it may cause the failure of the shielding wire and also create an induced over-voltage on the power line. It is a fact that most of the distribution power lines are exposed to the possibility of disturbances and equipment damage caused by the effect of induced voltages. These induced voltages are influenced by various parameter conditions that result in either the induced voltage being tolerated or becoming an over-voltage on the power line. Lightning and power line parameters are recognized to influence the variation in value and condition of an induced voltage. In addition, most researchers have evaluated the induced voltage with respect to the lightning parameter by assuming the lightning channel is vertical. However, in reality, the lightning channel is not vertical. The lightning has an inclined angle when it strikes the surface of the ground which can be observed at a height of several hundred metres and this creates a variation value in the induced voltage on a power line. Thus, there is a need for specific research that addresses this induced voltage on distribution power lines due to the effect of an inclined lightning channel and protection on the line. The induced voltages in this study were calculated by implementing the procedure provided by IEEE 1410-2010. Also, the impedance of the line protection such as a line arrester was calculated by considering the guide line provided by IEEE Working Group 3.4.11 to mitigate the induced over-voltage on power lines. The results indicate that the induced voltage caused by the inclined and vertical lightning channels show a difference of at least 41%. Moreover, variations in the lightning parameters such as the inclined angle, the velocity of the return stroke and the striking distance from the lightning give a declining trend of induced voltage for an increase in the inclined angle. Furthermore, line parameters such as the height of the conductor line and observation point angle also give a declining trend of induced voltage for an increase in the observation point angle. The results of the induced voltage influenced by the various parameters revealed that at the smallest inclined angle of less than 30°, and at a very low speed of return stroke velocity,$1.2 \times 10^8 \mathrm{m/s}$, at a minimum striking distance, 50m, at a 70°oobservation point angle and at the highest conductor line height, 15m, the lightning induced voltage exceeded the Basic Insulation Level (BIL) of 110kV and became an induced over-voltage. The line arrester results indicated that the induced over-voltage was suppressed to a safe level voltage of 33kV. Thus, the outcomes of these results may provide benefit for electrical power engineers when considering a protection scheme

to take into account the variation value of induced voltage due to the variation of inclined angle. Also, it may provide an advantage for academic research to be able to accurately calculate the induced voltage due to a variation of the inclined angle in an inclined lightning channel.

Abstrak tesis yang dikemukan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

VOLTAN TERARUH KILAT ATAS TALIAN KUASA PEMBAHAGIAN DISEBABKAN OLEH SALURAN KILAT BERSUDUT

Oleh

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Pelepasan cas kilat dari awan ke bumi adalah paling kerap berlaku. Ia menyumbang sekurang-kurangnya 90% pelepasan cas negatif ke bumi dan memberikan nilai arus puncak yang lebih banyak pada ketika kali pertama berlakunya pelepasan cas ke bumi. Justeru itu, ia menyebabkan kerosakan dawai pelindung dan menghasilkan lebihan voltan teraruh dalam talian kuasa. Walaubagaimanapun, talian kuasa pembahagian lebih banyak terdedah dengan gangguan dan kerosakan peralatan yang berpunca dari kesan lebihan voltan teraruh. Voltan teraruh ini dipengaruhi oleh pelbagai keadaan yang membawa samada voltan teraruh menjadi voltan yang diterima atau lebihan voltan teraruh dalam talian kuasa. Parameter kilat dan talian kuasa telah dikenalpasti mempengaruhi kepelbagaian nilai dan keadaan voltan teraruh. Selain itu, kebanyakkan penyelidik telah melakukan penilaian voltan teraruh dengan merujuk kepada parameter kilat dan menganggap bahawa saluran kilat

adalah menegak. Walaubagaimanapun, secara realitinya, saluran kilat adalah condong. Ia mempunyai sudut apabila panahan berlaku di permukaan bumi dan dapat diperhatikan dalam beberapa ratus meter dari permukaan bumi. Oleh itu, kajian terperinci merujuk kepada voltan teraruh dalam talian kuasa pembahagian dengan mengambil kira kesan saluran kilat bersudut perlu dilakukan. Voltan teraruh dikira dengan melaksanakan prosedur yang disediakan oleh IEEE 1410-2010. Juga, kerintangan pelindung talian seperti penangkap kilat dikira dengan mengambilkira panduan yang disediakan oleh IEEE Working Group 3.4.11 untuk mengurangkan lebihan voltan teraruh dalam talian. Keputusan menunjukkan voltan teraruh merujuk kepada saluran kilat bersudut dan menegak mempunyai sekurang-kurangnya 41% perbezaan. Selain itu, kepelbagaian parameter kilat seperti saluran sudut condong, halaju kilat dan jarak panahan kilat menunjukkan keputusan voltan teraruh mempunyai penurunan trend bagi setiap peningkatan nilai sudut condong. Selain itu, parameter talian seperti ketinggian konduktor talian dan sudut permerhatian menunjukkan berlakunya penurunan voltan teraruh bagi setiap peningkatan sudut pemerhatian. Oleh itu, keputusan voltan teraruh yang dipengaruhi oleh kepelbagaian parameter ditemui bahawa pada sudut condong yang paling kecil iaitu kurang daripada 30^0, pada kelajuan kilat yang rendah iaitu $1.2 \times 10^8\, m/s$, pada jarak panahan kilat yang minimum iaitu 50 m, pada sudut pemerhatian 70^0 dan pada konduktor talian yang tertinggi iaitu 15m, voltan teraruh telah melebihi Aras Penebat Asas, 110kV dan menjadi lebihan voltan teraruh. Manakala, keputusan dari penangkap kilat menunjukkan lebihan voltan teraruh telah dikurangkan kepada aras voltan yang selamat. Oleh itu, hasil keputusan ini menyediakan faedah kepada jurutera elektrik kuasa dalam mengambil kira kepelbagaian nilai voltan teraruh pada kepelbagaian nilai sudut condong. Juga, memberikan faedah kepada penyelidik akademik dalam mengira voltan teraruh dengan tepat merujuk kepada kepelbagaian nilai sudut condong dalam saluran kilat bersudut.

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I certify that a Thesis Examination Committee has met on **31 May 2013** to conduct the final examination of NORHIDAYU BINTI RAMELI on her thesis entitled ‘‘**Lightning Induced Voltage on Distribution Line Due to Inclined Lightning Channel**’’ in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The committee recommends that the student be awarded the Master of Science.

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DECLARATION

I hereby declare that the thesis is based on my original work expect for quotations and citations, which have been duly acknowledged. I also declare that is has not been previously or currently submitted for any other degree at Univerisit Putra Malaysia or other institutes.

NORHIDAYU BINTI RAMELI

Date: 31 May 2013

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BG	Bruce-Golde model
BIL	Basic Insulation Level
CFO	Critical Flash Over
EGM	Electro Geometry Model
FDTD	Finite Domain Time Domain
LIV	Lightning Induced Voltage
LIOV	Lightning Induced Over Voltage
MOSA	Metal Oxide Surge Arrester
MTLE	Modified Transmission Line with Exponential
TCS	Travelling Current Source
TL	Transmission Line model
TNB	Tenaga Nasional Berhad

CHAPTER 1

INTRODUCTION

1.1 Background

Lightning is an unpredictable natural phenomenon which manifests itself in a few different ways. The cloud-to-ground type with negative downward lightning is the most common type that contributes to some 90 % of the occurrences of lightning strikes [1]. There is a negative discharge more often than a positive discharge to the ground, and the negative discharge is known to give a higher value for the peak current during the first stroke as compared to the subsequent lightning strokes [2-3]. This characteristic contributes to the damage to electrical power apparatus and the danger to human life [4]. Lightning may also cause failure in a power system network such as medium and low voltage distribution lines which have a lower critical flashover (CFO) than the transmission system. For instance, in Malaysia, a statistical analysis of the performance of the electricity supply shows that at least 51 % of interruptions are caused by voltage transients [5].

Lightning affects electrical systems in two ways, namely a direct and an indirect strike. A direct strike is a lightning strike directly to a tower or to a phase conductor which causes backflashover and shielding failure respectively. On the other hand, an indirect strike is a lighting strike to the ground or nearby object which may cause an induced voltage or overvoltage on the power line [6, 7] which affects the medium and low voltage distribution power lines. Thus, indirect lightning is a major factor for consideration of the lightning damage phenomenon.

A lightning channel may be categorized as either vertical or inclined. The vertical lightning channel has received much attention in many research studies [8-11]. This lightning channel is perpendicular to the surface of the ground which gives the simplest solution for researchers to calculate the lightning induced voltage on the power line. However, in reality, the lightning often follows an inclined channel which can be observed at a height of several hundred metres to make an angle between the lightning channel and the surface of the ground [12, 13]. Using an inclined lightning channel in the studies will give an accurate result to calculate and evaluate the induced voltage on the power line with respect to the angle of inclination compared to a vertical lightning channel.

However, little research has been undertaken to evaluate induced voltages with respect to an inclined lightning channel. Also, to the best of the knowledge of the author, none of the previous research has evaluated protection devices such as a line arrester to include the effects of induced voltages due to inclined lightning channels. Thus, it is intended in this study to develop an appropriate algorithm to calculate the induced voltage due to an inclined lightning channel through a selection of various numerical methods. The numerical methods cover the procedures of calculating the induced voltage such as calculating the electromagnetic field by taking into consideration the current at different heights and times along the lightning channel. These procedures are presented through various methods and models such as the return stroke current model, the calculated electromagnetic field method and the coupling model which are explained in detail in Chapter 2.

In this work, the induced voltage with respect to an inclined lightning channel and protection devices such as line arresters is evaluated. The evaluation is based on the effect of the inclination and observation point angle on the variation of the lightning parameters and line such as the velocity of the return stroke current, the lightning striking distance and the height of the conductors on a multi-point distribution line. The outcome of this research will be useful for the utility companies and others involved in power engineering for their planning and selection of appropriate protection scheme for medium voltage distribution power lines.

1.2 Problem statement

The types of lightning channel and the influences of electromagnetic fields play a leading role in calculating the induced voltages on power lines. In lightning research, many studies assume that the lightning channel strikes vertically to the surface of the ground [8-11]. This contributes to the induced voltage through the influence of only the vertical electric field, E_z [14-15]. The induced voltages that arise from consideration of the soil resistive effect and the horizontal electric field, E_h have a more significant influence [16-18]. However, typically in reality the lightning channel is inclined whereby the lightning strikes the ground at a certain angle. This has been clearly observed at hundreds of metres from the surface of the ground [13].

According to references [19], the induced voltage caused by the inclined lightning channel is more significantly influenced by the resultant of the electric field, E_T between the vertical electric field, E_z and the horizontal electric field, E_h as shown in Figure 1.1. Therefore, it very important to consider the inclined lightning channel to calculate and evaluate the induced voltage at a specific inclined angle whereby it gives a variation value of induced voltage compared to the induced voltage causes by vertical lightning [12].

In addition, several studies have been undertaken to evaluate the induced voltage with respect to an inclined lightning channel through numerical calculation [12, 20-24]. As shown by references [12, 23-25], the time domain of the numerical calculation is applied in order to calculate the induced voltage. Further, the observation point with respect to the temporary charge on the lightning channel is evaluated for the scalar and vector potential at one point. Also, the full electromagnetic field is neglected and only the electric field is considered. In contrast, references [21-22] apply the frequency domain in their numerical calculation. The same issues are found when evaluating the observation point. However, their method is not a straight forward calculation because they need to convert the calculation from the frequency domain into the time domain. This implies long computation times [26]. Furthermore, different purposes are stated in evaluating the induced voltage. As undertaken by references [12, 21- 23], their purpose is directed more to the method for calculating the induced voltage. Reference [20] shows a method of evaluating the induced voltage based on the determination of the significance of an inclined lightning channel and a tortuosity lightning channel. In addition, references [24,25], extend this work.

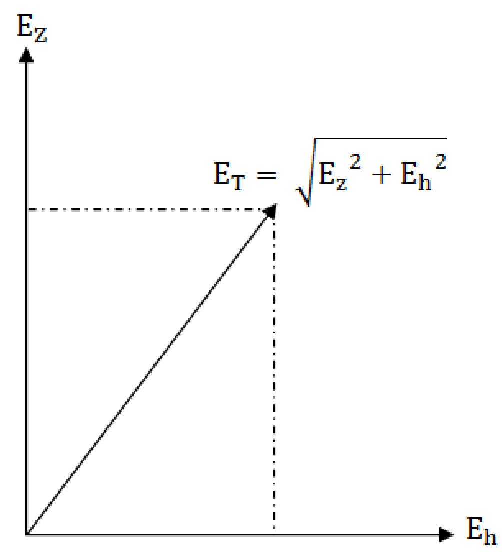

Figure 1.1 The electric field component due to the effect of an inclined lightning channel.

Thus, this thesis is to consider the time domain calculation whereby the point observation with respect to the temporary charge on the lightning channel will be evaluated based on the vector potential along a multi-point line. Also, the entire electromagnetic field components which consist of the magnetic field and the electric field are considered at different points. In addition, the evaluation of the induced voltage due to an inclined lightning channel is undertaken by focusing on the analysis sensitive parameters of the lightning and distribution line. It includes the inclined angle and observation point angle parameters. Also, the arrester effect will be included as protection to reduce the induced voltage due to an inclined lightning channel.

As a result, by developing an algorithm to calculate lightning induced voltage due to inclined lightning channel, it may be possible to provide a simple and accurate calculation which can be useful to electrical power engineers. This is due to the application of the time domain which provides the simplest way to calculate the electromagnetic field without the need to convert from the frequency domain. Finally, the accuracy of the calculation of the induced voltage will be improved due to considering multi-points along the line including the entire electromagnetic fields which are considered in vector potential form compared to other previous methods.

1.3 Objectives

The aim of this thesis is to investigate the lightning induced voltage due to an inclined lightning channel. Therefore, in order to achieve this aim, a few objectives are listed as follows:

1. To develop an algorithm to calculate the induced voltage due to an inclined lightning channel for a 33 kV distribution line.
2. To investigate the effect of the induced voltage on an inclined lightning channel due to lightning and line parameter variations.
3. To investigate the effectiveness of a line arrester model for mitigating lightning induced overvoltage due to an inclined lightning channel.

1.4 Scope of work

This thesis is concerned with the evaluation of lightning induced voltage due to an inclined lightning channel. The induced voltage caused by an indirect lightning strike appearing on a 33 kV line distribution system is investigated, including the installation of a line arrester to suppress the excess voltage to the safety level of the distribution line. In order to facilitate the above work, the following assumptions are made:

1. The lightning channel is a single channel without any branches.

2. The surface of the ground is flat and has infinite soil conductivity.

3. The power line is a single conductor without a shielding wire.

4. The lightning current is a step current.

1.5 Structure of the thesis

This thesis consists of five chapters which consist of the introduction, literature review, methodology, results and discussion and also the conclusion respectively. Chapter 1 gives an introduction to the thesis, the problem statement, aims and objectives and also the scope of work.

Chapter 2 presents the literature review. It gives a detailed explanation of the evaluation stages of the LIV procedure which consists of the evaluation of the channel base current, the return stroke current, electromagnetic fields and the coupling. Various line arrester models are also reviewed.

In Chapter 3, the methodologies for this thesis are presented. This includes the parameters of the 33 kVdistribution lines in Malaysia, and the development of an algorithm for calculating the induced voltage due to an inclined lightning channel.

Chapter 4 provides the results and discussion. Both of these elements represent the results of the induced voltage caused by an inclined lightning channel and the effectiveness of a line arrester is discussed. Finally, Chapter 5 provides the overall conclusion of the studies and recommendation for future work.

1.6 Summary

In this chapter, a brief explanation regarding the background of the research study is presented. The motivation, objectives and scope of this research study are stated and listed. Finally, the structure of this thesis for each chapter is described.

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