LOCATING NEARBY CLOUD TO GROUND LIGHTNING FROM MEASUREMENTS OF INDUCED VOLTAGES ON OVERHEAD CONDUCTOR'S ENDS

ZURAIMY BIN ADZIS

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

APRIL 2012

ACKNOWLEDGEMENT

First of all, I am greatly thankful to Allah SWT for giving me the opportunity to conduct this study and ideas that comes with it. I would like to express my gratitude and thanks to my supervisor, Associate Professor Dr. Zulkurnain Abdul Malek for giving his valuable time, advice and continuous encouragement towards the completion of my project from beginning till the end. His patience is a virtue.

Secondly, my appreciation goes to my family, who has been so tolerant and supporting me all these years. Thanks for their encouragement, love, and emotional support that they had given to me.

I also would like to extend my appreciation to everyone around me, those who taught me lessons in research and in life. This appreciation is also extended to those I have never met, but their knowledge is passed on to me through their publication, their contributions to whatever media available in the effort to promote knowledge. 'Kudos' to them and I wish to be able to contribute and have the impact to others just as they have done to me.

ABSTRACT

The lightning locating methods are applied to large areas with an array of sensors that is connected to a central computer, using either Time of Arrival techniques or Magnetic Direction Finding techniques, or both. However, a relatively significant error would be present in the assessment of ground flash density for a much smaller area due to the weaknesses of the location accuracy for smaller areas. This thesis introduces an alternative method of locating nearby lightning, which maximized the benefits of the induced voltages at terminated ends of an overhead conductor. It utilises the time differences to peak (Δt_p) and percentage differences of peak voltages (Δv_p), between lightning induced voltages (LIV) at both ends. Research work includes field measurements of LIV on ends of a 210 meter overhead conductor and computations of the same. Computation using established electromagnetic mathematical model programmed in C++ in time domain is presented and discussed. Results were validated against other researchers' work and measurements. A parametric study from the model with varying parameters in inducing voltage at both ends is also presented. Further analysis shows that Δt_p and Δv_p of the conductors were not significantly affected by the changes of the return stroke peak current, uniform finite ground conductivity, conductor's intrinsic inductance and terminating resistances. The mathematical model was also extended to longer conductors (350 meter span ground wires and 5 mile distribution cable) by taking into account of the effects of finite ground conductivity and earth return current. The results thus support the applicability of the proposed method. It is also shown that measurement of the induced voltage at both ends of the overhead conductor, with particular attention to Δt_p and Δv_p enables the inference of nearby cloud to ground (CG) lightning location. The modelling work is currently limited to vertically aligned CG lightning, un-attenuated and undistorted lightning return stroke current through the lightning channel with a uniform velocity and interference free.

ABSTRAK

Kaedah mengesan lokasi kilat diaplikasikan untuk kawasan yang besar dengan tatasusunan penderia yang bersambung kepada sebuah komputer pusat, mengguna pakai samada kaedah Waktu Ketibaan atau Pencari Arah Magnetik, atau kedua-duanya secara serentak. Namun ralat yang agak ketara wujud dalam penilaian ketumpatan kilat ke bumi untuk kawasan yang lebih kecil disebabkan kelemahan kejituan pengesan lokasi sistem tersebut untuk kawasan yang kecil. Tesis ini memperkenalkan kaedah lain dalam mengesan lokasi kilat berdekatan, memanfaatkan voltan teraruh pada hujung pengalir tergantung yang ditamatkan dengan perintang. Ia menggunakan perbezaan masa untuk memuncak (Δt_p), dan peratusan perbezaan puncak voltan (Δv_p) yang teraruh akibat kilat (LIV) di antara kedua-dua hujung pengalir tersebut. Kerja-kerja penyelidikan termasuk pengukuran tapak LIV pada pengalir tergantung sepanjang 210 meter dan juga pengiraan berbantu komputer untuk pengukuran tersebut. Pengiraan berbantu komputer menggunapakai model matematik elektromagnet yang diiktiraf, diaturcara menggunakan C++ dalam domain masa juga dibentang dan dibincangkan. Hasil keputusan dari pengaturcaraan dibanding dengan keputusan dan pengukuran dari penyelidik-penyelidik lain. Kajian parametrik dari model pengaturcaraan dengan parameter yang berbeza-beza dalam mengaruhkan voltan pada kedua-dua hujung pengalir juga dibentangkan. Analisa lanjut menunjukkan bahawa Δt_p dan Δv_p yang dicatatkan diantara kedua hujung pengalir tidak berubah secara ketara dengan perubahan arus puncak lejang kembali, keberaliran tanah terbatas yang seragam, kearuhan hakiki pengalir dan juga nilai rintangan penamatan. Kaedah ini juga dilanjutkan kepada pengalir yang lebih panjang (wayar bumi 350 meter pada sistem penghantaran elektrik dan juga wayar pengagihan sepanjang 5 batu) dengan mengambilkira kesan keberaliran tanah yang terbatas (bukan infiniti) dan arus pulang melalui bumi. Keputusannya memberangsangkan sekali gus menyokong kebolehgunaan kaedah baru ini. Juga ditunjukkan bahawa pengukuran voltan teraruh pada kedua-dua hujung pengalir tergantung dengan perhatian khusus kepada Δt_p dan Δv_p membenarkan anggaran lokasi kilat awan ke bumi (CG) yang berdekatan. Kerja permodelan ini terbatas kepada kilat CG yang menegak, arus kilat lejang kembalinya yang melalui saluran kilat tidak terlemah atau terherot dengan halaju yang seragam dan bebas gangguan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS/SYMBOLS

$\overline{B}$	-	magnetic field
(CG)	-	Cloud to ground
$\bar{A}$	-	vector potential
C	-	distributed capacitance
c	-	the speed of light
C++	-	Programming language
$\tilde{E}$	-	electric field
EMTP	-	Electromagnetic Transient Program
E_r	-	horizontal electric fields
E_y	-	The stray excitation function of horizontal electric field
E_z	-	vertical electric fields
F	-	Farad
FDTD	-	Finite Difference Time Domain
GPS	-	Global positioning system
H	-	Henry
I	-	Current
IMPACT	-	Improved Accuracy through Combined Technology
$\hat{J}$	-	current density
L	-	distributed inductance
LDN	-	Lightning Detection Network
LIV	-	lightning induced voltage
LLLS	-	Local Lightning Location System
LLP	-	Lightning Location Protection
LLS	-	lightning locating systems
LPATS	-	Lightning Positioning and Tracking System

m	-	meter
MDF	-	Magnetic Direction Finding
MDM	-	Modified Dipole Method
MODELS	-	language of the alternative transient program (ATP) version of EMTP, which is an enhancement to TACS
MTLE	-	Modified Transmission Line Exponential Model
MTTL	-	Modified Transmission Line Linear Model
NLDN	-	National Lightning Detection Network
R	-	Distance from source dipole to point of consideration
TL	-	Transmission Line Model
TLM	-	Total Lightning Mapping
TNBR	-	Tenaga Nasional Berhad Research
TOA	-	Time of Arrival
TOGA	-	Time-Of-Group-Arrival
TSL	-	Telecommunication Subscriber Lines
US	-	United States of America
UTM	-	Universiti Teknologi Malaysia
V	-	Voltage
VHF	-	Very high frequency
V^i	-	Incident voltage on ends of cable
WWLLN	-	World Wide Lightning Location Network
Δt_p	-	Difference of the peak time between induced voltages at both ends
Δv_p	-	Difference of the peak amplitude between induced voltages at both ends
φ	-	scalar potential
Ω	-	Ohm

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

Lightning activity in the United Kingdom, as reported by Lees have general trends that can be observed, but with significant local variations [1]. The data is gathered from a lightning location system employing magnetic direction finding methods for the period 1989 to 1998. While in the tropics, they are usually diurnal and occur mainly in the afternoon on land as shown by Hidayat [2], presenting the results from the lightning location network observing the activity on Java Island. The locating network in Java Island employs a combination of the time of arrival and magnetic direction finding techniques with four stations.

Lightning location methods adopted in lightning location systems basically depends on the Time of Arrival (TOA) and Magnetic Direction Finding (MDF). The TOA utilizes the difference of arrival time of the fields to each sensor and usually consist of three electric field sensors spaced widely apart for eliminating disambiguates from crossing parabolas of only two sensors. MDF uses the crossed loop antennas to determine the azimuth and elevation angles with reference to the antenna. The different intensities of the signals received between the two crossed loops are used to determine the azimuth and the elevation angle.

Both methods when combined gives better location accuracy and detection ability of the lightning locating system. The modern detection system such as the

Lightning Detection Network (LDN) is in use by Tenaga Nasional Berhad Research (TNBR) in Malaysia. It comprises of eight sensors placed strategically around the peninsular to detect location of cloud to ground (CG) discharges in real time. Their accuracy is now improved to ±200 meters. The lightning sensor has a nominal detection range of 370 km, within 85 percent or more lightning flashes detected. The lightning sensor can reliably discriminate against intra-cloud flashes and identify the stroke polarity for flashes that occur within 600 km of the lightning sensor [3].

The systems described above are for a wide area detection of up to hundreds of kilometers. Given the error of ±200 meters, an identified strike location may lie in an area of 160000 m^2. This area can also be viewed as "uncertainty area" and is around 16% error of a 1 km^2 area. If a lightning density of a 1 km^2 area is required for assessment of the risk factor of a building, this 16% error will require an added risk factor and thus added cost.

To overcome these additional risk factor and cost, a local or remote locating system of better accuracy is proposed. Initially the Local Lightning Location System (LLLS) proposed by the research team from Universiti Teknologi Malaysia (UTM) [4] tends to be a solution to the problem utilizing the lightning induced voltage (LIV) at the ends of an 'L' shaped configuration of two overhead telecommunication cables. The peak time difference between both ends of a single cable is referred to determine the x-coordinates of the strike location and the same parameter from the other cable is referred to determine the y-coordinates.

Upon further research via modeling exercise, a better method is proposed utilizing the LIV on the ends of a single overhead cable. This method may look similar to TOA or MDF method, but the evaluated parameters chosen and how the voltages build up makes it more accurate and sensitive. It may be considered as interferometry technique but at a smaller scale due to the single sensor in use that is a single overhead cable or conductor.

LIV on overhead conductors is of research interest due to their damaging effects to electric systems since 1930's. Though immune to LIV, high voltage transmission systems are still exposed to threat from direct lightning. Even then Gothberg and Brookes [5], had proposed a raw design of a wood and steel tower that can withstand direct lightning stroke. The indirect effects of lightning are also in interest of research until present.

Thottappillil [6] characterizes the total lightning electromagnetic pulse environment from combined individual processes in lightning such as return strokes, preliminary breakdown pulses, pulses associated with the leader process, K-changes and M-changes, the isolated narrow bipolar pulses, and the pulse bursts. Srinivasan [7] describes lightning as atmospheric electricity, its behavior and possibility to tap energy. Although brief, the explanation on atmospheric electricity is exact, but the possibility if tapping the energy from lightning is vaguely explained.

Distribution systems are vulnerable to nearby LIV and the present locating system partially helps the preventive measures against their damaging effects due to the location accuracy issue. Studies on the nearby LIV has been conducted for example by Omidiora and Lehtonen [8] where experimental results of measured LIV on overhead cables when lightning strikes a nearby tree, and in [9] whereby the Supervisory, Control and Data Acquisition (SCADA) information is correlated to the LLS data to automatically locate a fault on the line. They report the errors on LA contribution on their study and suggest the need for LLS data of better resolution to further improve the outcome of their study.

1.2 Problem Statement

The accuracy and sensitivity of large area lightning location systems are acceptable for the large area in concern. For example, a study conducted for the Guang Dong lightning location system (LLS) results in the median error of location accuracy (LA) of approximately 1.32 km and overall detection efficiency (DE) of approximately 86% [10]. Those data is for a coverage area of approximately 176,948 km^2. Although small in percentage, that error may be significant if we are considering the lightning risk for a building or a plant which may require LA of at most 100 m for a 1 km^2 area. If the data can be resolved further for study of the risk factor, a better risk factor can be achieved. That information would result in a more cost efficient lightning protection.

Many existing LLS are developed for covering large areas such as for a country or large district. Data from existing LLS is available but LA for that much smaller particular area is a concern. A solution for LA would be to have localized LLS covering a smaller specific area for a period of time. Further existing LLS uses a number of sensors either widely spaced, or vice versa when combined with interferometry concept. When the accuracy of locating and detecting CG lightning is of importance such as assessing the risk factor of a remote area, a better method with improved accuracy and sensitivity would be of a much better choice.

The need to have a better resolution of the ground flash density (GFD) maps is expressed by Kosmac [11], whereby the lightning threat in distribution networks is evaluated. Large location accuracy of a LLS remains a problem for that research and statistical method is employed to further improve the resolution of the LLS data from the available coarse data.

It would be of better advantage if the LIV on distribution and transmission cables is utilized to give information of approaching thunderstorm activity or exact location of the CG lightning to assess the immunity of the distribution networks against LIV. Furthermore, the LIV are available at terminated segments of the networks and thus readily available. Introduction of localized LLS would be of convenience in these types of studies.

A localized LLS would also be advantageous in an effort to evaluate the existing wide area LLS such as in [12] by Aulia. An example whereby the recorded and measured lightning striking the Canadian National Tower in Toronto is used to evaluate the LA and DE of the North American Lightning Detection Network (NALDN) which is presented in [13] by Lafkovici. Each strike to the tower would be compared to the detected and located strike data of the NALDN. A localized LLS described in the first paragraph would be suitable for this purpose as well and the application is not restricted to towers only but further expanded across the continent as the overhead cables spans throughout.

Paragraphs above describe the need for a local lightning locating system (LLLS) that would be able to locate CG lightning of some acceptable resolution within a particular area. The resulting data would be of better use in terms of assessing the lightning risk factor of that particular area, contributive data for research and even suitable for use in an effective early warning system. The outcome of this research aims to cater the problems listed above, in proposing a method that would be applicable for detecting lightning within a smaller area, with acceptable LA and DE, and most importantly of a low cost set-up. The proposed method would be applicable in systems of overhead conductor or conductors, with minimal measurements at spaced terminations and time synchronized by a global positioning system (GPS). The processing of the signals is in time domain thus applicable for real time measurement.

1.3 Objective

Recently, a study by the LLLS team had been done in order to achieve a better design of lightning protection such as the effect of distance and height of a Telecommunication Subscriber Lines (TSL) to lightning strike position [12]. From thereon, the objectives of this research is as follows

(i) To propose a new method of locating CG lightning strike location from the LIV at the ends of an overhead conductor terminated to ground by referring to Δt_p and Δv_p between both ends of the overhead conductor. Δt_p is the difference of the peak time and estimates the x-coordinate of the strike location, and Δv_p is the difference of the peak amplitude and estimates the y-coordinate of the strike location in an x-y axis on the ground from a plan view of the surrounding area.

(ii) To mathematically model the LIV at both ends of an overhead conductor employing available established model and simulate the LIV for different strike locations to show the relationship of Δt_p and Δv_p to the strike location.

(iii) To further extend the mathematical modeling to existing overhead conductor system i.e. telecommunication, distribution and transmission systems.

(iv) To identify the weaknesses of the proposed method and find solutions to overcome them.

1.4 Scope

Due to the vast area to be further assessed in the area of lightning and response of an overhead conductor to its electromagnetic field, the research is limited to

(i) The study of LIV due to the return stroke current of CG downward negative lightning. A lightning flash consists of many processes occurring in sequence and timeframes. The return stroke current is the most intense of them and therefore chosen with expectance of better sensitivity. Further the occurrence of the processes prior and after the return stroke does not alter the quantities of the two parameters in concern as they are spaced milliseconds apart and the LIV of each process can be singularly identified.

(ii) The results are from a mathematical modeling exercise with a number of assumptions as listed in Section 3.5.1 during the modeling stage. Nonetheless, the assumptions adopted are acceptable within their practical ranges in comparison to the techniques adopted in estimating the peak LIV for purposes of insulation coordination.

(iii) The proposed method and their following modeling work are concerned with only for conductors above ground. Underground cables are armored and their sheaths are grounded thus a better model will be required.

(iv) The research does not analyze the error of the LA and the DE. It does not consider the LIV from intra-cloud and inter-cloud discharges.

(v) The modeling results and the proposed method are analyzed for a flat area without terrains, structures or vegetations that would alter the propagation of the electromagnetic fields to the point of interest.

(vi) The overhead conductor is limited to a single overhead conductor terminated to ground.

1.5 Contributions of the research

The contributions from the research are listed below. They are arranged according to their importance and relevance.

(i) Proposal of a method to locate nearby lightning from simple analysis of the voltages induced at both ends of a terminated overhead conductor. The parameters Δt_p (peak time difference) and Δv_p (peak amplitude difference) between the two synchronized measurements at each terminated end is indicative of the lateral location of the CG return stroke (with respect to the overhead conductor stretch) and the distance away from the sides of the conductor respectively. The method performs better in terms of LA and DE than a large area network, for a given smaller area nearby the overhead conductor.

(ii) The development of a C++ based mathematical modeling program which is robust to the parameters of the CG return stroke current, overhead conductor, and of the surroundings such as the finite ground conductivity. The modeling aims to calculate the LIV on overhead conductors from dipoles of a vertically aligned upward CG return stroke channel current.

(iii) The analysis of the modeling results that shows the relationship of the CG strike location to Δt_p (peak time difference) and Δv_p (peak amplitude difference) in supporting the proposed method.

(iv) Analysis of the shortfalls of the proposed method prevalent from the results of the modeling exercise above. Amongst the shortfalls are the 'blind lines' that exists exactly on the perpendicular axis bisecting the overhead conductor at its center.

(v) Proposal of schemes of solution to overcome the shortfalls discussed above which utilizes the set-up of different configurations of a pair of overhead conductors.

1.6 Structure of the thesis

Chapter 2 details the related literature review of the research. They include review on existing lightning locating systems, C++ codes, lightning electromagnetic fields and their propagation through finite ground conductivity, coupling of fields to line, and travelling waves on overhead conductor. The reviews are by no means extensive but closely related to the research topics covered.

Chapter 3 spreads out the methodology and procedures adopted in obtaining the experimental results, on-site measurement results and a detailed explanation on the mathematical modeling exercise. Since the mathematical modeling is the result of the author's own effort from the basic engine from Sorwar [4], detailed but not exhaustive C++ modeling flow is presented.

Chapter 4 presents the results of the experimental works, on-site measurements, parametric evaluation of the mathematical modeling exercise and existing overhead system modeling for telecommunication cable, ground wire of a transmission system and a single phase distribution cable. Validation of the mathematical modeling result is made by comparison with the on-site measurements and other research modeling result which is established and compared with actual site measurements. In this chapter, the approach of the proposed method is further detailed based on the results generated.

Chapter 5 is devoted to discussing the outcome of the results in supporting the proposed lightning locating method applied on existing overhead conductor systems. Further evaluation reveals shortfalls of the proposed method. The shortfalls are further discussed in an effort to explain the proposed solution schemes to overcome those shortfalls. The proposed solutions have not been tested through the mathematical modeling exercise but by geometrical comparison and utilizing the TOA into the proposed method.

Chapter 6 concludes the contribution of the research and thesis with suggestion of further works based on shortcomings of the assumptions adopted in the mathematical modeling. A section is also devoted to possible usefulness of the proposed method and its advantage compared to existing locating system.

REFERENCES

1. Lees, M.I.; , "Lightning activity in the UK," *Lightning Protection of Wind Turbines (Digest No: 1997/303), IEE Half-Day Colloquium on* , vol., no., pp.2/1-2/3, 26 Nov 1997.

2. Hidayat, S.; Sirait, K.T.; Pakpahan, P.M.; Ishii, M.; Hojo, J.; , "Lightning characteristics on Java Island, observed by lightning location network," *High Voltage Engineering, 1999. Eleventh International Symposium on (Conf. Publ. No. 467)* , vol.2, no., pp.192-195 vol.2, 1999.

3. Abdullah, N.; Yahaya, M.P.; Hudi, N.S.; , "Implementation and use of lightning detection network in Malaysia," *Power and Energy Conference, 2008. PECon 2008. IEEE 2nd International* , vol., no., pp.383-386, 1-3 Dec. 2008.

4. Aulia. *A new lightning location system using telecommunication overhead lines.* Thesis, (M. Eng). Universiti Teknologi Malaysia; 2009

5. Gothberg, A. W.; Brookes, A. S.; , "Lightning Protection for Transmission Lines," *American Institute of Electrical Engineers, Transactions of the* , vol.56, no.1, pp.13-16, Jan. 1937.

6. Thottappillil, R.; , "Electromagnetic pulse environment of cloud-to-ground lightning for EMC studies," *Electromagnetic Compatibility, IEEE Transactions on* , vol.44, no.1, pp.203-213, Feb 2002.

7. Srinivasan, K.; Gu J.; , "Lightning as Atmospheric Electricity," *Electrical and Computer Engineering, 2006. CCECE '06. Canadian Conference on* , vol., no., pp.2258-2261, May 2006.

8. Omidiora, M.A.; Lehtonen, M.; , "Experimental performance of induced voltage on power line due to lightning discharge to nearby tree," *Modern Electric Power Systems (MEPS), 2010 Proceedings of the International Symposium* , vol., no., pp.1-5, 20-22 Sept. 2010.

9. Kosmac, J.; Djurica, V.; Babuder, M.; , "Automatic fault localization based on lightning information," *IEEE Power Engineering Society General Meeting, 2006.*

10. Chen, S.M.; Du, Y.; Fan, L.M.; He, H.M.; Zhong, D.Z.; , "Evaluation of the Guang Dong lightning location system with transmission line fault data," *Science, Measurement and Technology, IEE Proceedings* - , vol.149, no.1, pp.9-16, Jan 2002.

11. Kosmac, J.; Gasper, L.J.; Vladimir, D.; Zvonko, T.;, "Evaluation of lightning threat in distribution networks," *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on* , vol., no., pp.1-4, 8-11 June 2009.

12. Aulia; Abdul Malek, Z.; Adzis Z.; , "The Surge Induced Voltage on a Small scale Model of Telecommunication Subscriber Lines (TSL) in Different Height and Distance: Experimental Approach", *Commet, UTM*, 2008.

13. Lafkovici, A.; Hussein, A.M.; Janischewskyj, W.; Cummins, K.L.; , "Evaluation of the Performance Characteristics of the North American Lightning Detection Network Based on Tall-Structure Lightning," *Electromagnetic Compatibility, IEEE Transactions on* , vol.50, no.3, pp.630-641, Aug. 2008.

14. Md. Golam Sorwar Hossain. *Analysis of induced surges on overhead telecommunication subscriber line due to lightning return stroke*. Thesis, (M. Eng). Universiti Teknologi Malaysia. 1998.

15. Rakov, V. A., Uman, M.A. *Lightning physics and effects.* UK: Cambridge University Press. (2003)

16. Stolzenburg, M., W. D. Rust, and T. C. Marshall, Electrical structure in thunderstorm convective regions. 3. Synthesis, *J. Geophys. Res., D103,*14097-14108, 1998.

17. Cooray, V. *The Lightning Flash*, UK:IEE London, (2003)

18. M.A. Uman, D.K. McLain, and E.P. Krider. The Electromagnetic Radiation from a Finite Antenna, *Am. J. Phys*., 43, 33-38 (1975).

19. Uman, M.A.; , "Natural lightning," *Industrial and Commercial Power Systems Technical Conference, 1993. Conference Record, Papers Presented at the 1993 Annual Meeting* , vol., no., pp.1-7, 2-6 May 1993.

20. Mo, F.; Jiang, J.; Huang, Y.; Wang, T.; , "Study the induced voltage caused by lightning flash to overhead power lines tower," *Power Electronics and Motion Control Conference, 2009. IPEMC '09. IEEE 6th International* , vol., no., pp.2521-2526, 17-20 May 2009.

21. Napolitano, F.; Paolone, M.; Borghetti, A.; Nucci, C.A.; Rachidi, F.; Rakov, V.A.; Schoene, J.; Uman, M.A.; , "Interaction between grounding systems and nearby lightning for the calculation of overvoltages in overhead distribution lines," *PowerTech, 2011 IEEE Trondheim* , vol., no., pp.1-7, 19-23 June 2011.

22. Kumar, U.; Hegde, V.; Shivanand, V.; , "Preliminary Studies on the Characteristics of the Induced Currents in Simple Down Conductors Due to a Nearby Lightning Strike," *Electromagnetic Compatibility, IEEE Transactions on* , vol.48, no.4, pp.805-816, Nov. 2006.

23. Mousa, A.M.; Srivastava, K.D.; , "The implications of the electrogeometric model regarding effect of height of structure on the median amplitude of collected lightning strokes," *Power Delivery, IEEE Transactions on* , vol.4, no.2, pp.1450-1460, Apr 1989.

24. Haigh, S.J.; Hardwick, C.J.; , "The determination of induced voltage due to lightning with the aid of computer modelling," *Lightning and EMC, IEE Colloquium on* , vol., no., pp.4/1-4/7, 30 Jan 1996.

25. Nucci, C.A. Rachidi, F. “On the contribution of the electromagnetic field components in field-to-transmission line interaction “, *Electromagnetic Compatibility, IEEE Transactions on,* Nov 1995, Volume: 37 Issue: 4, page(s): 505 − 508.

26. Nucci, C.A.; , "The Lightning Induced Over-Voltage (LIOV) code," *Power Engineering Society Winter Meeting, 2000. IEEE* , vol.4, no., pp.2417-2418 vol.4, 2000.

27. Paolone, M. *Modeling of lightning induced voltages on distribution networks for the solution of power quality problems, and relevant implementation in a transient program*. Thesis, (PhD). University of Bologna. (2001)

28. Dommel, H., *Electromagnetic Transient Program Theory Book*, Oregon: Bonneville Power Administration. (1974)

29. A. K. Agrawal, H. J. Price, and S. H. Gurbaxani, “Transient response of multiconductor transmission lines excited by a nonuniform electromagnetic field,” *IEEE Trans. Electromagn. Compat., vol. EMC-22*, pp. 119–129, May 1980.

30. Ren, H.M.; Zhou, B.H.; Rakov, V.A.; Shi, L.H.; Gao, C.; Yang, J.H.; , "Analysis of Lightning-Induced Voltages on Overhead Lines Using a 2-D FDTD Method and Agrawal Coupling Model," *Electromagnetic Compatibility, IEEE Transactions on* , vol.50, no.3, pp.651-659, Aug. 2008.

31. Paolone, M.; Rachidi, F.; Borghetti, A.; Nucci, C.A.; Rubinstein, M.; Rakov, V.A.; Uman, M.A.; , "Lightning Electromagnetic Field Coupling to Overhead Lines: Theory, Numerical Simulations, and Experimental Validation," *Electromagnetic Compatibility, IEEE Transactions on* , vol.51, no.3, pp.532-547, Aug. 2009.

32. Peretto, L.; Rinaldi, P.; Sasdelli, R.; Tinarelli, R.; Fioravanti, A.; , "Implementation and Characterization of a System for the Evaluation of the Starting Instant of Lightning-Induced Transients," *Instrumentation and Measurement, IEEE Transactions on* , vol.56, no.5, pp.1955-1960, Oct. 2007.

33. Peretto, L.; Rinaldi, P.; Sasdelli, R.; Tinarelli, R.; , "A system for the measurement of the starting instant of impulsive transients [power systems]," *Instrumentation and Measurement Technology Conference, 2004. IMTC 04. Proceedings of the 21st IEEE* , vol.2, no., pp. 1394- 1398 Vol.2, 18-20 May 2004.

34. Xie, Y.; Xue, Y.; Chen, J.; Wang, H.; Xue, F.; , "Extensions of power system early-warning defense schemes by integrating wide area meteorological information," *Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 2011 4th International Conference on* , vol., no., pp.57-62, 6-9 July 2011.

35. Cummins, K.L.; Murphy, M.J.; , "An Overview of Lightning Locating Systems: History, Techniques, and Data Uses, With an In-Depth Look at the U.S. NLDN," *Electromagnetic Compatibility, IEEE Transactions on* , vol.51, no.3, pp.499-518, Aug. 2009.

36. Cummins, K.L.; Krider, E.P.; Malone, M.D.; , "The US National Lightning Detection Network™ and applications of cloud-to-ground lightning data by electric power utilities," *Electromagnetic Compatibility, IEEE Transactions on* , vol.40, no.4, pp.465-480, Nov 1998

37. Wu, Y.; Fan, C.; Li, Y.; Wang, B.; , "Design of Lightning Location System Based on Photon and Infrasound Detection," *Electronic Measurement and Instruments, 2007. ICEMI '07. 8th International Conference on* , vol., no., pp.1-603-1-606, Aug. 16 2007-July 18 2007.

38. Abidin, H.Z.; Ibrahim, R.; , "Thunderstorm day and ground flash density in Malaysia," *Power Engineering Conference, 2003. PECon 2003. Proceedings. National* , vol., no., pp. 217- 219, 15-16 Dec. 2003.

39. H. Ahmad, *Kilat dan Perlindungan*, Penerbitan UTM, 1998

40. M. P. Yahya, H. Ahmad and M. A. Alam, "Lightning Detection System in Malaysia." *National Technical Seminar on Standardisation and Development of Lightning Protection Technologies -Malaysian Environment*, PetalingJaya, Malaysia, 1996.

41. Hu, M.; Huang, X.; , "Lightning activity analysis and risk evaluation of transmission line," *Quality, Reliability, Risk, Maintenance, and Safety Engineering (ICQR2MSE), 2011 International Conference on* , vol., no., pp.158-161, 17-19 June 2011.

42. Diendorfer, G.; Schulz, W.; , "Ground flash density and lightning exposure of power transmission lines," *Power Tech Conference Proceedings, 2003 IEEE Bologna* , vol.3, no., pp. 3 pp. Vol.3, 23-26 June 2003.

43. Chen, S.M.; Du, Y.; Fan, L.M.; He, H.M.; Zhong, D.Z.; , "A lightning location system in China: its performances and applications," *Electromagnetic Compatibility, IEEE Transactions on* , vol.44, no.4, pp. 555- 560, Nov 2002.

44. Wang, D.; Yuan, T.; Zhang, G.; Zhang, T.; , "Fast electric field change pulses location technique," *Electromagnetic Compatibility (APEMC), 2010 Asia-Pacific Symposium on* , vol., no., pp.1158-1161, 12-16 April 2010.

45. Sattari, P.; Sheshyekani, K.; Hazrati, M.; Moini, R.; Sadeghi, S.H.H.; , "A TDOA-based approach for locating cloud-to-ground lightning strokes, using Taylor series expansion," *Electromagnetic Compatibility, 2006. EMC-Zurich 2006. 17th International Zurich Symposium on* , vol., no., pp.136-139, Feb. 27 2006-March 3 2006.

46. Hu, Z.X.; Wen, Y.P.; Zhao, W.G.; Zhu, H.P.; Liu, S.L.; , "Numerical Simulation of Lightning Location Based on Monte Carlo Method," *Management and Service Science, 2009. MASS '09. International Conference on* , vol., no., pp.1-4, 20-22 Sept. 2009.

47. Hu, Z.X.; Wen, Y.P.; Zhao, W.G.; Zhu, H.P.; , "Accuracy Analysis of the TDOA Method in a Lightning Location System," *Management and Service Science, 2009. MASS '09. International Conference on* , vol., no., pp.1-4, 20-22 Sept. 2009.

48. Orville, R.; Songster, H.; , "The East Coast Lightning Detection Network," *Power Delivery, IEEE Transactions on* , vol.2, no.3, pp.899-907, July 1987.

49. Tatsumi, M.; Idogawa, T.; Nakamura, S.; Higashi, S.; Sezaki, A.; Uenishi, K.; , "Lightning observation results by new LLS that uses LS8000 and CP8000," *Electromagnetic Compatibility (APEMC), 2010 Asia-Pacific Symposium on* , vol., no., pp.1150-1153, 12-16 April 2010.

50. Du, H.; Ma, H.; Zhang, Y.; , "A novel algorithm for real-time adaptive signal detection in lightning location system," *Information Science and Engineering (ICISE), 2010 2nd International Conference on* , vol., no., pp.1-4, 4-6 Dec. 2010.

51. Huang, Z.; Wang, X.; Chen, S.; Zhang, Y.; Dong, W.; Yin, Q.; , "Analysis on the induced overvoltage generated by near triggered lightning in the AWS power distribution system," *Electromagnetic Compatibility (APEMC), 2010 Asia-Pacific Symposium on* , vol., no., pp.1522-1525, 12-16 April 2010.

52. Silvino, J.L.; Mesquita, C.R.; Visacro, S.F.; , "Non-direct lightning current measurement for lightning location systems calibration," *Electronics Letters* , vol.39, no.6, pp. 504- 505, 20 March 2003.

53. Matsui, M.; Takano, N.; , "Evaluation of Lightning Location accuracy of JLDN with a lightning video camera system," *Electromagnetic Compatibility (APEMC), 2010 Asia-Pacific Symposium on* , vol., no., pp.1142-1145, 12-16 April 2010.

54. Abdul-Malek, Z.; Adzis, Z.; Aulia; Novizon; Abdullah, N.; , "Waveform and location analyses of localised lightning locating system," *High Voltage Engineering and Application (ICHVE), 2010 International Conference on* , vol., no., pp.132-135, 11-14 Oct. 2010.

55. Manoochehrnia, P.; Rachidi, F.; Rubinstein, M.; Schulz, W.; Diendorfer, G.; , "Benford's Law and Its Application to Lightning Data," *Electromagnetic Compatibility, IEEE Transactions on* , vol.52, no.4, pp.956-961, Nov. 2010.

56. Chowdhuri P., Li S., Yan P., ‘Review of research on lightning-induced voltages on an overhead line’*, Generation, Transmission and Distribution, IEE Proceedings*, Jan 2001, Volume: 148, Issue: 1 page(s) 91-95.

57. Kannu, P.D.; Thomas, M.J.; “Computation of lightning induced voltages on telecommunication subscriber lines”, *Electromagnetic Interference and Compatibility. Proceedings of the International Conference on*, 21-23 Feb. 2002 Page(s):79 - 83.

58. K Chrysanthou, C. Parente, M., ‘Data errors caused by surge voltages on paired-conductor lines’, *Power Delivery, IEEE Transactions*, Jan 2001, Vol 16, Issue: 1, pp 131-137.

59. Kannu, P.D.; Thomas, M.J.; “Lightning induced voltages on multiconductor power distribution line”, Generation, Transmission and Distribution, IEE Proceedings-, Volume 152, Issue 6, 4 Nov. 2005 Page(s):855 - 863.

60. Galvan, A.; Cooray, V.; Scuka, V.;, “Interaction of electromagnetic fields from cloud and ground lightning flashes with an artificial low-voltage power installation”, Electromagnetic Compatibility, IEEE Transactions on’ Volume 41, Issue 3, Aug. 1999 Page(s):250 – 257.

61. Rakov, V.A.; Rachidi, F.; , "Overview of Recent Progress in Lightning Research and Lightning Protection," *Electromagnetic Compatibility, IEEE Transactions on* , vol.51, no.3, pp.428-442, Aug. 2009.

62. Hoidalen, H.K.; Sletbak, J.; Henriksen, T.; , "Ground effects on induced voltages from nearby lightning," *Electromagnetic Compatibility, IEEE Transactions on* , vol.39, no.4, pp.269-278, Nov 1997.

63. Paulino, J.O.S.; Barbosa, C.F.; Lopes, I.J.S.; do Couto Boaventura, W.; , "An Approximate Formula for the Peak Value of Lightning-Induced Voltages in Overhead Lines," *Power Delivery, IEEE Transactions on* , vol.25, no.2, pp.843-851, April 2010.

64. Barbosa, C.F.; Paulino, J.O.S.; , "An Approximate Time-Domain Formula for the Calculation of the Horizontal Electric Field from Lightning," *Electromagnetic Compatibility, IEEE Transactions on* , vol.49, no.3, pp.593-601, Aug. 2007.

65. Baba, Y.; Rakov, V.A.; , "Voltages induced on an overhead wire by lightning strikes to a nearby tall grounded object," *Electromagnetic Compatibility, IEEE Transactions on* , vol.48, no.1, pp.212-224, Feb. 2006.

66. Rubinstein, M.; Uman,M. A.; “Methods for calculating the electromagnetic fields from a know source distribution: Aplication to lightning,” *IEEE transaction on Electromagnetic Compatibility,* vol. 31, May 1989.

67. Rubinstein, M.;, “An approximate formula for the calculation of the horizontal electric field from lightning at close, intermediate, and long range,” *IEEE Trans. Electromagn. Compat.*, vol. 38, pp. 531–535, Aug.1996.

68. Uman, M. A.;, “Lightning return stroke electric and magnetic fields,” J. Geophys. Res., vol. 90, pp. 6121–6130, 1985.

69. Rubinstein, M; Uman, M. A.;. “Methods for calculating the electromagnetic fields from a know source distribution: Aplication to lightning,” *IEEE transaction on Electromagnetic Compatibility,* vol. 31, May 1989.

70. Master, M.J.; Uman, M.A.; Beasley, W.H.; Darveniza, M.;, “Lightning induced voltages on power lines:Experiment,” *IEEE Trans. Power. App. Syst*., vol. 103,pp. 2519-2529, 1984.

71. Thottappillil, R.; Rakov, V.A.; “On the computation of electric fields from a lightning discharge in time domain,” *EMC. 2001 IEEE International Symposium on,* Volume 2, 13-17 Aug. 2001 Page(s):1030 - 1035 vol.2.

72. Nucci, C.A.; Rachidi, F.; Ianoz, M.; Mazzetti, C.; , "Comparison of two coupling models for lightning-induced overvoltage calculations," *Power Delivery, IEEE Transactions on* , vol.10, no.1, pp.330-339, Jan 1995.

73. Silveira, F.H.; Visacro, S.; , "On the Lightning-Induced Voltage Amplitude: First Versus Subsequent Negative Strokes," *Electromagnetic Compatibility, IEEE Transactions on* , vol.51, no.3, pp.741-747, Aug. 2009.

74. Sarkar, M.Z.I.; Ali, A.M.; , "Analysis of lightning induced electric field and its components on and above the lossy earth's surface by modified dipole technique," *TENCON '02. Proceedings. 2002 IEEE Region 10 Conference on*

Computers, Communications, Control and Power Engineering , vol.3, no., pp. 1893- 1896 vol.3, 28-31 Oct. 2002.

75. Siti Rabiatul Adawiyah, *Lightning Location from induced voltages: An experimental approach.* Thesis (BEng) Universiti Teknologi Malaysia, (2011)

76. Carson, J.R.;, “Wave propagation in overhead wires with ground return” Bell Systems Tech. Journal, Vol. 5. Pp539-554, 1926.

77. Aulia; Malek, Z. A.; Adzis, Z.; Novizon;, A New Localised Lightning Locating System Utilising Telecommunication Subscriber Line, *2ndIEEE International Conference on Power and Energy (PECon 08)*, December 1-3,2008, Johor Baharu, Malaysia

78. Taylor, C.; Satterwhite, R.; Harrison, C., Jr.; , "The response of a terminated two-wire transmission line excited by a nonuniform electromagnetic field," *Antennas and Propagation, IEEE Transactions on* , vol.13, no.6, pp. 987-989, Nov 1965.

79. Fink, D.G., Beaty, H.W., *Standard Handbook for Electrical Engineers. McGraw Hill Int. Edition.* (2000:14th Ed)

80. Le Vine, D. M., L. Gesell, and M. Kao (1986), Radiation From Lightning Return Strokes Over a Finitely Conducting Earth, *J. Geophys. Res.*, 91(D11), 11,897–11,908.

81. Rakov, V.A.; Uman, M.A.; , "Review and evaluation of lightning return stroke models including some aspects of their application," *Electromagnetic Compatibility, IEEE Transactions on* , vol.40, no.4, pp.403-426, Nov 1998.

82. Hoidalen, H.K.; Sletbak, J.; Henriksen, T.; , "Ground effects on induced voltages from nearby lightning," *Electromagnetic Compatibility, IEEE Transactions on* , vol.39, no.4, pp.269-278, Nov 1997.

83. Rubinstein, M.; Romero, C.; Rachidi, F.; Rubinstein, A.; Vega, F.; , "A two-station lightning location method based on a combination of difference of time of arrival and amplitude attenuation," *Electromagnetic Compatibility*

(APEMC), 2010 Asia-Pacific Symposium on , vol., no., pp.1154-1157, 12-16 April 2010.

84. Hoidalen, H.K.; , "Analytical formulation of lightning-induced voltages on multiconductor overhead lines above lossy ground," *Electromagnetic Compatibility, IEEE Transactions on* , vol.45, no.1, pp. 92- 100, Feb 2003.

85. Ibrahim, W.I.; Ghazali, M.R.; Ghani, S.A.; Malek, Z.A.; , "Measurement of vertical Electric fields from lightning flashes using parallel plate antenna," *Electrical, Control and Computer Engineering (INECCE), 2011 International Conference on* , vol., no., pp.466-471, 21-22 June 2011.

86. Rubinstein, M.; Romero, C.; Rachidi, F.; Rubinstein, A.; Vega, F.; , "A two-station lightning location method based on a combination of difference of time of arrival and amplitude attenuation," *Electromagnetic Compatibility (APEMC), 2010 Asia-Pacific Symposium on* , vol., no., pp.1154-1157, 12-16 April 2010.