UNIVERSITI PUTRA MALAYSIA

FORMULATION OF HYBRID FINITE-DIFFERENCE TIME-DOMAIN DIPOLE METHOD FOR LIGHTNING INDUCED VOLTAGE DUE TO LIGHTNING STRIKES TO TALL STRUCTURE

NORHIDAYU RAMELI

FORMULATION OF HYBRID FINITE-DIFFERENCE TIME-DOMAIN DIPOLE METHOD FOR LIGHTNING INDUCED VOLTAGE DUE TO LIGHTNING STRIKES TO TALL STRUCTURE

By

NORHIDAYU RAMELI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

July 2017

Dedicated to my husband, son and family

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

FORMULATION OF HYBRID FINITE-DIFFERENCE TIME-DOMAIN DIPOLE METHOD FOR LIGHTNING INDUCED VOLTAGE DUE TO LIGHTNING STRIKES TO TALL STRUCTURE

By

NORHIDAYU RAMELI

July 2017

Chairman : Mohd. Zainal Abidin Ab.Kadir, PhD PEng CEng
Faculty : Engineering

Lightning cloud delivers a certain amount of charge from the cloud to the earth and may affects power lines either directly or indirectly. In this case of an indirect strike, the coupling between the lightning electromagnetic field and nearby power lines causes a voltage to be induced on the power line. As far as the structure height is concerned, the higher the tower, the greater the chances of it being struck by lightning, which will result in higher induced voltage on the power line compared to the case of a strike to the ground. Consequently, such induced voltage outages and electromagnetic field may cause damage to any equipment exceed as its withstanding capability. Therefore, a proper study needs to be carried out to calculate the lightning electromagnetic field due to the lightning strike to a tall structure in which lightning induced voltages on distribution power line are created due to the lightning electromagnetic field coupling. In this study, the IEEE 1410-2010 guideline was followed to implement the stages of calculating induced voltage, namely, return stroke current, calculating the lightning electromagnetic field and evaluating the interaction of lightning electromagnetic field with the conductor line. For the stages of return stroke current, a model of DU current function as well as the engineering model which based on a distributed source representation were selected. The return stroke current was investigated based on effect of ground reflection factor, in which the effect of soil resistivity and grounding electrode arrangement were included. A new formulation of Hybrid FDTD-Dipole were proposed to calculate the lightning electromagnetic field. This method provide a straightforward formulation which is applicable to any current calculation and able to couple with the line conductor in evaluating the induced voltage. The proposed method was compared with the lightning electromagnetic field measurements at Peissenberg tower, German. Then, the Agrawal model was adopted to evaluate the induced voltage on the power line due to the lightning strike to a tall structure, in which Fukui thermal tower, Japan was used for the validation. The determination of the critical distance between the stricken tall structure and the overhead distribution line at Tanjung Rompin, Pahang, Malaysia was obtained where the results indicated that at least more than 10% reduction of the return stroke current was affected by the changes of ground reflection factor based on the relationship between the

soil resistivity and grounding electrode arrangement. Consequently, it also affected the lightning electromagnetic field evaluation, as well as reducing the lightning induced voltage peak by at least 20%. Besides that, the proposed method showed a good agreement with measured values. Lastly, the critical distance obtained showed that the higher the magnitude of lightning current, the longer the distance from a tall tower to the line will be exposed to the induced voltage flashover. Thus, the outcomes of these results may provide very useful information and enhance judgement skills for an electrical power engineer when considering the protection scheme of distribution systems where the lightning induced voltage is the major cause of line outages and affected the overall performance of the system.

Abstrak tesis yang dikemukan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

FORMULASI KAEDAH HIBRID PERBEZAAN TERHINGGA DOMAIN MASA DIPOLE BAGI VOLTAN TERARUH KILAT DISEBABKAN OLEH PANAHAN KILAT PADA STRUKTUR TINGGI

Oleh

NORHIDAYU RAMELI

Julai 2017

Pengerusi : Mohd. Zainal Abidin Ab.Kadir, PhD PEng CEng
Fakulti : Kejuruteraan

Kilat boleh menyampaikan sejumlah caj dari awan ke bumi dan memberi kesan pada talian kuasa samaada secara langsung atau tidak langsung. Dalam kes kilat secara tidak langsung, gandingan antara medan elektromagnet kilat dan talian kuasa berhampiran menyebabkan voltan teraruh pada talian kuasa. Dengan ketinggian struktur berkenaan, didapati lebih tinggi struktur atau menara, lebih besar peluang untuk disambar kilat, yang mana, ianya akan menghasilkan voltan teraruh yang lebih tinggi pada talian kuasa berbanding dengan kes panahan kilat ke tanah. Oleh itu, gangguan voltan teraruh dan medan elektromagnet kilat boleh menyebabkan kerosakan pada peralatan di mana melebihi keupayaan ketahanan peralatan ini. Oleh itu, kajian yang sewajarnya perlu dijalankan untuk mengira medan electromagnet kilat yang disebabkan oleh panahan kilat pada struktur tinggi di mana voltan teraruh pada talian kuasa pembahagian terhasil disebabkan oleh gandingan medan electromagnet kilat. Dalam kajian ini, garis panduan IEEE 1410-2010 diikuti untuk melaksanakan peringkat pengiraan voltan teraruh, iaitu arus sambaran kembali, mengira medan elektromagnet kilat dan menilai interaksi medan elektromagnet kilat dengan garis konduktor. Bagi peringkat arus sambaran kembali, fungsi arus DU model dan juga kejuruteraan model berdasarkan perwakilan pembahagian sumber dipilih. Arus sambaran kembali disiasat berdasarkan faktor refleksi tanah di mana kesan kerintangan tanah dan susun asas elektrod pembumian telah diperkenalkan. Satu formulasi baru iaitu kaedah Hibrid Perbezaan Terhingga Domain Masa-Dipole dicadangkan untuk mengira electromagnet kilat. Kaedah in menyediakan formulasi yang mudah, bersesuaian untuk digunakai dengan mana-mana arus pengiraan dan dapat berinteraksi dengan garis konduktor untuk menilai voltan teraruh. Kaedah yang dicadangkan telah dibandingkan dengan pengukuran medan electromagnet kilat di menara Peissenberg, Jerman. Kemudian, model Agrawal digunapakai untuk menilai voltan teraruh pada talian kuasa disebabkan oleh panahan kilat pada struktur tinggi di mana menara haba Fukui, Jepun digunakan untuk kesahihan. Penentuan jarak kritikal antara struktur tinggi dan talian kuasa diperolehi di Tanjung Rompin, Pahang, Malaysia. Hasilnya menunjukkan bahawa pengurangan sekurang-kurangnya lebih daripada 10% arus sambaran kembali terjejas oleh perubahan faktor refleksi tanah berdasarkan

hubungan antara kerintangan tanah dan susunan asas elektrod pembumian. Oleh itu, ia juga memberi kesan pada penilaian medan electromagnet kilat, dan juga pengurangan voltan teraruh kilat puncak sekurang-kurangnya 20%. Selain itu, formulasi baru yang dicadangkan menunjukkan hasil pengesahan yang tepat dengan hasil nilai ukuran. Akhir sekali, jarak kritikal yang diperolehi menunjukkan bahawa semakin tinggi magnitud arus kilat, semakin jauh jarak dari menara yang tinggi ke talian kuasa akan terdedah kepada voltan teraruh lampau. Oleh itu, hasil keputusan ini memberi maklumat yang berguna dan meningkatkan kemahiran penghakiman bagi jurutera elektrik kuasa apabila mempertimbangkan skim perlindungan bagi sistem talian pembahagian kuasa di mana voltan teraruh adalah punca utama gangguan talian yang memberi kesan kepada prestasi keseluruhan system.

ACKNOWLEDGEMENT

All praise is to supreme almighty Allah S.W.T, the only creator, sustainer and efficient assembler of the world and galaxies whose blessings and kindness have enabled to me to accomplish this thesis successfully.

I would like to express my most gratitude to my supervisor, Prof. Ir. Dr. Mohd Zainal Abidin Ab Kadir for his help and support, a great motivation and ideas. Without his guidance, this thesis would not be able to be completed.

Also, I would like to express the appreciation to Prof. Dr. Chandima and Dr. Norhafis Azis for his opinion, comments and suggestion regarding this thesis. Also, is much thankful to Dr Mahdi Izadi for their guidance throughout the work.

Last but not least, I also would like to express a very thankful and grateful to my husband and son, Mohd Zulfahmi Mohd Yusoff and Muhammad Amin Zulhaily, family and friends for their spiritual and moral support, understanding and cooperation during the earnings of this thesis.

I certify that a Thesis Examination Committee has met on 31 July 2017 to conduct the final examination of Norhidayu binti Rameli on her thesis entitled "Formulation of Hybrid Finite-Difference Time-Domain Dipole Method for Lightning Induced Voltage Due to Lightning Strikes to Tall Structure" 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 Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Mohd Amran bin Mohd Radzi, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Wan Fatinhamamah binti Wan Ahmad, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Jasronita binti Jasni, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Farhad Rachidi, PhD
Professor
Swiss Federal Institute of Technology
Switzerland
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 28 September 2017

This thesis was submitted to senate of Universiti Putra Malaysia and has been accepted as fulfilment of requirement for degree of Doctor of Philosophy. Members of the Supervisory Committee were as follows:

Mohd Zainal Abidin Ab Kadir, PhD, PEng, CEng
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Gorakanage Arosha Chandima Gomes, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Norhafiz Azis, PhD
Senior Lecture
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mahdi Izadi, PhD
Research Fellow
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ________________________ Date: __________________

Name and Matric No: Norhidayu Binti Rameli, GS 37846

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003(Revision 2012-2013) are adhered to.

Signature: ____________________
Name of Chairman
of Supervisory
Committee: Mohd Zainal Abidin Ab Kadir

Signature: ____________________
Name of Member
of Supervisory
Committee: Gorakanage Arosha Chandima Gomes

Signature: ____________________
Name of Member
of Supervisory
Committee: Norhafiz Azis

Signature: ____________________
Name of Member
of Supervisory
Committee: Mahdi Izadi

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BG	Bruce-Golde
BIL	Basic Insulation Level
CFO	Critical Flash Over
DU	Diendorfer Uman
FDTD	Finite Difference Time Domain
GRF	Ground Reflection Factor
LEMF	Lightning Electromagnetic Field
LIOV	Lightning Induced Over-Voltage
LIV	Lightning Induced Voltage
MoM	Method of Moment
MTLE	Modified Transmission Line with Exponential Decay
MTLL	Modified Transmission Line Linear
NCBC	New Channel Base Current
RS	Rolling Sphere
TCS	Travelling Current Source
TL	Transmission Line
TRF	Top Reflection Factor

LIST OF NOTATIONS

A	Area of dimension grid
a	Diameter of rod
a_r	Rolling sphere radius
B^s	Scattered magnetic field
B^i	Incident magnetic field
c	Speed of light
C'	Capacitor per step distance
d	Space distance between rods
E^s	Scattered electric field
E^i	Incident electric field
H	Height of lightning channel
h_d	Observation point height
h_s	Dept of soil
h_t	Height of tower
I_p	Peak of current
i_{first}	Lightning current first return stroke
i_o	Amplitude current for channel base current function
i_{subs}	Lightning current subsequent return stroke
k	Step distance along the power line
L_h	Length of horizontal rod
L_v	Length of vertical rod
L'	Inductor per step distance
N	Number of meshes in grid
n_r	Number of rods
n	Exponent value range 2~10
R	Distance from z' to observation point
r	Radial distance from tower to observation point
u^s	Scattered voltage
u^i	Incident voltage
v	Lightning return stroke velocity
x	Observation point
z_g	Ground impedance
z_t	Tower impedance
z'	Position height along the lightning channel
z'_{real}	Position height along the lightning channel with real lightning
z'_{image}	Position height along the lightning channel with image lightning
γ_g	Ground reflection factor
γ_t	Top reflection factor
Δt	Time step
Δx	Step distance along the power line
η	Amplitude correction factor
ρ	Soil resistivity
r_2	Decay time constant
r_1	Front time constant

CHAPTER 1

INTRODUCTION

1.1 Background

Lightning circumstance leads to disturbance or damage to objects on the earth. The possibilities lightning strike are either a direct strike to the object or an indirect strike to the surrounding ground surface area in the vicinity of the object. The lightning strike leads to the phenomenon of lightning induced voltage (LIV) or lightning induced overvoltage (LIOV) on an object which is located near the point of a lightning strike.

Today, the level of the lightning phenomenon has increased probably due to climate change. This situation causes lightning to represent a major contribution in the damage and disturbance that occurs to an object when it suffers from either a direct or indirect lightning strike. This may require the utility companies to pay great attention since such incidents can cause interruptions to systems, as well as have destructive effects on electrical equipment. It also causes economic loss when it becomes necessary to repair and replace equipment. There is also the possibility of having to pay compensation, penalties and fines to customers and/or regulatory authorities for damages incurred. Moreover, most researchers appear to agree that the performance of overhead distribution power lines will be affected by the influence of LIV [1]. As reported by Busrah [2], at least 35% of distribution power lines in Malaysia have been damaged by the effect of lightning and at least 32% of electronic devices have been damaged due to surge overvoltage. Also, in Malaysia, the breakdown statistics for medium voltage distribution power lines show at least 27% of faults were due to lightning events. In [3], it is reported that lightning was striked to the Telecom Malaysia towers, in which lead to the breakdown of the power line in residential houses, damage of wiring system and disruption of communication systems.

Furthermore, LIV on a distribution power lines can be expected to produce higher values of voltage due to the effect of a lightning strike on a nearby tall tower. Previous reseachers agree that the LIV created by the LEMF interaction with the conductor line is estimated to increase by at least 50% to 80% [4, 5]. In addition, with the presence of a tall tower at a flat ground surface and a tower height of more than 100 m, the tall tower has a higher chance of being struck by lightning [6-8]. This is due to the height of the tower itself that produces a large electric field at the top, so that upward connecting leaders from the tower will start earlier than the surrounding ground, and thus an attachment with the stepped leader of the lightning could be easily appeared [9, 10]. Thus, with the higher voltages that are created at the line and the frequency at which it is struck by lightning, the distribution power line is vulnerable to this lightning event. Consequently, users may be inconvenienced by such lightning-induced voltage outages. Also, it may cause damage to the equipment's due to the voltage exceeding from equipment withstanding capability. Therefore, the study of the interaction of lightning with tall towers on nearby distribution power lines becomes very important in order to avoid the possibility of damage to the lines. Also, it would be beneficial to the utility companies to build a new distribution line when faced with the presence of a tall tower in the surrounding area.

1.2 Problem Statement

Various studies have been undertaken to evaluate the LIV on objects caused by a direct lightning strike to a tall tower, either through measurement or simulation work. Measurement work was started by Yokohama et al. [11-13] and later on by Michishita et al. [14], in which, the LIV is characteristically measured based on the termination point along the power line. It has been found that, the LIV has a positive waveform for the closest distance and a negative waveform for far distances of the termination point. On the other hand, for the simulation work, various studies have mostly focused on the method of LEMF calculation, LIV, as well as investigating the parameter influence of LIV at the power line. It should be noted that, the simulation work in LIV determination requires several stages. It includes the stages of lightning return stroke current, the calculating of LEMF at several points of power lines as well as the calculation of LIV through the implementation of field-to-transmission line coupling model as documented in [15-20].

Furthermore, in order to calculate the LIV with the presence of a tall tower in the vicinity, the field-to-transmission line coupling models are proposed [10, 21-23]. The extended Rusck model which takes into account the presence of the tall tower is introduced [21-22]. The result indicates that the simulated works are in good agreement with the measure one in [14]. In addition, the parameters of the tower height and the current front time influence the LIVs on the distribution power line. It indicates that the LIVs have an increasing trend for the increases of tower height at the current front time reduction. However, they do not consider the reflection tower.

Moreover, the method of the 3D-FDTD was used to evaluate the LIV [10]. The simulated result showed good agreement with the measured ones and also, they found that LIVs were increased at the closest distance from the tall tower and according to the tower height [14]. Also, the LIVs experienced with the increasing trend at the highest and lesser value of reflection factors and lightning current front time, respectively. The study also indicated that the LIV with respect to the presence of the tall tower is able to produce the higher voltages compared to the LIV that strikes to the ground. However, the 3D-FDTD methods may consume memory storage, in which case, the grid meshes and discretization simulation are considered.

Later, the Hybrid Electromagnetic Circuit (HECM) model was proposed to evaluate the LIV [23]. The HECM method was developed by the current source among the Resistance, Inductance and Capacitance (RLC) components, with each one of them presented by a source of transversal and longitudinal currents [24]. They found that their approach was in good agreement with the measured one. However, their model was strictly in frequency domain and the inverse Laplace transform solution was used to transform it into the time domain.

In addition, in order to calculate the LIV with the presence of a tall tower, the LEMF approach and the field-to-transmission line coupling model was adopted [14-15, 25]. As shown by Michishita et al. [14], the LEMF approach was expressed through the Norton approximation and the LIVs described by the Agrawal model. They found that the LIVs were influenced by the finite ground conductivity at the farther end of the tall tower. Then, the 2D-FDTD method employed for determination of LEMF and the Agrawal model to generate the LIV [15]. The results indicated that the LIV depended on the ground conductivity, influenced to a certain extent by the return stroke speed and independent of the return stroke model. Finally, the simulated works were expended to evaluate the other parameter influence on the LIV such as the frequency dependent soil [25]. They concluded that the frequency dependent soil parameter was able to reduce the peak of the LIV. From the previous studies, most of the results were computed for the close distance range, which took into account the impact of ground conductivity [14-15, 25]. However, the ground conductivity can be neglected for distances of less than 2 km [26-27]. Although many studies have been undertaken in this area to date, more studies need to be conducted in terms of:

1. the reflected current due to the effect of ground reflection factor.
2. the computational method that needs to be accurate.
3. availability of the standard to determine the critical distance due to the lightning strike to a tall structure.

Therefore, these limitation are addressed in this work. It is identified as being of importance to electrical power engineers when considering a protection scheme for an electrical system since the LIV is recognised as a major cause of line outage which severely affects the overall performance of a system.

1.3 Objectives

The aim of this work is to formulate the lightning induced voltage due to lightning strikes to a tall structure. As such, in order to achieve this aim, a few objectives are set as:

1. To investigate the effect of ground reflection factor on the relationship of soil resistivity and the grounding arrangement of the tall tower on the lightning currents, LEMF and LIV.
2. To propose a hybrid formulation of FDTD and a dipole method for solving lightning electromagnetic field due to a tall tower, taking into account the charge position along the channel.
3. To evaluate the lightning induced voltage at distribution power line due to lightning strikes of a nearby tall tower.
4. To obtain the critical distance on lightning induced voltage flashover between a tall tower and distribution power line.

1.4 Scope of Work

This work has some limitations in order to achieve the following objectives:

1. It is assumed that the single lightning channel without branches strikes the tower vertically with the constancy of the return stroke velocity and disregarding any upward connecting leader.
2. The tower is assumed to be a uniform tower where the propagation speed along the tower is the speed of light and the tower reflection coefficient is frequency-independent.
3. The surface of the ground is assumed to be flat with perfect ground conductivity.

1.5 Thesis Organisation

This thesis comprises five chapters. Chapter 1 as an introduction to the thesis includes an overview, followed by the problem statement regarding the gap in the literature on this subject area. It includes also the objectives and the scope of the work.

A review of the available literature is presented in Chapter 2. This covers the procedures for determining the induced voltage as an effect of a direct lightning strike on a tall tower.

Chapter 3 is devoted to an explanation of the methodology adopted to conduct the work and meet its objectives. The chapter explains the development of an algorithm for the calculation of the lightning induced voltage (LIV) resulting from a direct lightning strike on a tall tower. Also, attention is paid to the validation work of the algorithm with measured work.

In Chapter 4, results are analysed and discussed with a consideration of limitation from previous works. Finally, Chapter 5 concludes this thesis and gives recommendations for future work.

REFERENCES

[1] IEEE Std 1410-2010, IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines.

[2] S. Mohd Busrah, TNB Research, Malaysia, 2008.

[3] R. A. Hamid, "Bahaya Menara Telekomunikasi," in *Utusan Malaysia*, ed. Melaka, 25 August 2009.

[4] W. Janischewskyj, A. M. Hussein, V. Shostak, I. Rusan, J-X.U and J-S. Chang, "Statistics of Lightning Strikes to the Toronto Canadian National Tower (1978-1995)," *IEEE Transactions on Power Delivery*, vol. 12, pp. 1210-1221, 1997.

[5] V. A. Rakov, "Transient Response of a Tall Object to Lightning," *IEEE Transactions on Electromagnetic Compatibility*, vol. 43, pp. 654-661, 2001.

[6] V. Cooray, An Introduction to Lightning: *Springer*, 2015.

[7] V. A. Rakov and M. A. Uman, Lightning Physics and Effects; *Cambridge University Press*, 2003.

[8] G. Vendeville, "At the CN Tower, Lightning Strikes Twice — and Again, and Again," in *Toronto Star*, ed. Canada, 24 June 2015.

[9] A. Piantini and J. M. Janiszewski, "Induced Voltages on Distribution Lines due to Lightning Discharges on Nearby Metallic Structures," *IEEE Transactions on Magnetics*, vol. 34, pp. 2799-2802, 1998.

[10] Y. Baba and V. A. Rakov, "Voltages Induced on an Overhead Wire by Lightning Strikes to a Nearby Tall Grounded Object," *IEEE Transactions on Electromagnetic Compatibility*, vol. 48, pp. 212-224, 2006.

[11] S. Yokoyama, K. Miyake, H. Mitani and A. Takanishi, "Simultaneous Measurement of Lightning Induced Voltages with associated Stroke Currents," *IEEE Transactions on Power Apparatus and Systems*, vol. 8, pp. 2420-2429, 1983.

[12] S. Yokoyama, K. Miyake and S. Fuki, "Advanced Observations of Lightning Induced Voltage on Power Distribution Lines," *IEEE Transactions on Power Delivery*, vol. 1, pp. 129-139, 1986.

[13] S. Yokoyama, K. Miyake and S. Fuki, "Advanced Observations of Lightning Induced Voltage on Power Distribution Lines. II," *IEEE Transactions on Power Delivery*, vol. 4, pp. 2196-2203, 1989.

[14] K. Michishita, M. Ishii, A. Asakawa and K. Kami, "Voltage Induced on a Test Distribution Line by Negative Winter Lightning Strokes to a Tall Structure," *IEEE Transactions on Electromagnetic Compatibility*, vol. 45, pp. 135-140, 2003.

[15] H.-M. Ren, B-H. Zhou, V. A. Rakov, L-H. Shi, C. Gao and J-H. Yang, "Analysis of Lightning-Induced Voltages on Overhead Lines Using a 2-D FDTD Method and Agrawal Coupling Model," *IEEE Transactions on Electromagnetic Compatibility*, vol. 50, pp. 651-659, 2008.

[16] S.Rusck, " Induced Lightning Overvoltages on Power Trasmission Lines with Special Reference to the Over-voltage Protection of Low Voltage Network," Transactions Research Instituition Technology, Stockholm, Sweeden, no. 120, pp1-118, 1958.

[17] C. Taylor and C. Harrison, "The Response of a Terminated Two-Wire Transmission Line Excited by a Nonuniform Electromagnetic Field," *IEEE Transactions on Antennas and Propagation*, vol. 13, pp. 987-989, 1965.

[18] A. K. Agrawal, H. J. Price and S. H. Gurbaxani, "Transient Response of Multiconductor Transmission Lines Excited by a Nonuniform Electromagnetic Field," *IEEE Transaction Electromagnetic Compatibility*, vol.EMC-22, no.3, pp. 119-129, May,1980.

[19] F. Rachidi, "Formulation of the Field-To-Transmission Line Coupling Equations in Terms of Magnetic Excitation Field," *IEEE Transactions on Electromagnetic Compatibility*, vol. 35, pp. 404-407, 1993.

[20] C. Nucci, F. Rachidi, M. Ianoz and C. Mazzetti, "Comparison of Two Coupling Models for Lightning-Induced Overvoltage Calculations," *IEEE Transactions on Power Delivery*, vol. 10, pp. 330-339, 1995.

[21] A. Piantini and J. M. Janiszewski, "Induced Voltages on Distribution Lines due to Lightning Discharges on Nearby Metallic Structure, " *IEEE Transaction on Magnetics*, vol. 34, no.5, Sep.1998.

[22] A. Piantini and J. M. Janiszewski, "An Improved Model for Lightning Induced Voltages Calculations," *IEEE/PES Transmission & Distribution Conference &Exposition*, Latin, America, 2004.

[23] P. Yutthagowith, A. Ametani, N. Nagaoka and Y. Baba, "Lightning-Induced Voltage Over Lossy Ground by a Hybrid Electromagnetic Circuit Model Method with Cooray-Rubinstein Formula," *IEEE Transaction on Electromagnetic Compatibility*, vol. 51, no. 4, Nov. 2009.

[24] F. H. Silveira, S. Visacro, J. Herrera and H. Torres, "Evaluation of Lightning-Induced Voltages Over Lossy Ground by the Hybrid Electromagetic model," *IEEE Transaction Electromagnetic Compatibility*, vol.51, no. 1, pp. 156-160, Feb. 2009.

[25] Q. Zhang, Y. Chen and W. Hou, "Lightning-Induced Voltages Caused by Lighting Strike to Tall Objects Considering the Effect of Frequency Dependent Soil," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 133, pp. 145-156, 2015.

[26] F. Rachidi, C. A. Nucci, M. Ianoz, and C. Mazzetti, "Influence of Lossy Ground on Lightning Induced Voltages on Overhead Lines," *IEEE Transaction Electromagnetic Compatibility*, vol. 38, no. 3, pp. 250-264, Aug.1996.

[27] V. Rakov, Lightning Electromagnetic; Modelling Lightning Strikes to Tall Towers, *IET Pub*, 2015.

[28] F. Heidler, Z. Flisowski, W. Zischank, Ch. Bouquegneau and C. Mazzetti, "Parameters of Lightning Current Given in IEC 62305-Background, Experience and Outlook," in *International Conference on Lightning Protection (ICLP)*, Uppsala, Sweden, June 23-26, 2008.

[29] V. Rakov., "Lightning Phenomenology and Parameters Important for Lightning Protection," in *International Symposium on Lightning Protecxtion (IX SIPDA)*, Foz do Iguacu, Brazil, Nov 26-30, 2007.

[30] C. Mazzetti," Lightning Physics and Lightning Protection:State of Art 2013", Warsaw University of Technology, Roma, Oct.2013.

[31] CIGRE," Lightning Parameters for Engineering Application," *Working Group C4.407*, August 2013.

[32] V. A. Rakov and F. Rachidi, "Overview of Recent Progress in Lightning Research and Lightning Protection," *IEEE Transactions on Electromagnetic Compatibility*, vol. 51, pp. 428-442, 2009.

[33] F. Rachidi, "The Quandary of Direct Measurement and Indirect Estimation of Lightning Current Parameters," *Impulse*, vol. 7, p. 11, 2004.

[34] S. Guerrieri, F. Heidler, C. A. Nucci, F. Rachidi and M. Rubinstein, "Extension of Two Return Stroke Models to Consider the Influence of Elevated Strike Objects on the Lightning Return Stroke Current and the Radiated Electromagnetic Field: Comparison with Experimental Results," in *Proceedings of International Symposium on Electromagnetic Compatibility*, 1996.

[35] A. Hussein,W. Janischeskyj, M. Milewski, V. Shostak, F. Rachidi and J.S. Chang, "Comparison of Current Characteristics of Lightning Strokes Measured at the CN Tower and at Other Elevated Objects," in *IEEE International Symposium on Electromagnetic Compatibility*, pp. 495-500, 2003,.

[36] A. Asakawa, K. Miyake, S. Yokoyama, T. Shindo, T. Yokota and T. Sakai, "Two Types of Lightning Discharges to a High Stack on the Coast of the Sea of Japan in Winter," *IEEE Transactions on Power Delivery*, vol. 12, pp. 1222-1231, 1997.

[37] F. Heidler, "Lightning Currents Measured at a Telecommunication Tower from 1992 to 1998," in *International Zurich Symposium on Electromagnetic Compatibility*, Zurich, Switzerland,Feb 20-21, 2001.

[38] G. Diendorfer, "LLS Performance Validation Using Lightning to Towers," *Impulse,* vol. 1, p. 11, 2010.

[39] A. M. Hussein, W. Janischewskyj, J-S. Chang, V. Shostak, W.A Chisholm, P. Dzurevych and Z-I. Kawasak, "Simultaneous Measurement of Lightning Parameters for Strokes to the Toronto Canadian National Tower," *Journal of Geophysical Research: Atmospheres (1984–2012),* vol. 100, pp. 8853-8861, 1995.

[40] A. Mosaddeghi, D. Pavanello, F. Rachidi and M. Rubinstein, "Electric and Magnetic Fields at Very Close Range From a Lightning Strike to a Tall Object," in *Asia-Pacific Symposium on Electromagnetic Compatibility(APEMC),* Singapore, May 19-23, 2008.

[41] S. A. Mosaddeghi, "Electromagnetic Enviroment Associated with Lightning Strikes to Tall Strike Objects," PhD, Ecole Polytechnique Federale De Lausanne, Suisse, 2011.

[42] N. M. Hatta, "Fault Analysis and Lightning Location System," Lightning Detection System Lab, Tenaga Nasional Berhad, Malaysia, Jan 2014-Dec, 2015.

[43] C. Nucci, G. Diendorfer, M. A. Uman, F. Rachidi, M. Ianoz and C. Mazzetti, "Lightning Return Stroke Current Models with Specified Channel-Base Current: A Review and Comparison," *Journal of Geophysical Research: Atmospheres (1984–2012),* vol. 95, pp. 20395-20408, 1990.

[44] C. A. Nucci, F. Rachidi, M. Ianoz and C. Mazzetti, "Lightning-Induced Voltages on Overhead lines," *IEEE Transactions on Electromagnetic Compatibility,* vol. 35, pp. 75-86, 1993.

[45] P. D. Kannu and M. J. Thomas, "Influence of Lightning Electric Field Components on the Induced Voltages on a Power Distribution Line," *Electric Power Systems Research,* vol. 64, pp. 247-255, 2003.

[46] C. E. R. Bruce and R.H.Golde," The Lightning Discharge," *Institute Electrical and Electric Engineering,* vol. 2, pp. 88, 1941

[47] G. Diendorfer and M. Uman, "An Improved Return Stroke Model with Specified Channel-Base Current," *Journal of Geophysical Research: Atmospheres (1984–2012),* vol. 95, pp. 13621-13644, 1990.

[48] C. Nucci and F. Rachidi, "Lightning-Induced Voltages on Overhead Power Lines. Part I: Return Stroke Current Models with Specified Channel-Base Current for the Evaluation of the Return Stroke Electromagnetic Fields," 1995.

[49] Y. Chen and L. Wang, "Research on Channel-Base Current of Lightning Return Stroke," in *Second International Conference on Mechanic Automation and Control Engineering (MACE),* pp. 7579-7582, 2011.

[50] V. Javor, "New Function for Representing IEC 61000-4-2 Standard Electrostatic Discharge Current," *Facta Universitatis*, *Series: Electronics and Energetics*, vol. 27, pp. 509-520, 2014.

[51] F. Rachidi, V. A. Rakov, C. A. Nucci and J. L. Bermudez, "Effect of Vertically Extended Strike Object on the Distribution of Current along the Lightning Channel," *Journal of Geophysical Research: Atmospheres (1984–2012),* vol. 107, pp. ACL 16-1-ACL 16-6, 2002.

[52] Y. Baba and V. A. Rakov, "On the Use of Lumped Sources in Lightning Return Stroke Models," *Journal of Geophysical Research: Atmospheres (1984–2012),* vol. 110, 2005.

[53] F. Rachidi, "Modeling Lightning Return Strokes to Tall Structures: Recent Developments," in *VIII International Symposium on Lightning Protection,* Sao Paulo, Brazil, Nov 21-25, 2005.

[54] Y. Baba and V. A. Rakov, "Lightning Electromagnetic Environment in the Presence of a Tall Grounded Strike Object," *Journal of Geophysical Research: Atmospheres (1984–2012),* vol. 110, 2005.

[55] S. Guerrieri, C. A. Nucci, F. Rachidi and M. Rubinstein, "On the Influence of Elevated Strike Objects on Directly Measured and Indirectly Estimated Lightning Currents," *IEEE Transactions on Power Delivery*, vol. 13, pp. 1543-1555, 1998.

[56] F. Rachidi, W. Janischewskyj, A. M. Hussein, C. A. Nucci, S. Guerrieri, B. Kordi and J-S. Chang, "Current and Electromagnetic Field Associated with Lightning-Return Strokes to Tall Towers," *IEEE Transactions on Electromagnetic Compatibility,* vol. 43, pp. 356-367, 2001.

[57] D. Pavanello, F. Rachidi, V. A. Rakov, C. A. Nucci and J. L. Bermudez, "Return Stroke Current Profiles and Electromagnetic Fields Associated with Lightning Strikes to Tall Towers: Comparison of Engineering Models," *Journal of Electrostatics,* vol. 65, pp. 316-321, 2007.

[58] A. Mosaddeghi, A. Shoory, F. Rachidi, M. Rubinstein and G. Diendorfer, "Lightning Return Strokes to Tall Towers: Ability of Engineering and Electromagnetic Models to Reproduce Nearby Electromagnetic Fields," *IEEE Transactions on Electromagnetic Compatibility,* vol. 54, pp. 889-897, 2012.

[59] D. Pavanello, F. Rachidi, W. Janischewskyj, M. Rubinstein, A. M. Hussein, E. Petrache, V. Shostak, I. Boev, C. A. Nucci, W. A. Chisholm, M. Nyffeler, J. S. Chang, and A. Jaquier, "On Return Stroke Currents and Remote Electromagnetic Fields Associated with Lightning Strikes to Tall Structures: 2. Experiment and Model Validation," *Journal of Geophysical Research: Atmospheres (1984–2012)*, vol. 112, 2007.

[60] V. A. Rakov and M. Uman, " Review and Evaluation of Lightning Return Stroke Models including Some Aspects of Their Application," *IEEE Transaction Electromagnetic Compatibility*, vol.40, pp.404-426, 1998.

[61] V. A. Rakov, "Return Stroke Models for Engineering Application," in *Lightning Protection*:The Instituition of Engineering and Technology, pp. 981-1012, 2010.

[62] F. Santamaria, J. A. Alarcon, C. G. Vargas, "Engineering Return Stroke Models a Review and Evaluation," *International Symposium on Lightning Protection*,Fortaleza, Brazil, Oct, 2011.

[63] Y. Baba and V. Rakov, "Transmission Line Model of Lightning Return Strokes Generalized to Include a Tall Grounded Strike Object and an Upward Connecting Leader," in *International Zurich Symposium on Electromagnetic Compatibility (EMC-Zurich)*, Suntec City, Singapore, Feb 28-March 03, 2006

[64] V. Rakov, "Transient Response of a Tall Object to Lightning," *IEEE Transactions on Electromagnetic Compatibility*,vol. 43, pp. 654-661, 2001

[65] A. Mimouni, F. Rachidi and Z-E. Azzouz, "A Finite-Difference Time-Domain Approach for the Evaluation of Electromagnetic Fields Radiated by Lightning Strikes to Tall Structures," *Journal of Electrostatics*, vol. 66, pp. 504-513, 2008.

[66] B. Kordi, R. Moini, W. Janischewskyj, A. M. Hussein, V. O. Shostack and V. A. Rakov, "Application of the Antenna Theory Model to a Tall Tower Struck by Lightning," *Journal of Geophysical Research: Atmospheres (1984–2012)*, vol. 108, 2003.

[67] Y. Baba and M. Ishii, "Numerical Electromagnetic Field Analysis of Lightning Current in Tall Structures," *IEEE Transactions on Power Delivery*, vol. 16, pp. 324-328, 2001.

[68] S. Visacro and F. Silveira, "Evaluation of Current Distribution along the Lightning Discharge Channel by a Hybrid Electromagnetic Model," *Journal of electrostatics*, vol. 60, pp. 111-120, 2004.

[69] F. Silveira and S. Visacro, "Lightning Effects in the Vicinity of Elevated Structures," *Journal of electrostatics*, vol. 65, pp. 342-349, 2007.

[70] O. Beierl, "Front Shape Parameters of Negative Subsequent Strokes Measured at the Peissenberg Tower," *International Conference Lightning Protection (ICLP)*, Berlin, Germany, 1992.

[71] W. Janischewskyj, V. Shostak, J. Barratt, A. M. Hussein, I. Rusan and J-S. Chang, "Collection and Use of Lightning Return Stroke Parameters Taking into account Characteristics of the Struck Object", *International Conference Lightning Protection (ICLP)*, Florence, Italy, 1996.

[72] J. Bermudez, M. Rubinstein, F. Rachidi, F. Heidler and M. Paolone, "Determination of Reflection Coefficients at the Top and Bottom of Elevated Strike Objects Struck by Lightning," *Journal of Geophysical Research: Atmospheres (1984–2012)*, vol. 108, 2003.

[73] S. Visacro, Lightning Protection; *IET Press*, 2010.

[74] R. Durham and M. O. Durham, "Lightning, Grounding, and Protection for Control and Communications Systems: Re-evaluated," in *Petroleum and Chemical Industry Conference Europe Conference Proceedings (PCIC EUROPE)*, Rome, Italy, June 7-9, 2011.

[75] J.-H. Choi, H-K.Shin, D-S. Kim and B-H. Lee, "Grounding Impedance Based on the Current Distribution for the Horizontal Ground Electrode Installed in Two-Layer Soil Structure," in *Asia-Pacific International Conference on Lightning (APL)*, Beijing, China, Nov 1-4, 2011.

[76] M. Unde and B. Kushare, "Cost Effective Design of Grounding Grid Using Ground Rods—A Case Study," in *IEEE Conference Power India*, pp. 1-6, 2012.

[77] IEEE Std 81-2012, IEEE Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Grounding System.

[78] IEEE Std 142-2007, IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems.

[79] L.W.Choun, C.Gomes, M.Z.A. Ab Kadir and W.F.W. Ahmad, "Analysis of Earth Resistance of Electordes and Soil Resistivity at Different Enviroments", *International Conference Lightning Protection (ICLP)*, Vieanna, Austria, 2012.

[80] S.D.Buba, W.F.W.Ahmad, M.Z.A. Ab Kadir, C.Gomes, J.Jasni and M.Osman, "Design of Distribution Substation Earth Grid in High Resistivity Soil Using CDEGS", *Power Engineering and Optimization Conference (PEOCO)*, Kedah, Malaysia, 2014.

[81] S.D.Buba, W.F.W.Ahmad, M.Z.A. Ab Kadir, C.Gomes, J.Jasni and M.Osman, "Effect of Earth Grid Conductor Spacing on the Safety Criteris of Substation Earthing", *IEEE International Conference Power and Energy (PECon)*, Sarawak, Malaysia, 2014.

[82] N. A. A. Rahman, "Study on Lightning Performance Improvement of the 33kV Tanjung Batu - Rompin Overhead Distribution Line," 2008.

[83] M. Rubinstein and M. Uman, "Methods for Calculating the Electromagnetic Fields from a Known Source Distribution: Application to Lightning," *IEEE Transactions on Electromagnetic Compatibility*, vol. 31, pp. 183-189, 1989.

[84] A. Safaeinili and M. Mina, "On the Analytical Equivalence of Electromagnetic Fields Solutions From a Known Source Distribution," *IEEE Transactions on Electromagnetic Compatibility*, vol. 33, pp. 69-71, 1991.

[85] R. Thottappillil and V. A. Rakov, "On the Computation of Electric Fields From a Lightning Discharge in Time Domain," in *IEEE International Symposium on Electromagnetic Compatibility (EMC)*, pp. 1030-1035, 2001.

[86] R. Thottappillil and V. Rakov, "Review of Three Equivalent Approaches for Computing Electromagnetic Fields from an Extending Lightning Discharge," *Journal of Lightning Research*, vol. 1, pp. 90-110, 2007.

[87] H. Motoyama,W. Janischeskyj, A. M. Hussein and J-S. Chang, "Electromagnetic Field Radiation Model for Lightning Strokes to Tall Structures," *IEEE Transactions on Power Delivery,* vol. 11, pp. 1624-1632, 1996.

[88] J. Bermudez, F. Rachidi, M. Rubinstein, W. Janischewskyj, V. O. Shostak, D. Pavanello, J-S. Chang, A. M. Hussein, C. A. Nucci and M. Paolone, "Far-Field-Current Relationship based on the TL Model for Lightning Return Strokes to Elevated Strike Objects," *IEEE Transactions on Electromagnetic Compatibility,* vol. 47, pp. 146-159, 2005.

[89] K. S. Yee, "Numerical Solution of Initial Boundary Value Problems Involving Maxwell's Equations in Isotropic Media," *IEEE Transactions on Antennas Propagation,* vol. 14, pp. 302-307, 1966.

[90] K. Tanabe, "Calculation Results for Dynamic Behavior of Grounding Systems Obtained Using the FD-TD Method," in *International Conference on Lightning Protection (ICLP),* pp. 452-45, Rhodes, Greece, Sept. 2007.

[91] C. Yang and B. Zhou, "Calculation Methods of Electromagnetic Fields Very Close to Lightning," *IEEE Transactions on Electromagnetic Compatibility,* vol. 46, pp. 133-141, 2004.

[92] P.A. Tirkas, C.A. Balanis, M.P. Purchine and G.C. Barber, ‘‘Finite-difference time-domain method for electromagnetic radiation, interference, and interaction with complex sturctures,’’ *IEEE Transaction on Electromagnetic Compability,* vol. 35, pp. 192-203, 1993.

[93] C. A. Sartori and J. R. Cardoso, "An Analytical-FDTD Method for Near LEMP Calculation," *IEEE Transactions on Magnetics,* vol. 36, pp. 1631-1634, 2000.

[94] Y. Baba and V. A. Rakov, "Influence of the Presence of a Tall Strike Object on Lightning Electromagnetic Fields," *Journal of Geophysical Research,* 2005.

[95] A. Shoory, R. Moini, S. H. H. Sadeghi and V. A. Rakov, "Analysis of lightning radiated electromagnetic fields in the vicinity of lossy ground,''*IEEE Transaction on Electromagnetic Compatibility*, VOL.47, NO.1, PP.131-145, 2005

[96] D. Djalel, A. Haddouche and B. Chellali, "Coupling Phenomenon Between the Lightning and High Voltage Networks," *Proceedings of Word Academy of Science, Engineering and Technology (WASET),* vol. 21, pp. 95-101, 2007.

[97] F.Rachidi, ‘‘A review of Field-to-Transmission Line Coupling Models with Special Emphasis to Lightning-Induced Voltage’’, *IEEE Transaction on Electromagnetic Compatibility,* vol. 54, no. 4, pp. 898-911, 2012.

[98] V.Cooray, F. Rachidi and M.Rubinstein, ‘‘Formulation of the Field-to-Transmission Line Coupling Equations in terms of Scalar and Vector Potentials’’, *IEEE Transactions on Electromagnetic Compatibility*, vol. PP, no. 99, pp. 1-6, 2017

[99] C. A. Nucci and F. Rachidi, "On the Contribution of the Electromagnetic Field Components in Field-To-Transmission Line Interaction," *IEEE Transactions on Electromagnetic Compatibility*, vol. 37, pp. 505-508, 1995.

[100] F. Rachidi,C. A. Nucci, M. Ianoz and C. Mazzetti, "Response of Multiconductor Power Lines to Nearby Lightning Return Stroke Electromagnetic Fields," *IEEE Transactions on Power Delivery*, vol. 12, pp. 1404-1411, 1997.

[101] V. Cooray, The Lightning Flash: *IET*, 2003.

[102] R. Thottappillil, M. A. Uman and V. A. Rakov, "Treatment of Retardation Effects in Calculating the Radiated Electromagnetic Fields From the Lightning Discharge," *Journal of Geophysical Research*, vol. 103, pp. 9003-9013, 1998.

[103] M. Izadi, "Improved Algorithm for Evaluation of Lightning Induced Overvoltage in Distribution Lines," MSc, Universiti Putra Malaysia, 2010.

[104] IEEE Working Group Report,"Calculating the Lightning Performance of Distribution Lines," *IEEE Transaction on Power Delivery*, vol.5, no.3, pp.1408-1417, July 1990.