UNIVERSITI PUTRA MALAYSIA

EFFECT OF BENDING DEGREE OF DOWN CONDUCTOR ON LIGHTNING CURRENT DIVERSION IN LIGHTNING PROTECTION SYSTEM INSTALLATION

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By

NORPISAH MOHD YUSOFF

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

July 2015

DEDICATION

I wish to dedicate my humble work to The Almighty ALLAH S.W.T
His messenger Prophet Muhammad S.A.W
My beloved husband Nik Nahar Nik Mohd. Isa
My dearest mum Hajjah Siti Daud
My late dad Hj. Mohd. Yusoff Mohd Nor
My lovely kids
Nik Muhammad Nafeiz, Nik Nur Nadia, Nik Nur Nadhira,
Nik Nur Nellysa, Nik Nur Nerryna,
Nik Muhammad Naufal and Nik Nur Nasywa Nedlyna

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Master of Science

EFFECT OF BENDING DEGREE OF DOWN CONDUCTOR ON LIGHTNING CURRENT DIVERSION IN LIGHTNING PROTECTION SYSTEMS INSTALLATION

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NORPISAH MOHD. YUSOFF

July 2015

Chairman : Jasronita Jasni, PhD
Faculty : Engineering

The major role of protection against lightning are to secure structures and every component connected to it from lightning damage by directing the high currents and dispersed it to the ground safely. Lightning protection of structures and premises becomes crucial in order to provide the safety and to ascertain that the installation of Lightning Protection System (LPS) is reliable and comply with the standards and specification assigned by the authority to assure the quality of services. LPS have been designed deliberately to get the overall protection via an external grid arrangement depends on the building constructions and level of protection needed as per standard. A LPS is composed of three main parameters which are the air termination network, the down conductor and the earth termination. The down conductor is the medium to divert the lightning current from the air termination to the earth termination system of protected structures. This research focused on the down conductor and its effects when it meets the bending part in the LPS installation. According to the standards and specifications, the down conductor shall be installed as short and straight as possible with particular attention shall be carried out eliminating sharp bends and curves to provide a low impedance path between the air termination network to the earth termination. However, due to the modern architecture and to fulfill aesthetical requirement of the building, the bending seems unavoidable. The aim of the research is to investigate and analyze the effect of the bending degree of the down conductor in the LPS installation since no particular experiment has been channeled away to this topic so far. Numerical (simulation) analysis has been applied using Ansoft Maxwell software. The down conductor in concern for the simulation is an Annealed Copper Tape that was injected with lightning impulse current waveforms as per standard at the various bending degree.The potentials and the fields involved are analyzed and the result was discussed in comparison with the straight conductor and the standard. The main findings conclude that the bending of the down conductor does give an effect where the distribution properties of magnetic field, electric field and current densities can be seen nonuniform along the conductor. The maximum value of magnetic field

and current densities located at the vertex of the bent part and are influenced by the bent angle. The magnetic field strength concentrated at the location of the bent and getting stronger as the bending angle getting sharper which is could lead to self-induced coupling and this behavior could cause current to directly flow or short through it and ignite dangerous sparking during lightning strike. The stronger the magnetic field, the greater will be the induced voltage produced along the bent conductor compared with the straight conductor which is hazardous in practice. The magnetic forced also may cause distribution of current densities at the bent part nonuniform in the sectional area and form a void. This phenomenon known as skin effect where current concentrated near the surfaces of the conductor caused by electromagnetic induction and current crowding that could reduce the cross sectional area for current conducting ability to the ground.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Sarjana Sains

KESAN DARJAH LENTURAN KEPADA PENGALIR TURUN BAGI MELENCONGKAN ARUS KILAT DI DALAM PEMASANGAN SISTEM PERLINDUNGAN KILAT

Oleh

NORPISAH MOHD. YUSOFF

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Pengerusi : Jasronita Jasni, PhD
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Peranan utama perlindungan kilat adalah memastikan struktur dan segala komponen yang bersambung kepadanya terlindung dari kerosakan atau bahaya yang berpunca dari panahan kilat yang membawa arus tinggi dengan mengalirkannya ke bumi dengan pantas dan selamat. Perlindungan kilat untuk struktur dan premis menjadi sangat penting bagi memberikan perlindungan dan tahap keselamatan yang diperlukan disamping memastikan bahawa pemasangan Sistem Perlindungan Kilat yang diaplikasikan adalah boleh dipercayai serta mematuhi piawaian dan spesifikasi yang ditentukan oleh pihak berkuasa demi menjamin kualiti perkhidmatan yang dikehendaki. Sistem Perlindungan Kilat direkabentuk secara terperinci bertujuan untuk mendapatkan perlindungan yang menyeluruh melalui susunan grid luaran bergantung kepada struktur sesuatu binaan bangunan itu dan tahap perlindungan yang diperlukan berdasarkan ketetapan piawaian.Sistem Perlindungan Kilat terdiri daripada tiga parameter utama iaitu rangkaian penamatan udara, pengalir turun dan rangkaian penamatan pembumian. Pengalir turun merupakan medium untuk melencongkan arus kilat dari rangkaian penamatan udara ke rangkaian penamatan bumi bagi struktur yang dilindungi. Tumpuan utama kajian ini adalah mengenai kesan lentur pada pengalir turun di dalam pemasangan Sistem Perlindungan Kilat. Menurut piawaian dan spesifikasi, untuk mengalirkan arus ke bumi dengan cepat dan selamat, pengalir turun perlu dipasang dengan laluan yang paling lurus dan pendek dengan perhatian khusus diberikan untuk mengelakkan sebarang lenturan tajam dan lengkungan bagi menyediakan laluan yang bergalangan rendah diantara rangkaian penamatan udara dan rangkaian penamatan pembumian. Namun begitu, disebabkan oleh senibina bangunan moden sekarang dan sebagai memenuhi ciri-ciri estetik sesuatu bangunan itu lenturan tersebut tidak dapat dielakkan dari berlaku. Tujuan kajian ini dilaksanakan adalah untuk menyiasat dan menganalisa kesan tahap lenturan terhadap pengalir turun berikutan tidak banyak kajian yang dibuat berkaitan dengan topik ini sebelum ini. Analisa berkomputer (simulasi) telah diaplikasikan dengan menggunakan perisian Ansoft Maxwell. Pengalir turun yang dipilih untuk analisa simulasi ini ialah pita kuprum yang disuntik dengan denyutan arus kilat

yang berbeza berdasarkan piawaian pada pelbagai sudut lenturan. Potensi dan medan yang berkaitan yang terhasil pada pengalir telah dianalisa dan hasil analisa tersebut dibincangkan serta dibuat perbandingan dengan pengalir tanpa lenturan dan juga ketetapan piawaian. Penemuan utama kajian merumuskan bahawa lenturan pada pengalir turun memberi kesan ke atas pengalir di mana pengagihan ciri-ciri medan magnet, medan elektrik dan kepadatan arusnya didapati tidak seragam sepanjang pengalir. Nilai maksima medan magnet dan kepadatan arus didapati bertumpu di kawasan lenturan dan nilai-nilai tersebut dipengaruhi oleh sudut lenturan. Medan magnet yang terbentuk di sepanjang pengalir menjadi bertambah kuat di kawasan lenturan bilamana sudut lenturan semakin tajam. Keadaan ini boleh mengakibatkan kepada penggabungan aruhan kendiri dan menjurus arus yang mengalir memintas kawasan lenturan dan boleh menjadi punca tercetusnya percikan bahaya semasa kilat menyambar pengalir. Semakin kuat medan magnet tersebut maka semakin tinggi voltan aruhan yang dihasilkan di sepanjang pengalir yang mempunyai sudut lenturan berbanding pengalir tanpa lenturan yang mana voltan tinggi ini adalah bahaya. Kekuatan medan magnet ini juga boleh menyebabkan kepadatan arus di kawasan lenturan menjadi tidak seragam di kawasan tertentu dan membentuk lompong pada pengalir. Fenomena ini dikenali sebagai kesan permukaan dimana kepadatan arus berada di permukaan pengalir disebabkan oleh aruhan elektromagnetik dan arus pusuan yang boleh mengecilkan ruang keratan rentas pengalir dan seterusnya mengurangkan keupayaan mengalirkan arus kilat ke bumi.

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I certify that a Thesis Examination Committee has met on 30 July 2015 to conduct the final examination of Norpisah Mohd Yusoff on her thesis entitled "Effect of Bending Degree of Down Conductor on Lightning Current Diversion in Lightning Protection System Installation" 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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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

I hereby confirm that:

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This is to confirm that:

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LIST OF ABBREVIATIONS

CKE	Cawangan Kejuruteraan Elektrik
IPJKR	Ibu Pejabat Jabatan Kerja Raya Malaysia
LPS	Lightning Protection System
LAT	Lightning Air Terminal
LPZ	Lightning Protection Zone
LPL	Lightning Protection Level
LLS	Lightning Location System
LEMP	Lightning Electromagnetic Pulse
SPD	Surge Protection Device
GFD	Ground Flash Density
FEM	Finite Element Method
FEA	Finite Element Analysis
L-S9	Specification for Lightning Protection System For Structures
IEC	International Electrotechnical Commission
BS	British Standard
NFPA	National Fire Protection Association
CDN	Coupling/Decoupling Network
HD	High Definition
CG	Cloud to Ground
CC	Cloud to Cloud
N_g	Cloud to Ground Flash
T_d	Thunderstorm Day
N_t	Average Annual Total Flash Density
Z	Value of Cloud Flash to Ground Flash Ratio

R	Risk
R_1	Risk of Deprivation of Human Life
R_2	Risk of Loss of Services to the Public
R_3	Risk of Loss of Cultural Heritage
R_4	Risk of Loss to the Economic Value
R_T	Tolerable Risk
L_1	Loss of Human Life or Permanent Injuries
L_2	Loss of Service to Public
L_3	Loss of Cultural Heritage
D_1	Injury of Living Being due to Touch & Step Voltages
D_2	Physical Damage due to Lightning Current Effects
D_3	Failure of Internal System due to LEMP
DLP	Defects Liability Period
BQ	Bill of Quantity
uPVC	Unplasticized Polyvynil Chloride
I_{peak}	Peak Current
Q_{short}	Short Stroke Charge
Q_{long}	Long Stroke Charge
Q_{flash}	Flash Charge
A	Tip of Air Termination Rod
B	Reference Plane
OC	Radius of Protected Area
h1	Height of an Air Termination Rod and Above the Plane
α	Protective Angle

Ω	Ohm
kA	Kilo Ampere
kV	Kilo Volt
A	Ampere
V	Volt
L	Inductance
C	Capacitor
S	Second
μs	Microsecond
EUT	Equipment Under Test
DUT	Device Under Test
AE	Auxiliary Equipment
U	High Voltage Source
R_c	Charging Resistor
R_s	Pulse Duration Shaping Resistors
R_m	Impedance Matching Resistor
R_{ext}	Extension Resistor
C_c	Energy Storage Capacitor
L_T	Rise Time Shaping Inductor
BEM	Bounday Elements
FDM	Finite Difference Method
H	Magnetic Field Intensity
B	Magnetic Flux Density
J	Current Density
D	Density of the Material

E	Electric Field
σ	Resistivity of Material
GUI	Graphical User Interface
2D	Two Dimensional
3D	Three Dimensional
ICCG	Choleski Conjugate Gradient Method
CDEGS	Current Distribution, Electromagnetic Field, Grounding and Soil Structure Analysis
MagNet	Electromagnetic Field Simulation Software 2D/3D
CAD	Computer Aided Design
EMS	Electromagnetic Simulation Software

CHAPTER 1

INTRODUCTION

1.1 Background

Malaysia categorized as prone to high lightning and thunderstorm activities due to its location that lies near the equator of latitude 1° - 7°N and longitude 100° - 119°E, where it is recorded to receive a high level of lightning activity throughout the year [1], [2]. Lightning discharges contain of several thousand amps to over 200,000 amps of electrical energy and even though a lightning discharge is within microseconds only, but it is able to cause enormous damage and destruction [3]. It is significant to understand the phenomenon and characteristic of the lightning because lightning cannot be prevented totally in the real condition, thus, it can only be intercepted and diverted to the ground via LPS that designed and constructed in such a manner to minimize the damage [4].

When LPS is struck, the potential of the conductor with regard to earth is raised and, unless suitable precautions are taken, the discharge may seek alternative paths to ground by side flashing to other metal in structure [5]. There is a probability of a risk of flashover from the protection system to any other metal on or in the structure. If such flashover occurs, part of the lightning current is discharged through internal installations such as pipes and wiring and hence constitutes a risk to occupants and the fabric of the structure [6]. Thus, a reliable LPS installation must encompass structural lightning protection and transient over voltage (electronic systems) protection.

The principal component of LPS of a building consists of the air terminal or lightning rod, the down conductor and the earth termination. Lightning tends to strike at the highest object, thus the air termination network, which is consists of lightning air terminal (LAT) or lightning rods installed along its ridges, performed to capture the lightning strike and become the preferred strike point in the lightning protection zone (LPZ) [7]. LAT(s) are connected by means of a down conductor arrangement to provide low impedance path to conduct the lightning current directing to the earth termination via the grounding grid, which dissipate the high surge which usually in the range of several kA into the earth [8]. Since the down conductor is the pathway to conduct the lightning current safely to the ground, keeping the impedance of down conductor as low as possible is thus indispensable to avert the development of excessive electric potential [9].

In order to reduce the possibility of side flashing, the down conductor route(s) should be as direct as possible with no sharp bends neither stress points where inductance, and hence impedance, is increased under impulse conditions. Gradual bends in the minimum of 200mm radius should be adopted whenever the bend is unavoidable to avoid flash over [10]. Besides that, there is mechanical effect occurring throughout the down conductor during the lightning strike [11]. Even though sectional area of a down conductor is given to satisfy the requirement for mechanical strength, but conductor with sharp bends tends to produce mechanical forces being raised in the bending area which could degrade the conductor and susceptible the conductor to electromagnetic interference [12]. Furthermore, cloud-to-ground lightning in the vicinity induces significant current in tall down conductors and other conducting structures [13]. The high lightning current could generate dangerous sparking in the degraded area and if there is any metal located nearby, the spark will invite dangerous flame and spread the fire to the surrounding.

1.2 Problem Statement

Modern architectures had brought up the varied conceptions of the roofs and ridges to the modern building completion. The placement and spacing of down conductors is often governed by architectural convenience. It is sometimes not possible to avoid the bending of the down conductor in the LPS installation for building and premises. It is an engineer's responsibility to design suitable LPS for the edifice to accommodate the architecture plan. To the best of the author's knowledge, open literature on this bending topic seems to be limited. There is no specific discussion regarding the potential due to the lightning impulse current in a bent conductor when lightning strikes.

None of the available standards had scientifically brought up the permissible of the bending angle that allowed for the down conductor in LPS. CKE, IPJKR Malaysia has a responsibility to design and maintain all the Electrical Installation inclusive LPS for government buildings and has issued the Specification For Lightning Protection System For Structures, L-S9 that compliance to the MS IEC 62305 as an additional specification to be applied in all their projects. According to the L-S9, the bending radii of the down conductor shall equal or shall not be less than 200mm and deep re-entrant loops also routing the round parapet or cornices shall be avoided, but a maximum height increase of 400mm is permissible for passing over the parapet wall with a slope of maximum 45˚ [14].

A typical pattern of roof usually can be done well and the LPS can be seen constructed as per layout and carry through the stipulation. Unfortunately, not all buildings had the same roof type. Multiple roof design effectuated the routing of down conductor to become more complicated. The efficiency of the existing bending degree allowed in the specification is always questionable during construction and installation of the LPS. Figure 1.1 shows the examples of the bent down conductor that does not satisfy the specification.

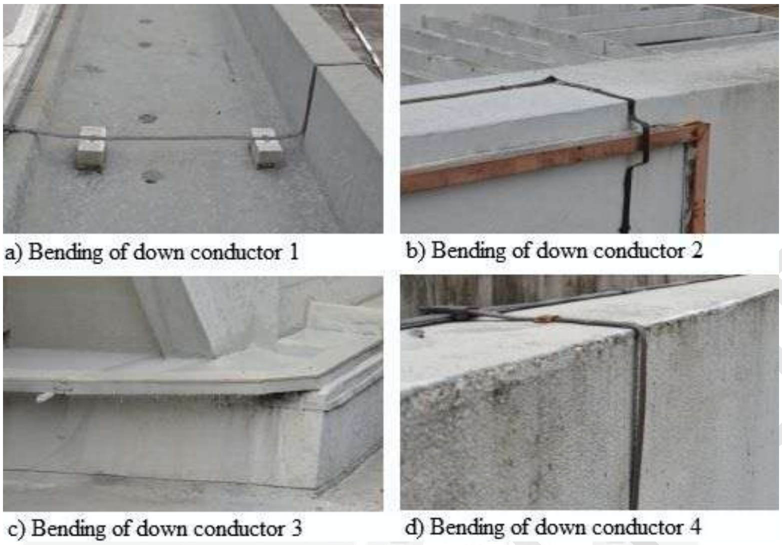

Figure 1.1: Down conductor installed in the actual site where bending degree does not meet the prescribed specifications

The transient current distribution and the transient magnetic field generated along the straight and curved conductor have been investigated by a few researchers [15] - [20]. Liu et.al revealed the result that under the large current curved conductor could possibly exhibit the magnetic force and surface temperature concentrated at the vertex [15]. In another experiment Liu et.al divulged the obstruction of heat transferred from the surface caused by the curvature and Hall Effect decreased current conducting ability on curved conductor [16]. The ohmic heating caused by curved shape with bending angle have influent by the electromagnetic force along the conductor was found by Hu et.al [17] - [19] and later they discovered the magnetic force, skin effect and joule heating affected and deformed curved conductor and finally broke [20].

However, the transient potential has not been mentioned in those experiments. The current and conductor used also do not comply with the lightning protection standard. In order to define the effect of the bending degree scientifically, the challenge is to investigate the distribution of potential, magnetic field, electric field and current density along the bent conductor when lightning strikes. Hence, proper analysis of those parameters on the straight conductor with different bending degrees is needed to see the effect of the bending for the down conductor. Due to a lack of facilities to do the experimental analysis, a computational method or numerical analysis (simulation) using software will assist to obtain those parameters required for the analysis. One of the methods used to study lightning effects consists of a simulation of lightning strike by injecting a surge current.

1.3 Objectives

The aim of this project is to investigate and thoroughly understanding the effect of bending degree of down conductor in LPS. In order to accomplish this purpose, the objectives are as follows:

1) To design and simulate the down conductor inclusive design the dataset for the excitation of surge waveform as per standard using software, with the different bending degree to obtain the distribution of potential, magnetic field, electric field and current density mapping.

2) To validate the result obtained on related fields from the simulation by a comparison with the theory and standard.

3) To analysis the result and propose the limit of minimum and maximum bending degree that are suitably best to be recommended to improvise the existing L-S9 specification if any.

1.4 Scope of work

The limitations and scope of work involved in this research are as follows:

1) Since lightning strike nearby generates an electromagnetic field that responsible for inducing currents in down conductor, the assigning of the down conductor to be utilized for the simulation must be based on an electromagnetic model to get the best result. ANSYS Maxwell 3D that uses FEA to solve electric, magnetostatic, eddy current and transient problems was chosen.

2) Design down conductor for the simulation, where Annealed Copper Tape with the datasheet as per Appendix A, in the dimension of 25mm (width) X 3mm (thickness) X 1000mm (length) as per L-S9 specification has been employed. Annealed copper tape has been used widely in LPS due to its high electrical conductivity, reliable and comparative price.

3) Design the surge waveform to be used in the simulation in accordance with IEC 60060 and MS IEC 62305. Both standards have been determined many types of surge waveform used for lightning experiment. For this project three types of surge waveforms will be used which are 1.2/50µs waveform (open circuit voltage), 8/20µs (short circuit current) and 10/350µs waveforms (short circuit current).

4) The peak value of the current injected for the simulation is 100kA, the value suggested and recommended by IEC 60060 and MS IEC 62305-1 Class III or Class IV lightning protection level, buildings with a low level of risk as housing or office buildings.

5) As part of the aim of this project is to investigate the effect of bending degree that does not meet the requirements of the L-S9 specification, as shown in Figure 1.1, which mostly made at an angle of 90°, the bending angle to be applied in the simulation is set running from 0° angle to 90° with step of 10° sequentially.

6) Results from the simulation are then compared with the theoretical and the standards to validate that the simulation which was carried out on down conductor is trustworthy and acceptable.

The weaknesses employing numerical analysis (simulation) on electromagnetic models are too much computation time, instability and requires high performance HD computer. Therefore, problems usually encountered when using Ansoft Maxwell is the time required to run the simulation often very long. The time period has not accounted for the time needed to repeat the process in the event of errors.

Despite the time required to complete one simulation is quite long, the software also very sensitive and vulnerable to lock or corrupted. Once the software running a simulation, if it happened that the computer lagging, then the simulation file will lock and corrupted. The new file need to be create and start all the steps all over again from the beginning and running new simulation.

1.5 Thesis Layout

This thesis comprises of five chapters specifically aim to define the effect of bending degree of down conductor.

1) Chapter 1 embraces the preliminaries of the research begin with the background overview followed by the problem statement on why the research needs to be performed. Then the objective of the research had pointed away and lastly scope of work involved was described.

2) Chapter 2 discloses literature review on lightning phenomena included GFD, damage due to lightning and risk assessment. Review continues to LPS and its standards and specification, LPL and LPZ followed by the main components of LPS. The characteristics of the lightning current and its parameters also have been reviewed followed by the lightning transient and simulation of lightning transient according to the standard. Later, reviews in related work on the successful previous similar experiments also have been conducted. Lastly, Ansys Maxwell Software, the software that has been chose in this project also has been reviewed thoroughly.

3) Chapter 3 emphasizes the methodology used in the experiment started with the literature review, including previous experiment done related to the objective of the project. Relevant standards also were reviewed for guidelines on designing and simulation. This followed by the design set up for the simulation, the properties of material used and selection on the

lightning waveform to be employed as per standard and the detail on the construction of the simulation also has been presented.

4) Chapter 4 presents the introduction and the results obtained from the simulation. The result and discussion made from the distribution of potential, magnetic fields, electric fields and current density captured for each bending angle that have been set up earlier in Chapter 3.

5) Chapter 5 concludes all the previous chapters in this thesis. Summary of the overall outcome such as results, findings and problems are provided. Suggestion and future recommended for future work then will be presented.

1.6. Summary

This chapter imparts the preliminaries of the overall research begin with the background overview followed by the problem statement on why the research need to be performed. The aim of the thesis is defined as comfortably as the relevant scope of study involved and lastly the overview of thesis layout is depicted briefly in each chapter.

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