# OZONE GENERATION USING PULSE POWER SOURCE WITH LIGHTNING WAVEFORM

NORHALIDA BINTI OTHMAN

A project report submitted in partial fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical-Power)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

JAN 2013

*Special for:*

*My beloved parents*

***Othman bin Abu Bakar***

***Timah binti Muhamad***

*also to my siblings*

***Hazila***

***Zulkifli***

***Hazlina***

***Mohd Shahril***

***Nurain***

*Dedicated, in thankful appreciation for support, encouragement and understandings to my supervisor*

***Assoc. Prof. Dr Zolkafle bin Buntat***

## ACKNOWLEDGEMENT

Firstly, Alhamdulillah, I praised to Allah S.W.T for His enormous blessings, I managed to complete my final project report successfully.

I want to express my gratitude and sincere appreciation to my supervisor, Assoc. Prof. Dr Zolkafle Buntat for his guidance, encouragement, advice, commitment and motivation to assist me in completing this project from the selection of project title until now. His idea and knowledge is very helpful to carry out the project and overcomes the problem occurred along the process to finish this project.

I'm also indebted to Universiti Teknologi Mara (UiTM) for funding my Master study. My appreciation also goes to my family, who has been so understanding and supportive to me all these years. Thanks for their encouragement, love, and supports that they had given to me.

Then, I would like to extend my appreciation to all staffs of the Institut Voltan Tinggi, UTM especially En. Anuar and to my fellow friends for their help and support.

# ABSTRACT

Recently, interest in production of ozone has grown rapidly in wide range of applications especially in industrial sector including oxidation, sterilization, bleaching processes and others. In nature, ozone is formed by the sun's ultraviolet rays and high energy electrical discharges during lightning storms. It is said that in each lightning strike, hundreds of tons of ozone had been generated in the atmosphere. Therefore, in this study experimental setup has been conducted to explore the potential possess by the lightning phenomena in generating huge amount of ozone in a repetitive strike. Lightning waveshape (1.2/50 μs) has been developed by single stage impulse voltage generator. This pulse is then applied through the reactor to produce the ozone. As a results, ozone does not form because ozone requires very fast pulse duration. So, the first study of ozone generation with lightning waveform in microsecond is not sufficient to produce ozone unless very high voltage is required. In addition, the parameter of the air flow rate and peak input voltage give effects on ozone concentration.

# ABSTRAK

Baru-baru ini, faedah dalam pengeluaran ozon berkembang pesat dalam pelbagai aplikasi terutamanya dalam sektor perindustrian termasuk pengoksidaan, pensterilan, proses pelunturan dan lain-lain. Secara semula jadi, ozon terbentuk oleh sinar ultraungu dari matahari dan pelepasan tenaga elektrik yang tinggi oleh semasa ribut kilat. Dikatakan bahawa dalam setiap panahan kilat, beratus-ratus tan ozon telah dijana dalam atmosfera. Oleh itu, dalam kajian ini eksperimen telah dijalankan untuk menentukan potensi fenomena kilat dalam menjana sejumlah besar ozon dalam panahan kilat yang berulang kali. Bentuk graf kilat (1.2/50 μs) telah dibangunkan oleh satu peringkat voltan penjana dedenyut. Kemudian, dedenyut ini telah digunakan melalui reaktor untuk menghasilkan ozon. Daripada keputusan, ozon tidak membentuk. Ini adalah disebabkan oleh ozon memerlukan tempoh masa denyutan yang cepat seperti dalam kajian yang terdahulu. Kajian telah mengenal pasti bahawa gelombang kilat dalam mikrosekon tidak mencukupi untuk menghasilkan ozon melainkan voltan yang sangat tinggi diperlukan. Di samping itu, parameter kadar aliran udara dan puncak input voltan telah dikenal pasti memberi kesan kepada kepekatan ozon.

# TABLE OF CONTENTS


| CHAPTER | TITLE | PAGE |
|---|---|---|
| | **DECLARATION** | ii |
| | **DEDICATION** | iii |
| | **ACKNOWLEDGEMENTS** | iv |
| | **ABSTRACT** | v |
| | **ABSTRAK** | vi |
| | **TABLE OF CONTENTS** | vii |
| | **LIST OF TABLES** | x |
| | **LIST OF FIGURES** | xi |
| | **LIST OF ABBREVIATIONS** | xiii |
| | **LIST OF SYMBOLS** | xiv |
| | **LIST OF APPENDICES** | xv |
| **1** | **INTRODUCTION** | 1 |
| | 1.1 Research Background | 1 |
| | 1.2 Problem Statement | 3 |
| | 1.3 Objectives | 4 |
| | 1.4 Scopes of the Project | 4 |
| **2** | **LITERATURE REVIEW** | 6 |
| | 2.1 What is Ozone ? | 6 |
| | 2.2 Methods in Generating Ozone | 8 |
| | 2.2.1 Corona discharge method | 8 |
| | 2.2.2 Ultra violet (UV) radiation method | 9 |
| | 2.2.3 Electrolysis method | 10 |

| | | | |
|---|---|---|---|
| | 2.3 | Applications of Ozone | 12 |
| | | 2.3.1 Water treatment and purification | 12 |
| | | 2.3.2 Sterilization process | 13 |
| | | 2.3.3 Decolorization process | 14 |
| | | 2.3.4 Odor treatment | 14 |
| | 2.4 | Electrical Discharges in Ozone Generation | 15 |
| | | 2.4.1 Dielectric barrier discharge technique | 16 |
| | | 2.4.2 Pulsed streamer discharge technique | 21 |
| | 2.5 | Research Progress on Ozone Generation | 24 |
| | 2.6 | What is Lightning? | 29 |
| | | 2.6.1 Lightning in nature | 30 |
| | | 2.6.2 Mechanism of lightning stroke | 32 |
| | | 2.6.3 Characteristics of lightning stroke | 33 |
| **3** | **METHODOLOGY** | | 35 |
| | 3.1 | Pspice Software | 35 |
| | 3.2 | Process of Analysis | 36 |
| | 3.3 | Development of Lightning Waveform 1.2/50 μs | 36 |
| | 3.4 | Designation of Ozone Chamber | 39 |
| | 3.5 | Experimental Set-Up | 41 |
| | 3.6 | Ozone Concentration Measurement | 47 |
| **4** | **RESULTS AND DISCUSSIONS** | | 48 |
| | 4.1 | Development of Lightning Waveform (1.2/50 μs) from Simulation | 48 |
| | 4.2 | Development of Lightning Waveform (1.2/50 μs) from Experimental | 50 |
| | 4.3 | Ozone Generation by Dielectric Barrier Discharge Technique | 51 |
| | 4.4 | Ozone Generation by Pulse Streamer Discharge Technique | 56 |

**5 CONCLUSION AND FUTURE WORKS** 58

5.1 Conclusion 58

5.2 Recommendations for Future Work 59

**REFERENCES** 61

Appendix A-B 66-67

# LIST OF TABLES


| TABLE NO. | TITLE | PAGE |
|---|---|---|
| 4.1 | Concentration of ozone in ppmv when flow rate is fixed | 53 |
| 4.2 | Concentration of ozone in ppmv when peak input voltage is fixed | 55 |

## LIST OF FIGURES


| FIGURE NO. | TITLE | PAGE |
|---|---|---|
| 2.1 | Schematic arrangement of a corona discharge ozone generator | 9 |
| 2.2 | UV destruction of ozone | 10 |
| 2.3 | Electrolytic ozone generator cell design | 11 |
| 2.4 | The chemistry of odor control | 15 |
| 2.5 | Dielectric barrier discharge electrode configuration | 17 |
| 2.6 | Pulse streamer discharge arrangement | 21 |
| 2.7 | The process of evaporation and condensation of water cycle | 32 |
| 2.8 | The impulse voltage waveform | 34 |
| 3.1 | Project flow | 37 |
| 3.2 | Single stage impulse generator | 37 |
| 3.3 | Schematic diagram of rotating spark gap | 37 |
| 3.4 | Schematic diagram of discharge chamber | 39 |
| 3.5 | The experimental configuration of discharge chamber | 39 |
| 3.6 | Complete circuit of experimental set up | 40 |
| 3.7 | The arrangement of single impulse voltage generator | 41 |
| 3.8 | The oxygen generator | 41 |
| 3.9 | The ozone analyzer BMT 964 | 41 |
| 3.10 | The arrangement in developing ozone | 42 |
| 3.11 | The coaxial cable RG-213/U | 43 |
| 3.12 | 5W ceramic resistor | 44 |
| 3.13 | Rotary spark gap | 45 |
| 3.14 | Variac supply | 46 |

| | | |
|---|---|---|
| 4.1 | Single stage impulse voltage generator with simulation values | 49 |
| 4.2 | Lightning waveform for single stage impulse generator | 49 |
| 4.3 | The (a) front and (b) tail time of lightning waveform | 50 |
| 4.4 | AC waveform | 52 |
| 4.5 | Effect of input voltage on concentration of ozone for different air flow rate | 53 |
| 4.6 | Effect of the air flow rates on ozone concentration at different peak input voltage | 55 |
| 4.7 | Repetitive pulse of lightning waveform | 56 |

## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| DBD | - | dielectric barrier discharge |
| PSD | - | pulse streamer discharge |
| HV | - | high voltage |
| UV | - | ultraviolet |

## LIST OF SYMBOLS

| | | |
|---|---|---|
| A | - | ampere |
| AC | - | alternating current |
| C | - | capacitor |
| cm/s | - | centimeter per second |
| DC | - | direct current |
| g/kWh | - | gram per kilowatt hour |
| kA | - | kiloamps |
| kA/μs | - | kiloamps per microsecond |
| kV | - | kilovolt |
| kV/cm | - | kilovolt per centimeter |
| kΩ | - | kilo ohms |
| l/min | - | litre per minute |
| mg/L | - | milligram per litre |
| mm | - | millimeter |
| nm | - | nanometer |
| $NO_x$ | - | nitrogen oxide |
| ns | - | nanoseconds |
| O | - | oxygen atom |
| $O_2$ | - | oxygen molecules |
| $O_3$ | - | ozone |
| pF | - | picofarad |
| ppm | - | parts per million |
| ppmv | - | volume per parts per million |
| pps | - | pulse repetition rate or pulse per second |
| R | - | resistor |
| rpm | - | revolutions per minute |
| $TiO_2$ | - | titanium oxide |

# LIST OF APPENDICES


| APPENDIX | TITLE | PAGE |
|---|---|---|
| A | How much ozone does one lightning strike produce? | 66 |
| B | Standard impulse voltage waveform | 67 |

# CHAPTER 1

# INTRODUCTION

## 1.1 Research Background

Industrial applications of ozone have widened in different areas including sterilization, deodorization, decolorization, bleaching and others. Ozone is currently being used as an alternative method for treatment of industrial wastes, chlorination of potable water, processing semiconductor devices and chemical synthesis. Besides that, use of ozone produces less energy consumption compared to chlorination process [1]. Thus, the necessity for ozone generation has increased the resulting surge in demand at the rate of grams per kilowatt hour (g/kWh) and at the same time, many volume per parts per million (ppmv) of ozone concentrations are produced. So, extensive research on a number of different experimental configurations and discharge techniques has been done recently to fulfill these demands [2].

Ozone is produced by electrical discharge that occurs when high electric field exists between two conductors that are separated by dielectric and a discharge gap with a gas contained oxygen passing through them. This high electric field causes electron flow through the discharge gap to provide energy dissociates oxygen molecules and tends to form ozone. Nevertheless, ozone cannot be shipped or stored in gaseous form due to its short lifetime. Ozone must be generated where it is required [1-2, 8].

Many techniques have been introduced by researchers to enhance the performance of ozone generator. The conventional methods to produce ozone are based on AC dielectric barrier discharges in a coaxial arrangement with at least one of the electrodes being insulated from gas by a glass dielectric barrier [3]. In addition, the silent electric discharge has been commonly used for many years to generate ozone and for other chemical processes. In the process of generation of ozone, presence of dielectric on one or both sides of electrodes is to control and maintain the electrical discharge as well as to distribute uniformly micro-discharges that appear over the entire electrode area [2-3]. Apart from silent electric discharge, pulsed streamer discharge [4], atmospheric pressure glow discharge [2], corona discharge and surface discharge techniques have been proposed for ozone generation.

Another promising techniques to generate ozone is using pulsed power as a power source for discharge reactor. Its short duration signal allows higher voltage to be applied to discharge area in creating higher fields for wider ionization process. It lengthens the time for complete breakdown voltage to occur and maintain the gas at ambient temperature thus avoid the use of expensive cooling system. This advantages help in increasing collision process between electron and oxygen atoms thereby increase the ozone production. Moreover, high voltage short-pulse power is very effective in applications for plasma synthesis. During short duration of pulse, the temperature of the ions and neutral gas does not increase much above the ambient temperature [5].

Basically in nature, ozone is formed by the sun's ultraviolet rays (UV) and the high energy electrical discharges that happen during lightning storms. It is said that in each lightning strike, hundreds of tons of ozone had been generated in the atmosphere as in Appendix 1. Therefore, it is the aim of this research to explore the potential possess by the lightning phenomena in generating huge amount of ozone in a repetitive strike.

Hence, in this study, the pulse power source with lightning waveform (1.2/50 μs) has to be developed as the pulse power waveform. The small ozone chamber that acts as a medium to generate ozone also has to be designed. Then, an experiment is

conducted to generate ozone by using lightning waveform in term of peak pulse voltage value and pulse duration with fixed pulse repetition rate (pps). The effect of reactor parameter dimension to ozone concentration will also be presented.

## 1.2 Problem Statement

For conventional methods, the major limitation in the production of ozone is related to the low efficiency of the process which makes ozone expensive. At present, the energy yield that has been determined in previous research ranges between 60 and 120 g/kWh from dry air and 200 – 274 g/kWh from pure oxygen gas [3, 6]. Since the theoretical limit of energy yield is about 1220 g/kWh in oxygen and about 400 g/kWh in pure air, almost 90% of the energy is lost as heat. From this percentage, it is obvious that the usage of electrical energy has been wasted.

Consequently, development pulsed power as a power source for discharge reactor is implemented to generate ozone. Pulsed power source has short duration signal that permits higher voltage to be applied to discharge area and creates higher fields for wider ionization process. Furthermore, the time for complete breakdown voltage is longer and the gas at ambient temperature is maintained by using pulsed power source.

On the other hand, this technique can avoid the usage of expensive cooling system. This advantages help in increasing collision process between electron and oxygen atoms hence increasing the ozone production. There are various types of pulsed power source that have been created to form ozone. For example, in 1996 as stated in [7], the researchers started to create ozone by using pulsed corona ozone generation. From the results, pulsed corona gives higher efficiency compared to DC corona. Then, the development of magnetic pulse compressor (MPC) has been constructed in [8]. It produced the pulse square voltage that acts as an input which is applied into the discharge chamber.

There are two main principles to generate ozone in nature which are by the sun's ultraviolet rays and the high energy electrical discharges that occurs during lightning storms. It is said that in each lightning strike, hundreds of tons of ozone had is generated in the atmosphere. On 30$^{th}$ October 2009, Science Daily reported that more than 1.2 billion lightning flashes occur around the world every year. It is discovered from the satellite installed and each of those billion lightning flashes produces a puff of nitrogen oxide gas ($NO_x$) that reacts with sunlight and other gases in the atmosphere to produce ozone. It means that hundreds tons of ozone are produced by lightning. Therefore, it is the aim of this work to explore the potential possess by the lightning phenomena to generate huge amount of ozone in repetitive strike in a laboratory.

## 1.3 Objectives

There are four objectives of the project as stated below:

1) To develop lightning waveshape (1.2/50μs) as a pulse power waveform
2) To develop small ozone chamber to generate ozone
3) To identify the effect of pulsed power source using lightning waveform
4) To study the comparison between AC source and lightning waveform source on the ozone concentration

## 1.4 Scopes of the Project

In this project, there are only two scopes will be considered in order to achieve the objectives. The scopes of the project are as the following:

i. Development of lightning waveform (1.2/50μs) from single stage impulse voltage generator

ii. Experimental setup

Experiment is conducted by combination of single stage impulse generator with discharge chamber to generate the ozone. The concentration of ozone will be measured through ozone monitor and will be discussed in Chapter 3.

## REFERENCES


[1] U. Kogelschatz,. Advanced Ozone Generation. *Process Technologies for Water Treatment,* S. Stucki, Ed., New York & London : Plenum. 1988. 87-120.

[2] Zolkafle Buntat. *Ozone Generation Using Electrical Discharges : A Comparative Study Between Pulsed Streamer Discharge and Atmospheric Pressure Glow Discharge*. PhD Thesis. Loughborough University, UK; 2005.

[3] B Eliasson, M Hirth and U Kogelshatz. Ozone Synthesis From Oxygen in Dielectric Barrier Discharges. *Journal of Physics D : Applied Physics*. 1987. 20 (11) : 1421-1437.

[4] Z. Buntat, I. R. Smith, N. A. M. Razli. Ozone Generation by Pulsed Streamer Discharge in Air. *Applied Physics Research*. 2009. 1(2) : 1-10.

[5] B. M. Penetrante and S. E. Schultheis. Non-thermal Plasma Techniques for Pollution Control. *Springer-Verlag, Series G : Ecological Sciences*. 34 (Part A & B).

[6] W. J. M. Samaranayake, Y. Miyahara, T. Namihira, S. Katsuki, R. Hackam and H. Akiyama. Pulsed Streamer Discharge Characteristics of Ozone Production in Dry Air". *IEEE Transactions on Dielectrics and Electrical Insulation*. 2000. 7(2) : 254-260.

[7] I. D. Chalmers, L. Zanella and S. J. MacGregor. Ozone Generation using Pulsed Corona in A Wire/cylinder Arrangement. *IEE Colloqium on Pulsed Power '96*. 1996. 7/1-7/5.

[8] T. Namihira, K. Shinozaki, S.Katsuki, R. Hackam, H. Akiyama and T. Sakugawa. Characteristics of Ozonizer Using Pulsed Power. *IEEE Conference on Pulsed Power Plasma Science*. 2001.

[9] B. Yusuf, A.Warsito, A. Syukur, I N. Widiana. Aplikasi Pembangkit Tekanan Tinggi Impuls Untuk Pembuatan Reaktor Ozon. 2011.

[10] I D Chalmers, R C Bairdy and T Kellyz. Control of An Ozone Generator-Theory and Practice. *Measurement Science Technology*. 1998. 9(6) : 983-988.

[11] Wayne Smith. What is Principles of Ozone Generation. *Watertec Engineering Pty*.

[12] Diann Gleason. Ozone 101. *Water Conditioning & Purification*, 8-10; 2011.

[13] F L Evan. Ozone in Water and Wastewater Treatment. *Ann Arbor Science Publishers Inc* First Edition, 1972.

[14] Y Nomoto, T Ohkubo, S Kanazawa and T Adachi. Improvement of Ozone Yield by A Silent-Hybrid Discharge Ozonizer", *IEEE Transactions on Industry Applications*. 1995. 31(6) : 1458-1462.

[15] Association for the Advancement of Medical Instrumentation. Guidelines for The Selection and Use of Reusable Rigid Sterilization Container Systems for Ethylene Oxide Sterilization in Health Care Facilities. ANSI/AAMI ST33 : 1996.

[16] Association of Operative Registered Nurses. *Standards, Recommended Practices and Guidelines.* Recommended Practices Sterilization. 2006.

[17] C. H. Wu, H. Y. Ng, "Degradation of C.I. Reactive Red 2 (RR2) Using Ozone-Based Systems : Comparisons of Decolorization Efficiency and Power Consumption. *Journal of Hazardous Materials*. 2008. 152(1) : 120-127

[18] P. Nigam, G. Armour, I. M. Banat, D. Singh, R. Marchant. Physical Removal of Textile Dyes and Solid State Fermentation of Dye Adsorbed Agricultural Residues. *Bioresource Technology*. 2000. 74(2) : 219-226.

[19] J. Wu, H. Doan, S. Upreti. Decolorization of Aqueous Textile Reactive Dye by Ozone. *Journal of Chemical Engineering*. 2008. 15(2) : 156-160.

[20] EPA Guidance Manual. *Alternative Disinfectants and Oxidants*. 3.1-3.52. 1999.

[21] S. Pekárek. Non-thermal Plasma Ozone Generation. *Acta Polytechnica*. 2003. 43(6) : 47-51.

[22] Zoran Falkenstein. Applications of Dielectric Barrier Discharges. *12th International Conference on High-Energy Particle Beams, Beams '98.* 1998. 117-120.

[23] Kirk R E and Othmer D F. *Encyclopedia of Chemical Technology*. Wiley Interscience : 4th Edition Vol. 17 ; 1996.

[24] Raizer Y P. *Gas Discharge Physics*. New York : Springer ; 1991.

[25] Gerhard J. Pietsch and Valentin I. Gibalov. Dielectric Barrier Discharges and Ozone Synthesis. *Pure & Applied Chemistry*. 1998. 70(6) : 1169-1174.

[26] U. Kogelschatz, B. Eliasson and W. Egli, "Dielectric-Barrier Discharges : Principle and Applications. *Journal Physics IV France 7*, 1997. 47-66.

[27] S. Pekárek, K. Usama. Ozone Generation by Surface Dielectric Barrier Discharge with $TiO_2$ Photocatalyst. *30th ICPIG*. 2011. 10-13.

[28] J Kitayama and M Kuzumoto. Analysis of Ozone Generation From Air In Silent Discharge. *Journal Physics D : Applied Physics 32*. 1999. 3032-3040.

[29] J Kitayama and M Kuzumoto. Theoretical and Experimental Study On Ozone Generation Characteristics of An Oxygen-Fed Ozone Generator In Silent Discharge. *Journal Of Appl. Physics.* 1997. 30 : 2453-2461.

[30] J. Salge, P. Brauman,. The Influence of The Voltage Wave On The Formation of Ozone. *Proceedings of 4th International Symposium on Plasma Chemistry*. 1979. 735-741.

[31] J. Salge, H. Karner, M. Labrenz, K. Scheibe and P. Braumann. Characteristics of Ozonizer Supplied by Fast Rising Voltages. *6th Conference on Gas Discharges and Their Applications*. 1980. 94-97.

[32] M. Shimizu, T. Nagahama, K. Yamamoto, Y .Kamase, F. Yamaguchi, T. Benibayashi, A. Mizuno. Development of An Ozone Generator Operated With Fast Rising Voltages. *Proceedings of 10th Ozone World Congress.* Monaco. March, 1991. 39-50.

[33] Meek J M and Craggs J D. *Electrical Breakdown of Gases*. John Wiley & Sons, New York. 1978.

[34] Schutze A, Jeong J Y, Babayan S E, Park J, Selwyn G S and Hicks R F. The Atmospheric-Pressure Plasma Jet : A Review and Comparison to Other Plasma Sources. *IEEE Trans. on Plasma Science*. 1998. 26(6) : 1685-1693.

[35] B Eliasson and U Kogelschatz. Non-Equilibrium Volume Plasma Chemical Processing. *IEEE Transactions on Plasma Science*. 1991. 19(6) : 1063-1077.

[36] W. J. M Samaranayake, R. Hackam and H. Akiyama. Ozone Synthesis Using A Pulsed Discharge. *Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Conference*. 2001. 449-452.

[37] C Monge, R Peyrous, C Lacaze, B Held and P Duroselle. Ozone Generation Device With Closed-Circuit Gas Flow Studies To Improve Ozone Production by Corona Discharge in A Wire to Cylinder Geometry Applications. *Proc. of 12th World Congress of the IOA*. Lille France. May 1995. 2 : 29-40.

[38] S. Uedaξ, F. Tanaka, K. Kouno, M. Akiyama, T. Sakugawa, H. Akiyama. Development of Compact Ozonizer using Wire to Plane Electrodes. *Pulsed Power Conference 2009, PPC'09*. 2009. 994 - 998.

[39] W.J.M Samaranayake, T. Namihira, S Katsuki, Y. Miyahara, T. Sakugawa, R.Hackam and H.Akiyama. Pulsed Power Production of Ozone using Nonthermal Gas Discharges. *IEEE Electrical Insulation Magazine*. July/August 2001. 17(4) : 17-24.

[40] Ryo Ono and Tetsuji Oda, "Ozone Production Process in Pulsed Positive Dielectric Barrier Discharge. *Journal Physics D : Appl. Physics.* 2007. 40 : 176-182.

[41] M. S. Naidu and V. Kamaraju (2004). *High Voltage Engineering*. (3rd ed.). New Delhi : Tata McGraw-Hill Publishing Company Limited.

[42] M. F. M. Basar, M. H. Jamaluddin, H. Zainuddin, A. Jidin, M. S. M. Aras Design and Development of A Small Scale System for Harvesting the Lightning Stroke Using the Impulse Voltage Generator at HV Lab, Utem. *2nd International Conference on Computer & Automation Engineering (ICCAE)*. 2010. 5 : 161-165.

[43] H. Z. Abidin and R. Ibrahim, "Thunderstorm Day and Ground Flah Density in Malaysia. *Power Engineering Conference 2003 (PECon 2003).* 2003. 217-219.

[44] Martin A.Uman. Natural Lightning. *IEEE Transaction on Industry Applications*, May-June 1994. 30(3) : 785-790.

[45] Lukas Staszewki. *Lightning Phenomenon – Introduction and Basic Information to Understand the Power of Nature.*

[46] Vladimir A. Rakov. Lightning Makes Glass. *29th Annual Conference of the Glass Art Society*. Tampa, Florida. 1999. 45-60.

[47] British Standard Institution (1995). *BS EN 61000-4-5*. London : British Standard Institution.

[48] M. S. Kamarudin, E. Sulaiman, M. Z. Ahmad, S. A. Zulkifli and Ainul Faiza Othman. Impulse Generator and Lightning Characteristics Simulation using Orcad Pspice Software. *Proceeding of EnCon*. 2008. 1032-1037.

[49] A. Haddad, Z. Abdul Malek, D.M. German and R.T. Waters. A Rotating Spark Gap for Double Impulse Experiments. *IEE Colloqium on Pulsed Power*, 1996. 17/1-17/4.

[50] H. Tamaribuchi, D. Wang, T. Namihira, S.Katsuki and H. Akiyama. Effect of Pulse Width on Generation of Ozone by Pulsed Streamer Discharge. *IEEE International Pulsed Power Conference*. 2007. 1 : 407-410.

[51] H. Ward Siver, N0AX and Mark J. Wilson, K1RO, ed (2010). *Chapter 20 : Transmission Lines*. The ARRL Handbook for Radio Communications (87th ed.). The American Radio League. ISBN 0-87259-144-1.

[52] N. H. Halim, A. Azmi, Y. Yahya, F. Abdullah, M. Othman and M. S. Laili, "Development of A Small Scale Standard Lightning Impulse Current Generator. *The 5th International Power Engineering and Optimization Conference (PEOCO2011)*. 6-7 June 2011. 426-431.