INVESTIGATION ON AIR + CO_2 GAS MIXTURES UNDER LIGHTNING IMPULSE

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A project report is submitted in partial

fulfillment of the requirement for the award of the

Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering

University Tun Hussein Onn Malaysia

DECEMBER 2016

DEDICATION

For my beloved parents, Mr Masri and Mrs. Chemek

ACKNOWLEDGEMENT

All praises due to Allah S.W.T, Lord of the universe, The Most Merciful and Gracious. Prayer for peace and prosperity to prophet, Nabi Muhammad S.A.W, his companion and also his beloved friends.

Alhamdulillah, first of all, I would like to express my sincere acknowledgement to Dr. Muhammad Saufi bin Kamarudin for his careful guidance, patience and advices which invaluable direction during the course of this project. His encouragement, understanding, and patience throughout the project and preparation of the thesis are forever appreciated.

Special thanks and earnest appreciation goes to my beloved family for their prayer, encouragement, patience, endurance and moral support. Not to forget, a thousand of gratitude and many thanks to all my friends whom been involved in the success of the completion of this study.

Last but not least, I would like to thanks everybody that involved in completing this project for helping me, giving ideas and valuable suggestion. The author prays that this project can benefit us all. Thank you.

ABSTRACT

This project aims to investigate the breakdown level of gas mixtures (air + CO_2) under lightning impulse. Specifically, this project also reveals the breakdown characteristics of air, carbon dioxide (CO_2) and the gas mixture (air + CO_2) with the purpose of making a comparison. The gas mixture has a ratio of 70% of CO_2 and 30% of air. These gases were tested inside the pressure vessel and subjected to 1 bar (abs) pressure. Standard (1.2/50 μs) lightning impulse was applied alongside with three electrode arrangements. The gap distance between electrodes is also varied ranging from 0.5 cm to 2 cm. It was found that highest U_{50} was recorded at the furthest gap length and when the insulating medium used was $CO_{2.}$ The rising trend of U_{50} is more obvious at sphere gaps as it provides more uniform fields. This U_{50} was calculated by using up and down method. Moreover, the highest maximum electric field (E_{max}) was found at non-uniform field gap namely rod-sphere gaps whereas the values were obtained with the help of FEMM simulation software. The E_{max} of rod-sphere when the air is used as an insulating medium has revealed that it is directly proportional to the gap length in which probably due to the self-restoration of air at the non-uniform field is less compared to other gas hence causing the drop-off insulation strength. As the gap distance between electrodes is small, the highest field utilization factor was recorded which is 0.93 (5 cm sphere), 0.86 (2 cm sphere) and 0.11 (rod-sphere) as a result of the field dispersed uniformly at short gaps. It was also noticed that the E_{max} is inversely proportional to the field utilization factor (η) whereas the risen of η has a huge impact to the value of E_{max}. However, this project is restricted to normal room temperature (26° Celsius) and no humidity factor is considered.

ABSTRAK

Projek ini bertujuan untuk mengkaji tahap pecah tebat bagi campuran gas (udara + CO_2) apabila dikenakan denyutan kilat. Secara khususnya, projek ini juga mendedahkan ciri-ciri tahap pecah tebat bagi udara, karbon dioksida (CO_2) dan campuran gas (udara + CO_2) dengan maksud membuat perbandingan. Campuran gas mempunyai nisbah 70% daripada CO_2 dan 30% daripada udara. Gas-gas ini telah diuji di dalam bekas kedap udara dan tertakluk kepada tekanan 1 bar (abs). Piawai denyutan kilat (1.2/50 μs) telah digunakan bersama-sama dengan tiga jenis konfigurasi elektrod. Jarak di antara elektrod juga di ubah dari 0.5 cm hingga 2 cm. Telah didapati bahawa U_{50} tertinggi dicatatkan pada jarak di antara elektrod yang paling jauh dan apabila medium penebat digunakan adalah CO_2. Graf kenaikan U_{50} adalah lebih jelas pada konfigurasi sfera-sfera kerana ia menyediakan medan elektrik yang lebih seragam. Nilai U_{50} ini telah dikira dengan menggunakan kaedah naik dan turun. Selain itu, telah didapati bahawa medan elektrik maksima (E_{max}) tertinggi diperolehi pada medan yang tidak seragam iaitu konfigurasi rod-sfera dimana nilai-nilai E_{max} telah diperolehi dibantu oleh perisian simulasi FEMM. Nilai E_{max} untuk konfigurasi rod-sfera apabila udara digunakan sebagai medium penebat telah mendedahkan bahawa ia adalah berkadar terus dengan jarak di antara elektrod di mana mungkin disebabkan oleh pemulihan diri udara pada medan yang tidak seragam adalah kurang berbanding gas lain dengan itu menyebabkan kejatuhan kekuatan penebat. Pada jarak di antara elektrod yang paling pendek, faktor penggunaan medan (η) tertinggi telah dicatatkan iaitu 0.93 (sfera 5 cm), 0.86 (sfera 2 cm) dan 0.11 (rod-sfera) disebabkan oleh medan tersebar seragam pada jarak yang pendek. Ia juga telah disedari bahawa E_{max} adalah berkadar songsang dengan η dimana peningkatan nilai η mempunyai kesan yang besar kepada nilai E_{max}. Walau bagaimanapun, projek ini adalah terhad kepada suhu normal (26 ° Celsius) dan tiada faktor kelembapan dipertimbangkan.

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LIST OF ABBREVIATIONS

AC	-	Alternate Current
DC	-	Direct Current
IEC	-	International Electro Technical Commission
SF_6	-	Sulfur Hexafluoride Gas
CO_2	-	Carbon Dioxide
FEMM	-	Finite Element Method Magnetic
E_{max}	-	Maximum Electric Fields
$\|E\|$	-	Electric Field Intensity
UV	-	Ultra Violet
U_{50}	-	Breakdown Voltage
HV	-	High Voltage
UTHM	-	Universiti Tun Hussien Onn Malaysia
η	-	Field Utilization Factor

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CHAPTER 1

PROJECT OVERVIEW

1.0 Introduction

In common, once the electrical equipment has been manufactured, it needs to undergo some testings such as conduction testing before it can be commercialized. This testing is purposely to reveal if the equipment can withstand normal operating voltage and able to realize the task for each equipment, such as delivering rated power, breaking the circuit and arresting surges. However, in real practices, conduction testing is not enough to evaluate the characteristics of high voltage equipment or transmission lines. Hence, the study of abnormal flow is essential. Abnormal flow in high voltage equipment is referring to the occurrence of faults either by man-made faults or nature occurrence faults. This testing is vital in order to determine the maximum permissible voltage or maximum stresses that high voltage equipment could withstand and also minimum safe clearance between electrodes. Usually, the dielectric strength of insulating material is investigated in laboratories by using various types of electrode configurations. In general, there are three major types of insulating material which is solid, liquid and gas which have a different value of permittivity and conductivity [1]. However, the only insulating medium considered in this project is gas.

The measurement of breakdown level can be investigated under three general voltages; direct voltage (DC), alternating voltage (AC) and lightning impulse voltage. This project only considers lightning impulse voltage with several arrangements of electrodes namely sphere gaps (5 cm), sphere gaps (2 cm) and rod to sphere. Nonetheless, sphere gaps electrodes are adopted as calibration device by IEEE standard and IEC 60060-1:2010, high-voltage test techniques; in measuring breakdown values of insulating material and to determine minimum safe clearance between electrodes [2]. An extensive study by researcher shows that the field distribution, breakdown voltage level, and minimum safe clearance are affected by the types of electrode arrangements being used. An experiment carried out by Athanasios Maglaras and Leandros Maglaras [3] demonstrates that rod-rod and rod-electrode arrangements are affecting field distribution whereas field distribution in the rod to rod configuration is dispersed uniformly rather than rod to plane configuration. Other than that, previous work by Hairierosniza Rosdi entitled 'Air breakdown characteristics in plane-plane and sphere gap configuration' shows that the field distribution of plane to plane gap contributes to the non-uniform field as it is approaching zero when gap spacing is increased [4].

The breakdown voltage of sphere gaps is proportional to the gap distance as proven by Hairierosniza Rosdi [4]. It means that the longer distance between gaps, the higher voltage will be applied to the insulating medium thus the breakdown voltage will be higher. In another sphere gap electrode experiment, conducted by Ahmad Azlan Hamzah [5], the effect of distances between sphere gaps has been studied. The highest value of breakdown voltage is recorded at the longest distance between sphere gaps. An improvement of dielectric strength of insulating material is explored in rod to plane arrangement as mentioned by P. N. Mavroidis, P. N. Mikropoulos, C. A. Stassinopoulos and M. Zinonos, whereas rod to plane has been covered by dielectric material [6].

1.1 Problem Statement

The main problem that happened nowadays to a conventional insulating medium such as Sulfur hexafluoride gas (SF_6) contributes to a long-term effect on earth and personnel [7]. Even though that the dielectric strength of SF_6 is approximately 2.5 times higher than air and nitrogen, the side effect from this gas is it has a potential to contribute to global warming effect and also toxic byproducts which could affect the human health [7]. This condition urges the needs of developing a new mixture of gas in order to reduce the greenhouse effect. Hence, this project constructed a form of gas mixture whereas carbon dioxide was mixed up with air with a ratio of 70% of air and 30% of CO_2. The gas mixture has been investigated with different types of electrode arrangements under lightning impulse.

Obviously, the electric field cannot be measured directly from experiment. Several studies have revealed the manual calculations of electric fields by using Laplace's and Poisson's equation [8], [9], [10]. As a result, the calculation of electric field becomes complicated and could take the time to solve. Therefore, finite element method magnetics (FEMM) software is used to simulate the electrode arrangements in order to illustrate electric field stress that happens surround the electrodes. In addition, the magnitude of the electric field can be obtained either. FEMM is software that able to solve complex finite element analysis in most electrostatic problems in respect to the electrode arrangements.

1.2 Objective

Objectives of this project are as follows:

a) To determine the breakdown strength of air, CO_2, and air + CO_2 when impulse voltage is applied to different types of electrode arrangements.
b) To evaluate field utilization factor based on data obtained from FEMM simulation and calculation.
c) To evaluate maximum electric field between specified electrode configurations just before breakdown occurs.
d) To acquire impulse voltage according to standard 1.2/50 μs waveform in respect with standard tolerance.

1.3 Project Scope

There are several scopes of this project. The scopes are:

a) Only air, CO_2, and CO_2 + air mixture were used as an insulating medium.

b) Sphere gaps, rod to sphere and plane to plane electrode arrangements were chosen for measurement.
c) Other types of applied voltages are not considered.
d) Standard room temperature (26 °C) is considered.
e) Standard tolerances are in accordance to BS EN 60060-1:2010.
f) The ratio of carbon dioxide to air is 70:30 (1 atmosphere abs pressure).
g) Maximum gap distance is 2 cm.
h) Only positive lightning impulse is considered.

1.4 Contribution of Study

This study has contributed:

a) Able to demonstrate the relationship between different types of gas under lightning impulse.
b) Determine the effects of field uniformity on breakdown level.
c) Able to reveal the relationship of breakdown voltage versus gap distance.
d) Determine the effects of electrode arrangements on breakdown voltage.

1.5 The Organization of Thesis

This thesis consists of six chapters:

Chapter 1: This chapter deals with the basic introduction to the lightning impulse and project background for this thesis. Moreover, problem statement, objectives, and project scopes are also stated in this chapter.

Chapter 2: This chapter divided into two parts. The first part describes some information regarding lightning impulse voltage and also about gas being used as an insulating medium. For the second part, it consists of the previous related work associated with this project.

Chapter 3: This chapter deals with the methodology of the project. In this chapter, the planning of the project is demonstrated and steps were taken during conducting the experiment are explained. Moreover, the selected electrode arrangements are explained in detail which is drawn using DraftSight software. Then each electrode configuration is simulated using FEMM software and the results have been discussed.

Chapter 4: This chapter shows the result and analysis for air breakdown obtained both from the experiment and simulation. In the experiment, three different electrode configurations which are sphere gaps (5 cm), sphere gaps (2cm) and rod to sphere were investigated under lightning impulse in order to obtain breakdown voltage (U50) in respect with the changes of the gap distance. Moreover, the result for electric field (E_{max}) obtained from the simulation is demonstrated. Other than that, the simulation also showed the graph of voltage and field intensity, |E| for each electrode arrangement.

Chapter 5: This chapter describes the breakdown characteristics of three gas types which are air, CO_2 and the gas mixture (air + CO_2). These gases are tested inside the pressure vessel subjected to pressure = 1 bar (abs). The same electrode arrangements and gap length were retained. The effect of humidity is not considered and this breakdown measurement was taken at normal room temperature.

Chapter 6: The final chapter includes the whole conclusion of the project and also some important discussions about the future work or recommendation that can be added to improve the project in future.

CHAPTER 2

A REVIEW ON AIR AND GAS INSULATION

2.0 Introduction

Before carrying out an experiment, extensive studies need to be conducted to improve some general knowledge related to the topic being studied. Obviously, a literature review is a process of collecting, analyzing of data and also information gathering. The required data and information can be collected from a variety of sources such as journals, articles, reference books, online database and others. Moreover, these studies can enhance one's understanding of the behavior as well as the characteristics of lightning impulse.

2.1 Lightning Impulse Standard Waveform

Lightning impulse voltage is an overvoltage due to lightning. They are considered as an external overvoltage and dependent on the system voltages. An impulse voltage is a unidirectional voltage which rises more or less rapidly to a maximum value without appreciable oscillations and then decays, relatively, slowly to zero. Usually, the standard waveform used for testing is 1.2/50 μs. The first number (1.2 μs) represent the front time T1 and the second number (50 μs) is a tail time T2. In the standard lightning waveform, T1 is taken when the waveform is reaching the peak voltage/current and T2 is measured during 50% of the peak magnitude [2].

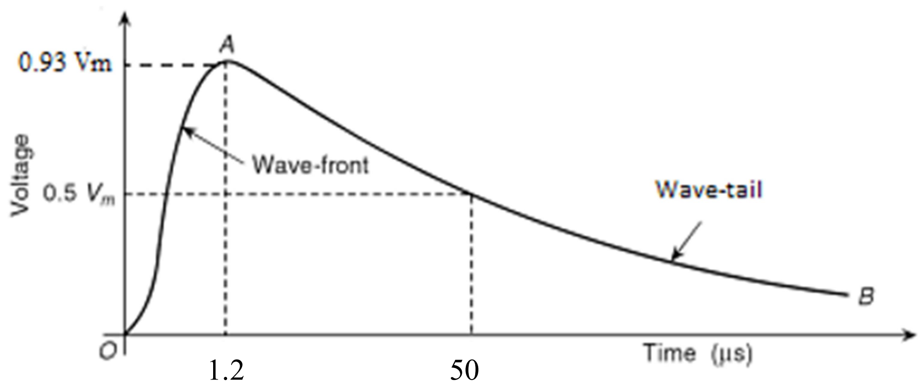


Figure 2.1: Standard lightning impulse voltage [2].

By referring to Figure 2.1 above, the wave-front is occupying the rising part (O-A) of the impulse waveform. The duration of this wave is obviously starting from zero until 1.2 μs, which the magnitude of lightning impulse is at highest peak at this moment. Meanwhile, decaying part is occupied by wave-tail where its duration is starting after the waveform has reached the peak value until it ends at B. The combination of both waves is actually imitating the behavior of real lightning waveform which it's occurs for the shortest time. In real practices, the impulse voltage measurement is relying on the equipment efficiency. In order to ensure that the standard waveform can comply, therefore standard tolerances need to be followed. The tolerances for front time and tail time are as follows:

Table 2.1: Standard tolerances of lightning impulse waveform [2].

Impulse voltage waveform	**Front time**	**Tail time**
Tolerances	± 30%	±20%
Time taken	1.2 μs	50 μs
Voltage magnitude	0.9 V_{peak}	0.5 V_{peak}

2.2 Basic Breakdown Processes

Over many decades, the researcher has identified concepts which contribute to the formation of a basic picture of a breakdown in air.

2.2.1 Primary electrons

In free space region, primary electrons regularly trapped in air and the occurrence of that incident happens very fast [11]. This incident caused negative ions to be formed after the creation of cosmic rays or other radiations and could be worst whenever strong electric field existed. Eventually, these ions will collide with other molecules and could further produce secondary electrons.

2.2.2 Ionization

The interchanged of energy between the particles or gas mainly by the collision. The collision is mainly caused by electrons that were produced by radiation. The ionization process takes place when energy inside electron is higher than energy potential (bond). The electron is said to be leading positive ion inside this process and a number of electrons could be larger at the strong electric field. The further process resulting formation of electrons avalanche and the insulating medium is changing its properties from an insulator to a conductor. Else, in other words, it is in total breakdown. Figure 2.2 below illustrates ionization process due to electrons.

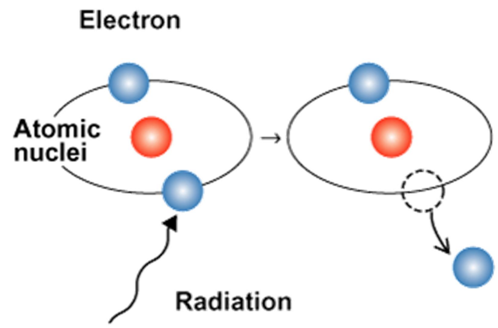


Figure 2.2: Ionization process due to electron [12].

2.2.3 Excitation

Excitation of neutral atoms occurs due to lower energies obtained from ionization. This excitation does not make electrons in an atom to move freely. Then these excited atoms will come back normal and can be dissolved in Ultra-Violet (UV) light.

2.3 Townsend's Experimental Setup

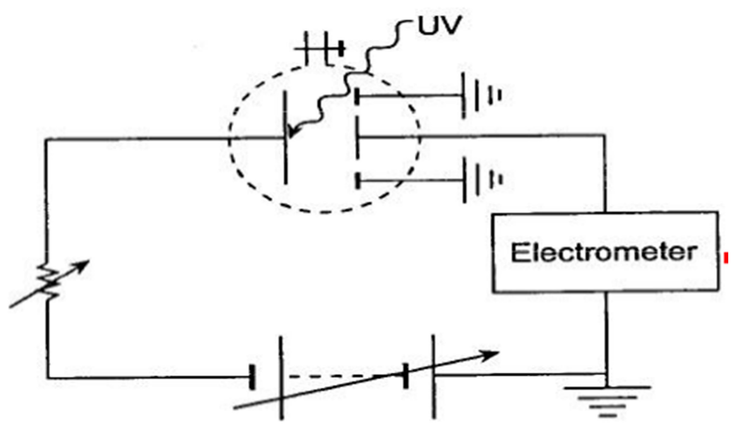


Figure 2.3: Townsend's test setup with variable voltage sources [13].

Figure 2.3 shows Townsend's experiment that involves measurement of the growth of current at uniform field gap with a static voltage applied. The test setup comprises a parallel plate electrode system enclosed in a glass chamber containing a gas at a low pressure. The use of parallel plate is to ensure a uniform field is applied to the electrodes arrangement. UV light was used to irradiate the cathode surface in the gaseous medium. A variable source of potential was connected externally across the electrodes in series with an electrometer to measure small leakage current. The measurement results were plotted as the current-voltage growth characteristic shown in Figure 2.4.

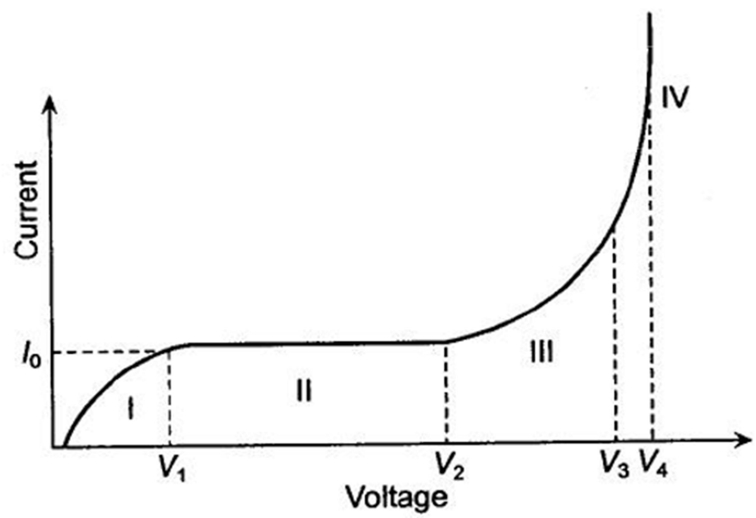


Figure 2.4: Current versus voltage characteristics [13].

From the graph of current versus voltage obtained from Townsend's experiment, there are four regions where ionization takes place. Each region has their principle that needs to be understood. For region I, the current increases linearly with respect to voltage. This increment is then limited by saturation level of current inside insulating medium. Then for region II, the saturated current takes place where current flow is stable, the electron is still inside molecules bond. Next, the current level increases exponentially in region III, which means that numerous secondary electrons produced by the collision initiating the form of an avalanche. Lastly, in region IV, the dielectric is said to be in breakdown where current flow is permissible between potentials.

2.4 Impulse Voltage Generator

The voltage or current magnitude of the impulse waveform is depending on the number of circuit stages that being used. Higher impulse voltage requires multiple stage circuits. The impulse generator set can be categorized into two:

i. Single stage circuit

ii. Multiple stage circuit or Marx Generator

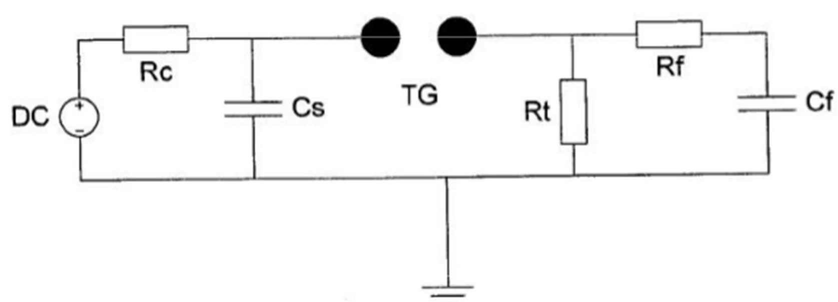


Figure 2.5: Single-stage lightning impulse circuit [13].

This single-stage circuit is mainly used for the generation of relatively low-impulse voltage. In common, impulse circuit consists of two individual components:

i. ‘charging’ component causing the wave front
ii. ‘discharging’ component causing the wave tail

The circuit shown in Figure 2.5 formed the overall wave shape (rise and decay lines). The stage capacitor Cs is initially charged and dependent of supply voltage magnitude. Then it is discharged via a spark gap (TG). When the spark gap is triggered, immediately the capacitor voltage appears across the ‘tail’ resistance Rt and then gradually reducing its magnitude thus forming the wave tail. At the moment wave tail is conducting, the voltage across the tail resistance Rt causes the voltage begins to build up across the front capacitance Cf resulting wavefront waveform is produced. The Cf is usually the voltage divider [13]. The test object is connected across the front capacitance and it is due to this part of the circuit that the voltage waveform cannot raise to the peak instantaneously. The standard time taken by the wave front to reach peak value is 1.2 µs while for wave tail to reach half of total waveform is 50 µs.

2.5 Gas Insulated Applications

Gas insulated medium is widely being used in various applications. Some of the applications are:

2.5.1 Gas-insulated high-voltage switchgear (GIS)

SF_6 is one of the gasses which are commonly used in industries where it has a higher quenching arc property. Its dielectric strength is 2.5 times greater than air [14].

Figure 2.6: Gas insulated switchgear used in the industry [14].

2.5.2 Gas-insulated transmission lines (GIL)

For typical applications up to 400 kV, the insulation gas is composed of up to 80% nitrogen and only 20% SF_6. The gas is not poisonous and can easily be detected. Mostly, GIL is used for transmission systems with 345 kV to 550 kV operation voltages and 2500 A to 5000 A operation current [15].

2.6 Finite Element Method Magnetic

FEMM is a suite of software for solving low-frequency electromagnetic problems on two-dimensional planar and axisymmetric domains. The software currently addresses linear/nonlinear magnetostatic problems, linear/nonlinear time harmonic magnetic problems, linear electrostatic problems, and steady-state heat flow problems [16]. There are two types of problems commonly being used to solve electromagnetic problems which are electrostatic and magnetostatic problems.

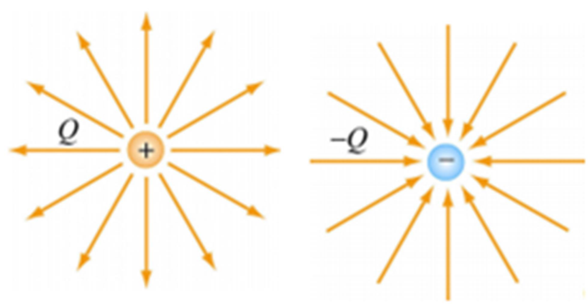
Finite element method magnetic (FEMM) is widely used in the numerical solution of electric field problems. In contrast to other numerical methods, FEMM is a very general method and also a versatile tool for solving a wide range of electric field problems. At first, the whole domain is fictitiously divided into small areas/volumes called elements. The potential, which is unknown throughout the problem domain, is approximated in each of these elements in terms of the potential at their vertices called nodes. As a result of this, the potential function will be unknown only at the nodes.

2.7 Up and Down Method

In this method, the voltage applies to the testing object increases in discrete steps until breakdown occurs; thereafter the voltage is lowered after each breakdown and raised after each withstands. Such an iterative procedure enables the 50% breakdown level to be established with an acceptable degree of accuracy but provides no information about the standard deviation of the distribution. A low-probability withstand level can be calculated, but this involves the assumption of a value for the standard deviation, which can involve a significant error. The method is suitable when the comparison of performances is required.

2.8 Electric Field

As shown in Figure 2.7, the electric field direction is radially outward for a positive charge and radially inward for a negative charge. This field is generated by electrically charged and time-varying magnetic field. Moreover, the electric field describes force experienced by a motionless positively charged to negatively charge.



(a) (b)

Figure 2.7: Field lines for (a) positive charge and (b) negative charge [17].

When the same positive and positive charge meets, it will repel meanwhile the opposite sign charges will attract to each other. This phenomenon can be seen in Figure 2.8 below. Furthermore, the electric line produces by a point charge will never cross to each other.

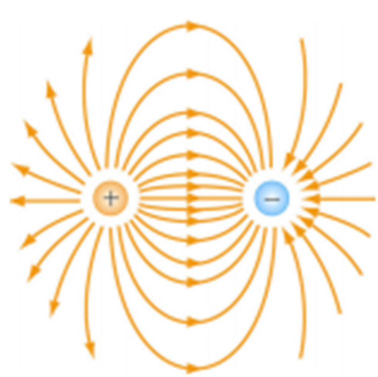


Figure 2.8: Field lines for an electric dipole [17].

2.8.1 Uniform and Non-Uniform Field

The explanation of field uniformity is as follows:

i. Uniform Field

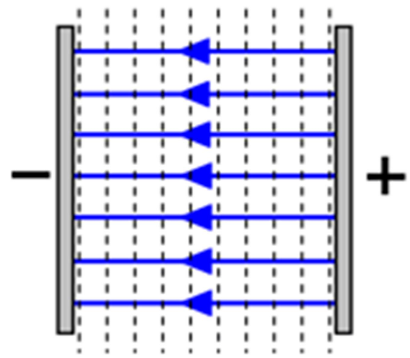


Figure 2.9: Magnitude and direction are the same at all points [18].

A uniform field is one whose magnitude and direction are same at all points in space and will exert the same force of charge regardless of the position of charge is space likewise shown in Figure 2.9 above. It is presented by parallel and evenly spaced lines. The equipotential surfaces (dotted lines) drawn normal to the field lines are also equidistance from each other.

ii. Non-uniform fields

A non-uniform field is one which is not uniform, it has either different magnitudes or directions or both different in a given region of space. The field depends on the inversely square of the distance from the point charge. The equipotential surfaces are also unequal distances (closely spaced near the charge and further separating as it is moving away from the charge) [18].

2.9 Previous Related Works

Previous works are vital for a researcher in order to enhance knowledge that is related to this project. These works can be referred either from journals, articles or papers.

Thesis entitled "Air Breakdown Characteristics in Plane-Plane and Sphere Gap Electrode Configuration under Lightning Impulse" presented by Hairierosniza binti Rosdi [4] is basically a project regarding the breakdown of air which has been investigated under lightning impulse. There are two configurations have been used which are plane to plane and sphere gaps. The distance between electrodes was varied from 0.5 cm, 1 cm until 2.5 cm. Approximately 20 shots were taken for each distance and up and down method has been referred. This method was used to obtain high accuracy results. Moreover, this project is referring to British Standard BS EN 60060 that explained in detail about the general definitions and test requirements for high voltage test techniques. In fact, TERCO's lightning impulse circuit was used to obtain the lightning impulse waveform referring to the standard tolerances. The results obtained from this project shows that the smaller surface of electrodes, the possibility for air to breakdown is higher. This is proven by plane to plane electrodes configuration whereas it has a smaller surface dimension and tends to breakdown faster rather than sphere gaps which have a wide surfaces. It means that the dielectric strength for the plane to plane configuration is lower than that of sphere gaps. This condition verified by both experiment and simulation which the breakdown voltage is lowest for all distances in experiment whilst in simulation, the highest E_{max} values also recorded at the plane to plane means that higher stress occurs at all distances for this arrangement. Other than that, the gap distance between electrodes also plays a vital role in order for breakdown to take place. In another word, gap distance also referred as a safe clearance between electrodes. The highest probability for breakdown to occur is when the gap distance between electrodes is at lowest distances.

Paraselli Bheema Sankar [19] has presented his works that are "Measurement of Air Breakdown Voltage and Electric Field Using Standard Sphere Gap Method". This thesis purposes to simulate the air breakdown voltage experimentally in high voltage laboratory. This project has selected air as an insulating medium to fill in electrodes gap. The gap spacing between electrodes influenced the breakdown level of insulating medium. In this work, a standard diameter of 25 cm spheres is used for modeling of electrode arrangement and also a measurement of air breakdown voltage. Moreover, this experiment is only conducted at the normal temperature and pressure. Finite element method is also used to simulate the electric field between standard sphere electrodes. The relative air density factor and maximum electric field are measured in MATLAB environment for different temperature and pressure. The electric field distribution for sphere gap arrangement is also calculated with the help of COMSOL. This project has revealed the performance characteristics of air breakdown voltages and electric field behaviors under impulse voltage. Furthermore, the gap distance between electrodes is also taken into consideration. It is concluded that with the increase of gap between spheres, the breakdown voltage, and electric field strength are increased and is inversely proportional to sphere radius. Other than that, the temperature is inversely proportional to the maximum electric field and relative air factor density while the pressure shows the same trend. MATLAB software was used to observe the effect of humidity variation which is not changeable during the experiment. Moreover, the electric field which cannot be seen during the experiment is also observed by using FEMM software.

A paper entitled "Breakdown Characteristics of CF_3I/CO_2 Gas Mixtures under Fast Impulse in Rod-Plane and GIS Geometries" presented by L. Chen, P. Widger, C. Tateyama, A. Kumada, H. Griffiths, K. Hidaka and A. Haddad [20] shows that fast impulse voltage was used to investigate the breakdown level of gas mixture which is CF_3I/CO_2, tested using rod to plane arrangement. This paper intended to investigate an alternative gas mixture in order to replace existing SF_6 gas that contributes to the environmental effect. The ratio of 30/70% was selected for CF_3I/CO_2 mixture which has undergone an experiment under lightning impulse (1.2/50 μs) and a steep-front impulse voltage generator (rise time of 16 ns). Additionally, the effect of breakdown level with different gap length and pressure are also observed. The gap distances between electrodes being used are 1 cm, 3 cm, and 5 cm. A pressure vessel made of mild steel was manufactured to withstand high gas pressure being used in this experiment. After that, the gas mixture is recycled using gas recovery system in order to investigate the breakdown level in medium voltage gas insulated switchgear (GIS). The graphs of voltage against time and voltage against distance are constructed based on results obtained. The breakdown voltage is obtained by using up and down method. The highest breakdown voltage recorded at longest gap distance and the effect is greater than that of steep front square voltage. This is due to the front rise time of steep front square waveform which took a less time to breakdown. Therefore, a much higher voltage is required for the leader to cross the gap and to initiate a direct breakdown. The first task is subjected to 1 bar (abs) pressure and continues to 2 bars (abs) pressure. In general, the breakdown level increases when the pressure increased. Time taken to breakdown is defined in average form whereas the lowest pressure of lightning impulse shows that the breakdown event occurs faster rather than when higher pressure applied. Meanwhile, when the applied voltage is a steep front square waveform, at high pressure, the breakdown event tends to occur faster. However, less time to breakdown still possessed by lightning impulse. Then, the experiment was carried out using GIS which is filled with the same gas mixture at atmosphere pressure obtained from the recycled chamber. The gap distance for the contact separation is approximately 3 cm. At first, both results from the previous test and GIS test are compared and the final result showed that the higher breakdown occurs due to the fact that the contact of GIS is distributing more uniform field rather than the previous test.

A Recent study by Hafizah binti Nor Azmuddin [21] in her project entitled 'Air Breakdown Characteristics in Rod-Plane and Sphere-Plane Electrode Configuration under Lightning Impulse' shows the effect of air breakdown level once lighting impulse is applied. This project is mainly focusing on two electrode configurations which are rod-plane and sphere-plane. A manual guide from TERCO's book is being referred in order to construct the lightning impulse circuit. Only one stage lightning impulse circuit is considered in this project allowing only impulse voltage up to 100 kV. The distance between electrodes for both configurations have been varied from 0.5 cm, 1.0 cm, 1.5 cm, 2.0 cm and 2.5 cm. FEMM software was used to design the electrodes in order to simulate the electric field occurs surround them based on breakdown voltage obtained from the experiment. In order to record the breakdown voltage, up and down method (U_{50}) was used. The author has compared the results for both electrode configurations and found that the lowest breakdown voltage is recorded at rod-plane geometry, thus providing more electric fields (E_{max}) at shortest gap distance. Meanwhile, sphere-plane records highest breakdown level at the same time providing the lowest E_{max} compared to the rod-plane configuration. Both configurations demonstrate a linear increasing breakdown voltage for all distances. In addition, this project also presenting the simulation of the electric field using FEMM which shows the stress level that could be applied to the electrodes.

Emel Onal [22] has presented his paper entitled “Breakdown Characteristics of Gases in Non-Uniform Fields”. The present paper describes a study of the breakdown level of SF_6, CO_2, N_2 and also air. The non-uniform field which is rod plane arrangement was used and tested experimentally under alternating voltages (AC). The rod has a 1 mm tip radius meanwhile the diameter of the plane is 75 mm. Moreover, the distance between electrodes is also varied from 5 to 25 mm. The experimental results have shown that the breakdown voltages of SF_6 in the practical range of pressure (100-200 kPa) are always higher than those of other gasses. Although at short gaps, the breakdown strength of SF_6 is superior at the pressure range from 100-500 kPa, at 25 mm electrode gap spacing and 300 kPa the breakdown voltage of air is 7.8% higher than that of SF_6. At above pressures of 400 kPa and 15 mm electrode gap spacing, there exists a critical field where the breakdown voltage of CO_2 has a maximum value.

2.10 Summary of Previous Related Works

Previous works are very useful for the author in order to get some general ideas related to the project. Table 2.2 below shows the summary of previous related works. Based on previous works, the author found that the most common things affecting breakdown level are gap spacing, types of electrodes, electrode arrangements, pressure, insulating medium, and temperature. Finite element analysis software is always being used for modeling and simulation of the electric field which it is hard to calculate manually. As a result, the author found that non-uniform field contributes to the highest electric field (E_{max}), which means that higher stress occurs to that particular electrode. Thus, the probability for the insulating medium to breakdown is also high. Meanwhile, the uniform field provides lowest E_{max} compared to the non-uniform field.

Table 2.2: Summary of previous related work.

Title	Author	Summary
Air Breakdown Characteristics in Plane-Plane and Sphere Gap Electrode Configuration under Lightning Impulse	Hairierosniza binti Rosdi	Investigate the level of breakdown for two different configurations which are plane to plane and sphere gaps electrode. This project literally using air as an insulating medium. This project reported that the smaller the surface of the electrode, the greater the electric field, thus the probability for air to breakdown is higher.
Measurement of Air Breakdown Voltage and Electric Field Using Standard Sphere Gap Method	Paraselli Bheema Sankar	Study about air breakdown characteristics when impulse voltage is applied. This project is basically using a standard sphere gap which is 25 cm. With the help of MATLAB and FEMM software, the effects of the electric field, temperature and pressure can be simulated. Different gap lengths are also being considered whereas the highest breakdown voltage is recorded at the longest gap distance.

Breakdown Characteristics of CF_3I/CO_2 Gas Mixtures under Fast Impulse in Rod-Plane and GIS Geometries	L. Chen, P. Widger, C. Tateyama, A. Kumada, H. Griffiths, K. Hidaka and A. Haddad	The objective of this paper is to investigate alternative gas mixture in order to replace existing SF_6 gas. CF_3I/CO_2 gas mixture was developed and then tested using the rod to plane arrangement. The breakdown characteristics of 30/70% CF_3I/CO_2 gas mixture was experimentally determined using (i) a lightning impulse generator (1.2/50) and (ii) a steep-front impulse voltage generator (rise time of 16 ns). Gap spacing and gas pressure parameters are affecting the V-t characteristics of the gas mixture. The results also showed that, at longer gap distance, steep-front voltage is recording highest breakdown voltage compared to lightning impulse. Moreover, a medium gas insulating switchgear (GIS) is also used in order to investigate the breakdown characteristics. The same gas mixture was recycled and then tested using GIS.
Air Breakdown Characteristics in Rod-Plane and Sphere-Plane Electrode Configuration under Lightning Impulse’	Hafizah binti Nor Azmuddin	This project is planned to do an investigation of air breakdown characteristics when the lightning impulse is applied. Basically, two arrangement have been used which are rod-plane and sphere-

		plane. Both configurations showed significant differences breakdown level which the rod-plane arrangement records highest electric field resulting the possibility for breakdown to occur is very high. Only positive lightning impulse is considered in this project.
Breakdown Characteristics of Gases in Non-Uniform Fields	Emel Onal	This paper has presented the breakdown characteristics of SF_6, CO_2, N_2 and also air. Alternating voltages (AC) has been chosen as a supply voltage. The breakdown level is investigated by using the rod to plane arrangement which clearly having a non-uniform field. Additionally, the gap distance between electrodes is varied from 5 mm to 25 mm. Moreover, the effect of pressure changes is also observed. The result shows that for all electrode gaps the breakdown strength of N_2 increases with increasing pressure. It exhibits linear breakdown-pressure behavior. Air has recorded minimum breakdown strength meanwhile SF_6 has shown that it has a highest dielectric strength throughout this

		experiment. Clearly, this project has revealed the effect of breakdown level depends upon the polarity of the voltage, the pressure, electrode gap spacing, field uniformity and the nature of the gas.

CHAPTER 3

EXPERIMENTAL SETUP AND SIMULATION TECHNIQUES

3.0 Introduction

Research methodology refers to the procedures to conduct a study in order to achieve the project objectives. It is a careful planning and as a guideline before the experiment can be carried out. This project methodology will focus on the lightning impulse circuit, simulation, modeling procedures as well as the lightning impulse standard verification. Moreover, the steps taken to form a gas mixture will be described in detail in this chapter.

3.1 Project Activities

In this project, planning should be made properly to ensure that this project can be completed on time. Many aspects have been taken into account and this project requires several stages upon completion. Figure 3.1 shows the flowchart of the project planning. This project basically divided into two parts which are the experimental setup for lightning impulse and the simulation using FEMM software.
Additionally, the lightning impulse test was verified in accordance with the standard IEC 60060:2010 [2].

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