MEASUREMENT OF AIR BREAKDOWN VOLTAGE AND ELECTRIC FIELD USING STANDAD SPHERE GAP METHOD

A Thesis submitted in partial fulfillment of the requirements for the degree

of

Master of Technology
in
Power Control and Drives

By

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(Roll No: 209EE2168)

June-2011

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Under the Guidance of
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CERTIFICATE

This is to certify that the thesis entitled, **"Measurement of Air Breakdown Voltage and Electric Field using Standard Sphere Gap Method"** submitted by **Mr. Paraselli Bheema Sankar** in partial fulfillment of the requirements for the award of Master of Technology Degree in **Electrical Engineering** with specialization in **"Power Control and Drives"** at the National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date:

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Date:
Place:

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ABSTRACT

Rapid growth in power sector of nation has given the opportunity to power engineers to protect the power equipment for reliable operation during their operating life. It has been seen from the studies conducted by power engineers that one of the main problem in high voltage (HV) power equipment is the degradation of insulation i.e., quality of insulation of power equipment. In electrical power system, HV power equipments are mainly subjected with spark over voltage. These over voltage which may causes by the lighting strokes, switching action, determine the safe clearance required for proper insulation level. Normally, the standard sphere gaps are widely used for protective device in such electrical power equipments. The sphere gaps are commonly used for measurements of peak values of high voltages and have been adopted by IEC and IEEE as a calibration device. The sphere gaps are filled up with insulating medium such as liquid insulation (transformer oil), solid insulation (polyester, paper) and gas insulation (SF_6, N_2, CO_2, CCl_2F_2 etc). Normally air medium is widely use as an insulating medium in different electrical power equipments as its breakdown strength is 30 kV/cm. Therefore electrical breakdown characteristic of small air gap under the different applied voltage has its great significance for the design consideration of various air insulated HV equipment.

In this work to simulate the air breakdown voltage experimentally in high voltage laboratory, standard diameter of 25 Cm spheres are used for measurement of air breakdown voltages and electric field of the high voltage equipments. The above experiment is conducted at the normal temperature and pressure. Finite element method is also used for finding 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 arrangements is also calculated with the help of COMSOL. In addition the influence of the humidity on air breakdown test has been also considered in this study. Humidity correction factor also considered in this work for maintain constant air breakdown voltage. Finally, the experimental result has been compared with theoretical, and simulation results.

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Thesis overview

CHAPTER-1

Thesis Overview

1.1 Introduction

Rapid growth in power sector of nation has given the opportunity to power engineers to protect the power equipment for reliable operation during their operating life. It has been seen from the studies conducted by power engineers that one of the main problem in high voltage power (HV) equipment is the degradation of insulation i.e., quality of insulation of power equipment. As the high voltage power equipments are mainly subjected with spark over voltage causes by the lighting strokes, switching action, a protective device is used for determine the safe clearance required for proper insulation level. The sphere gaps of different configuration are commonly used for this purpose [1-4].

The sphere gaps are commonly used for measurements of peak values of high voltages and have been adopted by IEC and IEEE as a calibration device. Many materials are used to make spheres like aluminum, steel, brass, light alloys, bronze and copper. The electric breakdown strength of a gas-insulated gap between two metal electrodes can be improved considerably when one or both of the electrodes are covered with a dielectric coating. The effect of the coating depends on the electrode shape, voltage polarity, pre-charging and the duration and form of the applied voltage [7]. In the past several decades, extensive amount of research work has been done to understand the fundamental characteristics of the electrical breakdown. Therefore, electrical breakdown characteristic of small air gap under the different applied voltage has its great significance for the design of overhead line, substation equipment and various air insulated HV equipment. In this study to simulate the air breakdown voltage experimentally in high voltage laboratory at NIT Rourkela, Aluminum made standard spheres of diameter 25 cm is used for measurement of air breakdown voltages and electric field of the high voltage equipments. The above experiment is conducted at the normal temperature and pressure. In addition the influence of the humidity on air breakdown test has been also considered in this study. The simulation of such air breakdown voltage has been carried out in the MATLAB environment. Finally, the experimental result has been compared with theoretical, and simulation results.

1.2 Motivation and objective of the Thesis

In electrical power system, high voltage (HV) power equipments are mainly subjected with spark over voltage. These over voltage which may causes by the lighting strokes, switching action, determine the safe clearance required for proper insulation level. To avoid these problems in high voltage power equipments sphere gap method is considered as one of the standard methods for the measurement of peak value of DC, AC and impulse voltages. This method is used for measuring breakdown strength of insulating materials and chooses which material has more breakdown strength. The sphere gap method is not complex and the accuracy is acceptable. This method is done in high voltage power networks because it have fallowing advantages like magnitude of current will be small, power loss will be less, it will reduce the voltage drop at line impedance and transmit power at high voltage it should give better voltage regulation.

The main objective of the thesis is

- To conduct the practical experiment of air breakdown voltage in high voltage laboratory, the theoretical study is the most important for understanding the performance characteristics of the air breakdown voltage.
- To find the air breakdown voltage and electric field for different gap between sphere electrodes using standard sphere gap experimental setup.
- To find the air breakdown voltage and electric field using finite element method for comparison among all the studies.
- To study the performance characteristics of air breakdown voltage and electric field with respect to sphere-gap, sphere-radius and humidity.
- To analyze the critical effects of maximum electric field and relative air density factor with the effect of atmosphere temperature and pressure. Also find the humidity correction factor.
- To observe effectiveness of maximum electric field between the two standard sphere electrodes by using finite element method.

1.3 Literature Review

Different topologies are developed for measure the air breakdown voltage, maximum electric field and humidity correction factor by using standard sphere gap method [1-33]. A. S. Pillai and R. Hackam are presented his work on Electric field and potential distributions for unequal spheres using symmetric and asymmetric applied voltages in 1983 [1]. E. Kuffel, W. S. Zeangle & J. Kuffel are published book on High Voltage Engineering Fundamentals for getting basic fundamentals of my work [2]. Author M. S. Naidu and V. Kamaraju together published book on High Voltage Engineering help for presented work in this thesis [3]. J. H. Colete and J. V. Merwe have done their work on the breakdown electric field between two conducting spheres by the method of images in 1998 [5]. The field utilization factor and the maximum electric field at spark over of the standard sphere gaps are proposed by Nishikori, S. Kojima, and T. Kouno in 2001 [6]. S. Phontusa and S. Chotigo have highlighted their work on the proposed humidity correction factor of positive dc breakdown voltage of sphere-sphere gap at h/δ lower than 13 g/m^3 in 2008 [8]. The humidity effect on breakdown voltage is observed by the reference of P. N. Mikropoulos, C. A. Stassinopoulos and B. C. Sarigiannidou has proposed work on positive streamer propagation and breakdown in Air considering the Influence of humidity [14]. In addition, IEC Publication 60052 shows the voltage measurement by means of standard air gaps [21]. The effect of dielectric barriers to the electric field of rod-plane air gap is recognized by A. Kara, O. Kalenderli and K. Mardikyan [25]. G. Olivier, Y. Gervais and D. Mukhedkar have presented a new approach to compute uniform field breakdown of gases [30].

1.4 Organization of the Thesis

The thesis is organized in six important chapters in which each chapter has its own way of describing and analyzing the fundamentals of the work followed by the theoretical, experimental and simulation results reveals the lubricity of the work

Chapter 1: This chapter deals with the basic introduction of the work and literature review on air breakdown voltage, electric field calculation, humidity correction factor etc. It also includes the organization of the Thesis work.

Chapter 2: In this chapter the breakdown of the different insulating material has been studied. It also covers the basic definition of "air breakdown voltage" and its nature in all insulting materials like air, gas, liquid and solids. This chapter also includes the different types of electrode arrangement (sphere-sphere, sphere-plate, rod-rod, rod-plate and plate-plate) of air breakdown voltage.

Chapter 3: This chapter deals with the experiment setup for air breakdown voltage using standard sphere- sphere electrode arrangement. In this chapter the apparatus required for measurement of air breakdown voltage, description of equipment used for air breakdown test, schematic diagram for air breakdown voltage and experimental procedure for conducting the air breakdown voltage are discussed.

Chapter 4: This chapter discussed about the measurement of air breakdown voltage using standard sphere gap method. In this chapter the detail study of the air breakdown mechanism both theoretical and simulation has been done. It also covers the study of air breakdown mechanism using Finite Element Method for finding the electric field between the sphere electrodes. In addition the effect of the humidity on air breakdown voltage has been discussed in detail. How humidity of atmosphere can influence on the air breakdown voltage and measurements of humidity correction factor are also been discussed clearly in this chapter.

Chapter 5: In this chapter discusses about results and discussion part of the thesis and all the results are furnished in a tabular as well as the graphical form to clarify the objective of the thesis. It is also covers the different type of performance characteristics of air breakdown voltage with different physical condition.

Chapter 6: Finally, in this chapter includes the conclusion of the project work and also some important discussion about the future work of the thesis which helps the advancements in technology.

CHAPTER -2

Breakdown Voltage of Insulating Materials

CHAPTER-2

Breakdown Voltage of Insulating Materials

In insulating materials valence electrons are tightly bonded to their atoms. However, insulators cannot resist indefinite amounts of voltage. With enough voltage applied, any insulating material will eventually succumb to the electrical "pressure" and electron flow will occur. An insulator is also called as a dielectric, is a material that resists the flow of electric charge. These materials are used in electrical equipment as insulators or insulation. Their function is to support or separate electrical conductors without allowing current through themselves [4]. Breakdown voltage is known as a characteristic of an insulator it can defines the maximum voltage difference that can be applied across the material before the insulator conducts and collapses. Breakdown voltage is also called as the "striking voltage" [7]. The breakdown voltages of insulating materials are divided into four types like air, gases, liquids and solids.

2.1 Breakdown Voltage of Air

The breakdown in air (spark breakdown) is the transition of a non-sustaining discharge into a self-sustaining discharge. The buildup of high currents in a breakdown is due to the ionization in which electrons and ions are created from neutral atoms or molecules, and their migration to the anode and cathode respectively leads to high currents. Townsend theory and Streamer theory are the present two types of theories which explain the mechanism of breakdown under different conditions as temperature, pressure, nature of electrode surfaces, electrode field configuration and availability of initial conducting particles [6-7]. Normally air medium is widely use as an insulating medium in different electrical power equipments and over head lines as its breakdown strength is 30kV/cm.

2.2 Breakdown Voltage of Gases

The gases are act as excellent insulators at normal temperature and pressure. The current conduction is on the order of 10^{-10} A/cm^2. This current conduction results from the ionization of air by the cosmic radiation and the radioactive substances present in the atmosphere and the earth. At higher fields the charged particles may gain sufficient energy between collisions to cause ionization on impact with neutral molecules. It is known that during an elastic collision, an electron loses its little energy and rapidly builds up its kinetic energy which is supplied by an external electric field. On the other hand, during elastic collision, a large part of the kinetic energy is transformed into the potential energy by ionizing the molecule struck by the electron. Ionization by electron impact under strong electric field is the most important process leading to breakdown of gases. This ionization by radiation or photons involves the interaction of radiation with matter. Photoionisation occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionization energy and is represented as $A + h\nu \rightarrow A+ + e$ where A represents a neutral atom or molecule in the gas and $h\nu$ the photon energy. Photo ionization is a secondary ionization process and is essential in the streamer breakdown mechanism and in some corona discharges. If the photon energy is less than the ionization energy, it may still be absorbed thus raising the atom to a higher energy level. This is known as photo excitation [4, 7].

The most common dielectric materials are gases. Many electrical apparatus use air as the insulating medium, in a few cases other gases such as N_2, CO_2, CCl_2F_2 (Freon) and SF_6 (hexafluoride) are used. Various phenomena occur in gaseous dielectrics when a voltage is applied. When low voltage is applied, small current flow between the electrodes and the insulation retains its electrical properties. If the applied voltage is large, the current flowing through the insulation increases very sharply and an electrical breakdown occur. A strongly conducting spark formed during breakdown, practically produces a short circuit between the electrodes. The maximum voltage applied to the insulation at the moment of breakdown is called the breakdown voltage. In order to understand the breakdown phenomenon in gases, the electrical properties of gases should be studied. The processes by which high currents are produced in gases are essential. The electrical discharges in gases are of two types;

i) Non-sustaining discharges

ii) Self-sustaining types.

One process that gives high breakdown strength to a gas is the electron attachment in which free electrons get attached to a neutral atoms or molecules to form negative ions. Since negative ions like positive ions are too massive to produce ionization due to collisions, attachment represents an effective way of removing electrons which otherwise would have led to current growth and breakdown at low voltages. The gases in which attachment plays an active role are called electronegative gases. Two types of attachment are encountered in gases

a) Direct attachment: An electron directly attaches to form a negative ion.

$$AB + e \cdots \rightarrow AB^{-} \tag{2.1}$$

b) Dissociative attachment: The gas molecules split into their constituent atoms and the electronegative atom forms a negative ion.

$$AB + e \cdots \rightarrow A + B^{-} \tag{2.2}$$

A simple gas for this type is the oxygen and others are sulphur hexafluoride, Freon, carbon dioxide and fluorocarbons. In these gases, ‘A’ is usually sulphur or carbon atom and ‘B’ is oxygen atom or one of the halogen atoms or molecules. There are different types of gas insulating materials are used in high voltage power equipments like SF_6, N_2, CO_2, CCl_2F_2 etc [4, 10].

2.3 Breakdown Voltage of Liquids

The electrical breakdown in liquids is less advanced than is in case of gases or even solids. Many aspects of liquid breakdown have been investigated over the last decades, but the findings and conclusions of the many workers cannot be reconciled and so produce a general theory applicable to liquids, as the independent data are at variance and sometimes contradictory. Liquid insulating materials are used for filling transformers, circuit breakers and as impregnates in high voltage cables and capacitors. For transformer, the liquid dielectric is used both for providing insulation between the live parts of the transformer and the grounded parts besides carrying out the heat from the transformer to the atmosphere thus providing cooling effect. For circuit breaker, again besides providing insulation between the live parts and the grounded parts, the liquid dielectric is used to quench the arc developed between the breaker contacts. The liquid dielectrics mostly used are petroleum oils. Other oils used are synthetic hydrocarbons and halogenated hydrocarbons and for very high temperature applications silicone oils and fluorinated hydrocarbons are also used [4].

Three most important properties of liquid dielectric are (*a*) The dielectric strength (*b*) The dielectric constant and (*c*) The electrical conductivity. Other important properties are viscosity, thermal stability, specific gravity, flash point etc. The most important factors which affect the dielectric strength of oil are the, presence of fine water droplets and the fibrous impurities. The presence of even 0.01% water in oil brings down the dielectric strength to 20% of the dry oil value and the presence of fibrous impurities brings down the dielectric strength much sharply. Therefore, whenever these oils are used for providing electrical insulation, these should be free from moisture, products of oxidation and other contaminants [4, 11].

The breakdown in liquid insulating materials on a model which is an extension of gaseous breakdown, based on the avalanche ionization of the atoms caused by electron collision in the applied field. The electrons are assumed to be ejected from the cathode into the liquid by either a field emission or by the field enhanced thermionic effect (Shottky's effect). This breakdown mechanism explains breakdown only of highly pure liquid and does not apply to explain the breakdown mechanism in commercially available liquids. It has been observed that conduction in pure liquids at low electric field (1kV/cm) is largely ionic due to dissociation of impurities and increases linearly with the field strength. At moderately high fields the conduction saturates but at high field (electric), 100 kV/cm the conduction increases more rapidly and thus breakdown takes place. Different types of liquid insulating materials are used in high voltage power equipments like transformer oil, cementitious, phenolic, polyisocyanurate, Polyurethane etc [4, 11].

2.4 Breakdown Voltage of Solids

Solid insulating materials are used almost in all electrical equipments, be it an electric heater or a 500 MW generator or a circuit breaker, solid insulation forms an integral part of all electrical equipments especially when the operating voltages are high. The solid insulation not only provides insulation to the live parts of the equipment from the grounded structures, it sometimes provides mechanical support to the equipment. In general, of course, a suitable combination of solid, liquid and gaseous insulations is used. The processes responsible for the breakdown of gaseous dielectrics are governed by the rapid growth of current due to emission of electrons from the cathode, ionization of the gas particles and fast development of avalanche process. When breakdown occurs the gases regain their dielectric strength very fast, the liquids regain partially and solid dielectrics lose their strength completely [11].

The breakdown voltage of solid materials is affected by many factors viz. ambient temperature, humidity, duration of test, impurities or structural defects whether AC, DC or impulse voltages are being used, pressure applied to these electrodes etc. The mechanism of breakdown in solids is again less understood. However, as is said earlier the time of application plays an important role in breakdown process, for discussion purposes, it is convenient to divide the time scale of voltage application into regions in which different mechanisms operate. The various mechanisms are: (*a*) Intrinsic Breakdown (*b*) Electromechanical Breakdown (*c*) Breakdown Due to Treeing and Tracking (*d*) Thermal Breakdown (*e*) Electrochemical Breakdown [7].

Under some certain strictly controlled experimental conditions the breakdown of solids may therefore be accomplished by a process similar to gas breakdown. Under normal industrial conditions, however, the same solid materials are found to exhibit a wide range of dielectric strength, depending upon the conditions of the environment and the method of testing. The measured breakdown voltage is influenced by a large number of external factors such as temperature, humidity, duration of test, whether AC, DC, or impulse voltage is applied, pressure applied to the electrodes, discharges in the ambient medium, discharges in cavities and many other factors. There are different types of solid insulating materials are used in high voltage power equipments like Mica muscovite, High-grade porcelain, Capacitor paper, Ebonite, Polythene, Polystyrene, Acrylic resins etc [2].

2.5 Different Type of Electrode Arrangement for Measurement of Breakdown Voltage

IEC 60052 sets four recommendations concerning the construction and use of standard air gaps for the measurement of peak values of some like alternating voltages of power frequencies, full lightning impulse voltages, switching impulse voltages and direct voltages are involves unusual problems that may not be familiar to specialists in the common electrical measurement techniques. These problems increase with the magnitude of the voltage, but are still easy to solve for voltages of some 10 kV only, and become difficult if hundreds of kilovolts or even megavolts have to be measured. The difficulties are mainly related to the large structures necessary to control the electrical fields, to avoid flashover and sometimes to control the heat dissipation within the circuits also. The high voltage power equipments have large stray capacitances with respect to the grounded structures and hence large voltage gradients are set up. A person handling these equipments and the measuring devices must be protected against these over voltages. For this, large structures are required to control the electrical fields and to avoid flash over between the equipment and the grounded structures. Sometimes, these structures are required to control heat dissipation within the circuits. Therefore, the location and layout of the equipments is very important to avoid these problems [21]. There are various types of electrode arrangements and circuits for measurement of high voltages and currents. Those are (*i*) Sphere-Sphere (*ii*) Sphere-Plate (*iii*) Rod-Rod (*iv*) Rod-Plate (*v*) Plate-Plate

(i) Sphere-Sphere

The standard sphere gap is the one of the standard methods for the measurement of peak value of DC, AC and impulse voltages and is used for checking the high voltage power equipments and other voltage measuring devices used in high voltage test circuits. Two identical metallic spheres are separated by certain distance form a sphere gap. Also, the gap length between the spheres should not exceed a sphere radius. If these conditions are satisfied and the specifications regarding the shape, mounting, clearances of the spheres are met, the results obtained by the use of sphere gaps are reliable to within ±3%. It has been suggested in standard specification that in places where the availability of ultraviolet radiation is low, irradiation of the gap by radioactive or other ionizing media should be used when voltages of magnitude less than 50 kV are being measured or where higher voltages with accurate results are to be obtained.

In this arrangement one sphere normally shall be connected directly to earth. Low ohmic shunts may be connected between the sphere and earth of special purpose. The surfaces of spheres shall be cleaned and dried but need not be polished. In normal use the surfaces of spheres become roughened and pitted. The surface should be rubbed with fine abrasive paper and the resulting dust removed with lint-free cloth any trace of oil or grease should be removed with a solvent. Moisture may condense on the surface of the sparking points in conditions of high relative humidity causing measurements to become erratic. So the spheres are made with their surfaces are smooth and their curvatures as uniform as possible. The curvature should be measured by a spherometer at various positions over an area enclosed by a circle of radius 0.3 *D* about the sparking point where '*D'* is the diameter of the sphere and sparking points on the two spheres are those which are at minimum distances [4, 7].

Sphere gaps can be arranged in vertically, typically with the lower sphere grounded (earthed), and horizontally from each other. The surroundings do have an effect on the breakdown voltage, as they alter the field configuration. Standard clearances are specified for spheres of various sizes in both configurations. These clearances reduce the effect of the surroundings to less than the specified accuracy (e.g. 3%). In the following: 'D' is the diameter of the spheres, 'S' is the spacing of the gap, $S/D \leq 0.5$. 'A' is the height of the lowest point of the HV sphere above the ground. 'B' is the radius of clearance from surrounding constructions. Figure 2.1 shows the vertical arrangement of sphere gap method.

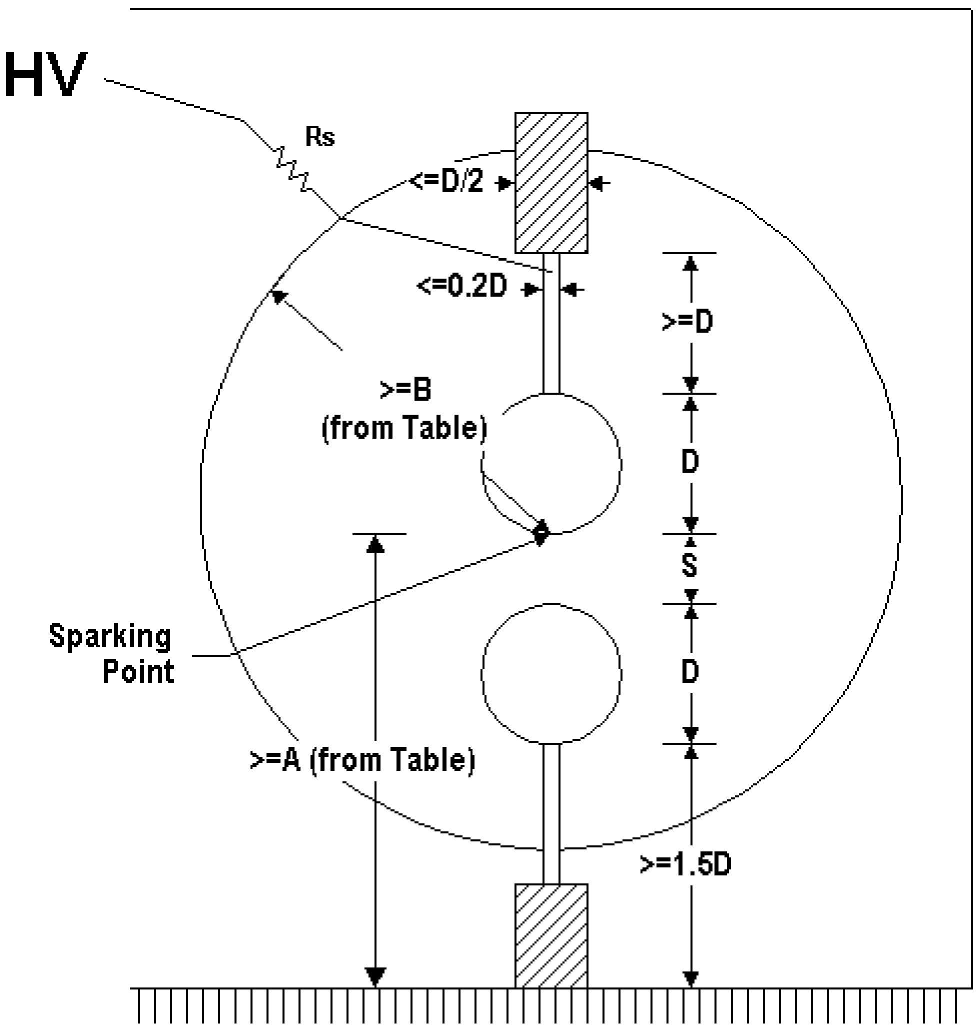

Fig.2.1. Vertical sphere gap schematic diagram [12].

The insulator supporting the upper sphere should be less than 0.5 D in diameter. The sphere itself should be supported by a conductive metal shank no more than 0.2 D in diameter and at least D in length (that is, the sparking point should be at least 2D from the lower end of the upper insulator). The high voltage lead should not pass near the upper electrode. Ideally it should be led away from shank avoiding crossing a plane perpendicular to the shank at least 1 D away from the sphere (i.e. 2 D away from the sparking point, until it is outside of a sphere of radius B from the sparking point. The top of the lower electrode should be at least 1.5D above the (presumably) grounded floor. Figure 2.2 indicates horizontal sphere gap arrangement.

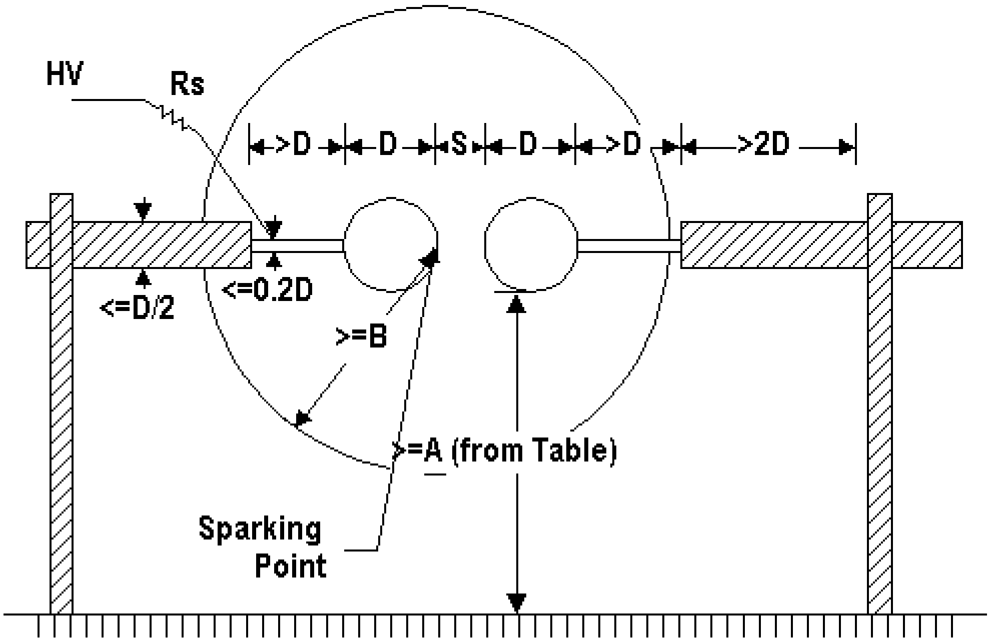

Fig.2.2. Horizontal sphere gap schematic diagram [12].

Horizontal gaps are much the same as vertical gaps, except that both electrodes are insulated. The insulators should be longer, at least 2D long (putting the sparking point at least 4D from the supports: 2D for the insulator, 1D for the shank, 1D for the sphere). And, both spheres should be the appropriate clearance from the floor or external objects. In these arrangements or smaller size, the spheres are placed in horizontal configuration whereas large sizes (diameters), the spheres are mounted with the axis of the sphere gaps vertical and the lower sphere is grounded [12]. The sphere-sphere electrode arrangement is shown in Fig.2.3.

Fig.2.3. Sphere-Sphere electrode arrangement.

In either case, it is important that the spheres should be so placed that the space between spheres is free from external electric fields and from bodies which may affect the field between the spheres [12].

(ii) Sphere-Plate

A sphere-plane electrode system was designed and used for the measure the breakdown voltage and electric field in all types of insulating materials. This electrode arrangement is considered as a non-uniform field because the surfaces of both the electrodes are not similar. The maximum electric field in gap between the electrodes is

$$E_{Max} = 0.9\frac{V}{x}\ \frac{a+x}{a} \tag{2.3}$$

where, V is the Voltage applied, x is the distance between the sphere and the plane plate and a is the radius of the sphere. The sphere-plate electrode arrangement is shown in Fig.2.4.

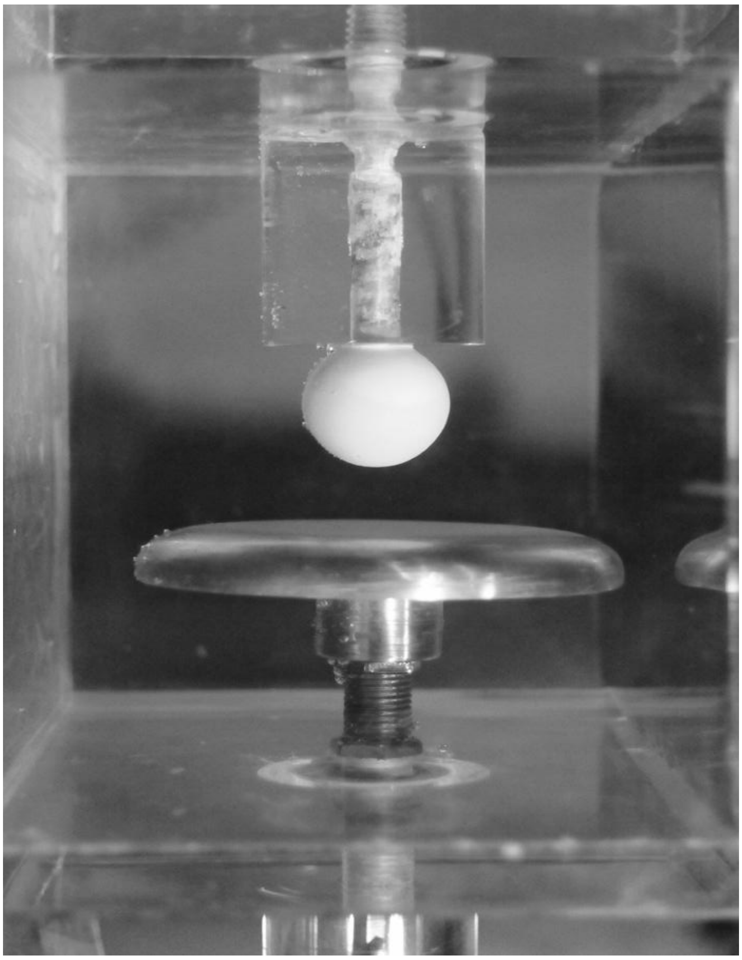

Fig.2.4. Sphere-Plate electrode arrangement [32].

(iii) Rod-Rod

Rod gap is used to measure the peak values of power frequency alternating voltages, direct voltages and impulse voltages. The gap usually consists of two 1.27 cm square rod electrodes square in section at their end and are mounted on insulating stands so that a length of rod equal or greater than one half of the gap spacing overhangs the inner edge of the support. The breakdown voltages as found in different gap lengths as well as any atmospheric conditions also. The breakdown voltage for the same spacing and the uncertainties associated with the influence of humidity, rod gaps are no longer used for measurement of AC or impulse voltages.

The breakdown voltage in gap between the electrodes is

$$V = \delta(A + BS)\, 4\sqrt{5.1 \times 10^{-2}(h + 8.65)}\ \text{kV} \qquad (2.4)$$

where, h is the absolute humidity in gm/m3, B is independent of the polarity of voltage, A is polarity dependent and has the values of the high voltage electrode and S is gap spacing between electrodes [7]. Rod-Rod electrode arrangement is given in the Fig.2.5.

Fig.2.5. Rod-Rod electrode arrangement [20].

(iv) Rod-Plate

In this arrangement the ground effect also affects the breakdown voltage of the rod-plate air gaps but in a quite different way than the Polarity Effect. The values of the breakdown voltage depend on the maximum value of the field strength in the gap between the electrodes, as well as the corona leakage current through the gap. According to the Polarity Effect the breakdown voltage is considerably higher in the arrangement with negative polarity on the rod because of the intensive corona effects. The ground effect the breakdown voltage is higher in the arrangement with the rod grounded because the maximum value of the field strength is lower. Ground effect is intense in small rod-plate air gaps, while the influence of the corona leakage current and the Polarity Effect appears in longer air gaps. This electrode arrangement is considered as a non-uniform field because the surfaces of both the electrodes are not similar.

The average value of the field strength of an air gap is defined by equation

$$E_{av} = \frac{V}{G} \quad (2.5)$$

The field factor (or efficiency factor) n is

$$n = \frac{E_{max}}{E_{av}} = \frac{2G}{r.ln\frac{4G}{r}} \quad (2.6)$$

where, V is the applied voltage, G is the gap length, E_{max} is the maximum value of the field strength and r is the radius of the rod's tip [20]. The rod-plate electrode arrangement is displayed in Fig.2.6.

Fig.2.6. Rod-Plate electrode arrangement [20].

(v) Plate-Plate

The plate- plate electrode arrangement is also called as uniform field spark gap. These gaps provide accuracy to within 0.2% for alternating voltage measurements an appreciable improvement as compared with the equivalent sphere gap arrangement. The advantages of this electrode arrangement are no influence of nearby earthed objects, no polarity effect. However, the disadvantages are very accurate mechanical finish of the electrode is required, Careful parallel alignment of the two electrodes and Influence of dust brings in erratic breakdown of the gap. This is much more serious in these gaps as compared with sphere gaps as the highly stressed electrode areas become much larger. Hence, a uniform field gap is normally not used for high voltage measurements. Plate-Plate electrode arrangement is shown in the Fig.2.7.

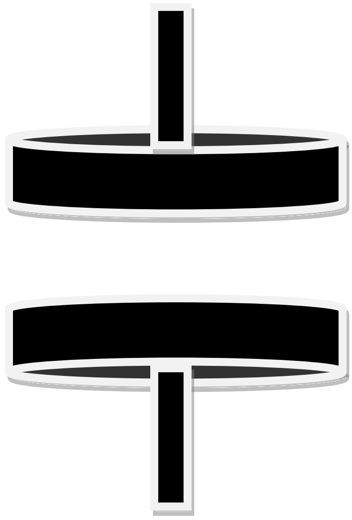

Fig.2.7. Plate-Plate electrode arrangement.

At normal temperature and pressure the breakdown voltage of air in the gap between plate- plate electrodes is

$$V = 24.22\,S + 6.08\sqrt{S} \tag{2.7}$$

where, S is the gap length between the electrodes. In recent years, however, there has been a growing interest in the effects of the electrode area and stressed volume on the breakdown voltage of plate-plate gaps. The uniformity of the field along the electrode surface has also taken on a certain importance as it directly affects both the useful electrode area and stressed volume. In plate-plate electrode arrangement electric field is maintained maximum and uniform [7].

CHAPTER - 3

Experiment Setup for Air Breakdown Voltage using Standard Sphere-Sphere Electrode Arrangement

CHAPTER-3

Experiment Setup for Air Breakdown Voltage Using Standard Sphere-Sphere Electrode Arrangement

3.1 Apparatus Required for Measurement of Air Breakdown Voltage

To conduct the air breakdown test using standard sphere-sphere electrode in the high voltage laboratory the following apparatus is required

(a) Control Panel
(b) Circuit Breaker
(c) High Voltage Transformer
(d) High Voltage Filter
(e) Voltage Divider
(f) Sphere-sphere gap arrangement

3.2 Description of Used Equipment for air Breakdown Voltage Measurement

The brief description of all used equipments for measurement of air breakdown voltage is given below.

(a) Control Panel

It is the one of the important integral part for conducting the air breakdown voltage by using standard sphere gap method. The control panel consists of all the measuring instruments including the safety, controlling switch such as voltmeter, ammeter, circuit breaker, alarm etc. which is shown in Fig. 3.1. The main function of the control panel is to control all equipment under test.

Fig.3.1. Control panel used for conducting the air breakdown test.

By changing the knob of the voltage regulator applied voltage is changed on the test objects. In this experiment the gap distance between the spheres is changing from control panel by controlling the motor speed connected to the gear box of the movable sphere electrode. During the experiment the breakdown voltage at the particular gap distance between the sphere electrodes is displayed in the control panel.

(b) Circuit Breaker

A circuit breaker is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit. The main function of circuit breaker is to indentify fault in circuit and isolate it. In high voltage circuits mainly occurring faults are symmetrical faults, asymmetrical faults and earth faults. Once a fault is detected and the contacts within the circuit breaker must open to interrupt the circuit, some mechanically stored energy contained within the breaker is used to separate the contacts and although some of the energy required may be obtained from the fault current itself. The circuit breaker contacts must carry the load current without excessive heating, and must also withstand the heat of the arc produced when interrupting the circuit. Contacts are made of copper or copper alloys, silver alloys, and other materials. Service life of the contacts is limited by the erosion due to interrupting the arc. Miniature and high-voltage circuit breakers have replaceable contacts. When a current is interrupted, an arc is generated. This arc must be contained cooled and extinguished in a controlled way, so that the gap between the contacts can again withstand the voltage in the power circuit. Hence, once the fault condition has been cleared then the contacts must again be closed to restore power to the interrupted circuit. Circuit breakers are made in varying sizes, from small devices that protect an individual household appliance up to large switchgear designed to protect high voltage circuits feeding industries. These high voltage circuit breakers improve the system stability and availability.

(c) High Voltage Transformer

A transformer is a static device. It transfers electrical energy from one circuit to another circuit through inductively coupled conductors the transformer's coils. A varying current in primary winding creates a varying magnetic flux in the transformer's core and thus a varying magnetic field through the secondary winding. This varying magnetic field induces a varying electromotive force (EMF) in the secondary winding. This effect is called mutual induction. In this arrangement high voltage step up transformer having power rating of 15 kVA, 400V/100kV is used which is shown in Fig. 3.2. As the voltage goes up, the current goes down by the same proportion.

Fig.3.2. High voltage transformer used for air breakdown test.

(d) High Voltage Filter

In high voltage power networks are suffered mainly with higher order harmonics in the supply, to reduce these harmonics high voltage filters are mostly used. Due to the higher order harmonics; increased losses, resonance problems between the inductive and capacitive parts of the power network, overloading of capacitors, leading to malfunctioning and premature aging, interference with telecommunications and computers, disturbances in ripple control systems and high currents in neutral conductor's problems are occurred. These filters have several benefits like higher power factor, improved voltage stability and network losses, filtering of harmonics in the system, avoidance of resonance problems and amplification of electrical disturbances.

(e) Voltage Divider

The voltage divider is also an important part of the experiment used for measurement of high voltage. Voltage divider is also known as a potential divider. This is a simple linear circuit that produces an output voltage (V_{out}) that is a fraction of its input voltage (V_{in}). Voltage division refers to the partitioning of a voltage among the components of the divider. It is commonly used to create a reference voltage or to get a low voltage signal proportional to the voltage to be measured and may also be used as a signal attenuator at low frequencies. Potential divider is used to measure voltages in power equipments, reasonable gain without losing stability of circuit.

3.3 Experimental Procedure for Conducting the Air Breakdown Voltage

To conduct the air breakdown test between the sphere electrode all the measuring instrument is standardized as per IS 2071. The experimental setup for air breakdown study between the two spheres electrode are shown in Fig.3.3.

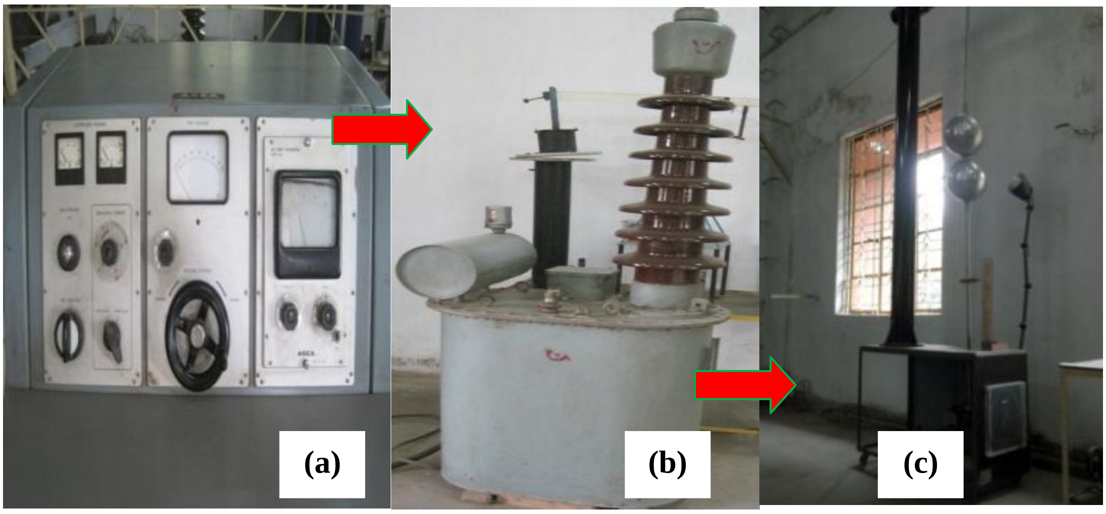

Fig.3.3. Experimental setup in high voltage test laboratory for study of air breakdown voltage using standard sphere gap method (a) Control panel for conducting the air breakdown test (b) High voltage transformer (c) Two spheres are arranged vertically having 25 cm diameter each.

The schematic diagram for experimental setup of air breakdown voltage test using standard sphere gap method is shown in Fig. 3.4.

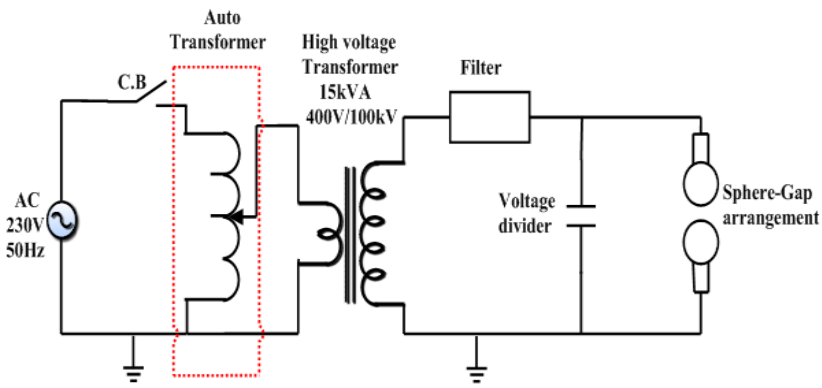

Fig.3.4. Schematic Circuit showing the source and Breakdown voltage measuring unit using standard sphere gap method.

In this study two identical sphere electrodes have been used for the experimental study of the short air gap. The sphere electrodes are vertically aligned. The lower sphere electrode which is above the ground plane is grounded where as the top sphere electrode is connected with HV connector. The used sphere electrode has a diameter of 25 cm and the electrode is made of Aluminum material with nickel coating and air is acting as an insulating medium between sphere electrodes. Before conducting the test the two sphere electrodes are cleaned with carbon tetra chloride (CCl_4) so that it is free from floating dust particles, fibers. The upper sphere electrode is connected in the high voltage terminal and the lower electrode is connected with the ground terminal. With the application of the high voltage between the sphere electrodes, a non-uniform electric field is generated as the surfaces of the sphere electrodes are not uniform. The HV electrode is energized from the 50 Hz transformer with a power rating of 15kVA with a transformation ratio of 400V/100kV. The applied voltage is raised to 75% of the estimated voltage and thereafter the voltage is raised 2% of the test voltage per second.

The test voltages are applied through the filter unit to isolate the noise of the transformer from the measuring circuit and current limiting device for protect in case of complete breakdown and prevent the high frequency current to the high voltage lead. At the inception of the breakdown the circuit is immediately disconnected from the supply and the breakdown voltage is recorded. A coupling device with connecting cable is associated with the measuring circuit for the measurement of the applied high voltages magnitude. The experimental study has been conducted for air breakdown test between the sphere electrodes at normal temperature of 31.1℃, atmospheric pressure of 760 mm of Hg and also the humidity of the air has been recorded 14% during the experiment. For each 0.5 cm of gap between the sphere electrodes, the air breakdown voltage is recorded in this study. The gap between the sphere electrodes is varies from the range of 1cm to 5.5 cm.

CHAPTER -4

Measurement of Air Breakdown Voltage and Electric field using Standard Sphere Gap Method

CHAPTER-4

Measurement of Air Breakdown Voltage and Electric field using Standard Sphere Gap Method

4.1 Theoretical Study of Air Breakdown Voltage

Measurement of high voltages and currents are having more complex and these equipments have large stray capacitance and large voltage gradient. High voltage equipments are protected against over voltages. Sphere gap method is the one of the standard method for measurement of peak values of AC, DC voltages in high voltage circuits. The gap distance between the spheres should not exceed the radius of the sphere. In short duration of time we can measure the breakdown voltage using this method. Sphere electrodes are made with many materials like aluminum, steel, brass, light alloys, bronze and copper [2].

The electric breakdown strength of a gas-insulated gap between two metal electrodes can be improved considerably when one or both of the electrodes are covered with a dielectric coating, so-called hybrid insulation. The effect of the coating depends on the electrode shape, voltage polarity, pre-charging and the duration and form of the applied voltage. Dielectric barriers in air and oil gaps are well known for bringing improvement to the electric breakdown strength and widely used in high voltage engineering. For example in oil insulated power transformers. Barriers help preventing short circuiting caused by the bridging of particles in the transformer oil, increasing the withstand voltage compared to an oil gap without barriers.

In this method air is acting as an insulating medium between the spheres. The atmospheric air is the combination of various types of gas molecules which influence the breakdown voltage of the system. By increasing the applied voltage between the sphere gaps the breakdown of air takes place at a certain applied voltage which is call as breakdown voltage. The influence of the grounded objects and the shanks, connecting the spheres to the HV supply and to the ground, on the breakdown voltage and the field between equal spheres was reported to be small (a few percent) and depended on the dimensions of the spheres, the gap separation, and the shanks [2-18].

To conduct the practical experiment of air breakdown voltage in high voltage laboratory, the theoretical study is the most important for understanding the performance characteristics of the air breakdown voltage. The voltage between the spheres rose till a spark passes between the two spheres. The value of the voltage required to spark over (breakdown) depends upon the dielectric strength of air, the size of the spheres, the distance between the spheres, humidity of the air and many other factors. The breakdown voltage of a sphere gap increases by increasing the pressure quantity and decreases by increasing the temperature quantity. The air density factor

$$\delta = \frac{293b}{760(273+t)} \tag{4.1}$$

where, atmospheric pressure is 'b' in mm of Hg and Temperature is't' in ºC and the breakdown voltage of air between the sphere gap

$$\mathrm{V} = \frac{27.2\delta r\left(1+\frac{0.54}{\sqrt{\delta r}}\right)\frac{s}{r}}{0.25\left(\frac{s}{r}+1+\sqrt{\left(\frac{s}{r}+1\right)^2+8}\right)} \tag{4.2}$$

where, gap between sphere electrodes is 'S' in cm and radius of the sphere electrode is 'r' in cm, electric field in the gap is $\frac{\mathrm{V}}{d}$ where, distance between the sphere electrode is 'd' in cm. Some of the other factors which influence the breakdown value of air are briefly discussed in below [7-19].

(a) Impact on Nearby Earthed Objects

The impact on nearby earthed object on the direct voltage breakdown of horizontal gaps was studied by E. Kuffel and Husbands. The breakdown voltage reduced materially especially when the gap length exceeded a sphere radius. The experiments were conducted on 12.5 cm diameter sphere and gap between the sphere electrodes is varies from the range of 1cm to 5.5 cm. The reduction in the breakdown voltage for a given *S*/*D* fitted closely into an empirical relation of the form

$$\Delta \mathrm{V} = \mathrm{m} \ln \frac{\mathrm{B}}{\mathrm{D}} + \mathrm{C} \tag{4.3}$$

where, ΔV is the per cent reduction in voltage in the breakdown voltage, B is the radius surrounding metal cylinder and m and C are the factors dependent on the ratio *S/D* [7].

(b) Impact on Dust Particles

When a dust particle is floating between the electrodes gaps these results into wandering breakdown in homogeneous or slightly inhomogeneous electrode configurations. When the dust particle comes in contact with one electrode under the application of DC voltage, it gets charged to the polarity of the electrode and gets attracted by the opposite electrode due to the field forces and the breakdown is triggered shortly before arrival. Sphere gaps subjected to AC voltages are also sensitive to dust particles but the probability of wandering breakdown is less. Under DC voltages wandering breakdowns occur within a few minutes even for voltages as low as 80% of the nominal breakdown voltages. This is a major problem, with high DC voltage measurements with sphere gaps [7].

In this method maximum electric field is

$$E_{max} = 27.9\delta(1 + 0.533\sqrt{\delta r}) \qquad (4.4)$$

According to IEC 60052 (2002) the breakdown voltage values U (kV) measured under actual conditions with the temperature t (^{o}C), the pressure P (mmHg) and the absolute humidity h (%) were reported to standard reference atmosphere as defined by Eq.

$$U = \frac{V}{\delta * K} \qquad (4.5)$$

As the air breakdown voltage is also depends on the humidity in the air, considering the humidity factor (k) in this study the modified air breakdown voltage.

$$V = \delta \times \left[1 + \left(0.002 \times \left(\frac{h}{\delta} - 8.5\right)\right)\right] \times U \qquad (4.6)$$

where, $k = \left[1 + \left(0.002 \times \left(\frac{h}{\delta} - 8.5\right)\right)\right]$ and 'U' is the voltage at standard reference atmosphere [8, 21].

4.2 Simulation Study of Air Breakdown Voltage

The present research work focused on the experimental validation of the air breakdown characteristics in high voltage test laboratory and a thorough comparison is made with the theoretical calculations with computer simulation results. The present research work includes comparison of experimental results with the results derived from the empirical formulations (Eqn.4.1, 4.2 and 4.6) with the MATLAB environment. To simulate the practical breakdown test of air the input parameters such as sphere diameter, gap between sphere electrodes, atmospheric pressure, humidity presence in air and temperature are taken 25 cm, range from 1 cm to 5.5 cm, 760mm of Hg, 2-32% and 31.1℃ respectively.

In this study the unknown parameters such as air breakdown voltage and electric field for each 0.5 cm of gap between the sphere electrodes are calculated and further compared with the experimental study. As the air breakdown voltage and electric field is the function of electrode geometry, the different radius of sphere electrodes (i.e., 2.5cm, 5cm, 7.5cm and 12.5cm) are also considered in computer simulation. In this simulation study the maximum electric field and relative air density factor are determined at each temperature (10^0 to 80^0C; -10^0 to -80^0C) and pressure (710 to 780 torr.) of atmosphere. Humidity correction factor, air breakdown voltage and maximum electric field are found at different humidity of air in atmosphere.

4.3 Finite Element Method for Electric Field

Finite element method is used in a wide variety of engineering problems like solid mechanics, dynamics, heat problems, fluids and electrostatic problems. Finite element analysis cuts a structure into several elements (pieces of the structure). This process results in a set of simultaneous algebraic equations. The behavior of electric field is based on the nature of electrodes (uniform and non-uniform). Finite element method uses the concept of piece wise polynomial interpolation. By connecting elements together, the electric field quantity becomes interpolated over the entire structure in piece wise fashion. In this method indeterminate structures are solved. It can be handled complex loadings like nodal load (point loads), element load (pressure, thermal and inertial forces) and time or frequency dependent loading [33].

The modeling and analysis of electric field distribution in sphere-sphere electrode is done by using COMSOL software. In this software to construct sphere gap arrangement using all the required numerical and physical parameters. And find out maximum electric field in between sphere electrodes. The apparatus, shown in Fig.3.3, consists mainly of two vertically fixed sphere electrodes separated with a gap. The electrodes serve as the electrodes that are connected to a high-voltage transformer driven by the frequency-convertible power supply. Two spheres were made with aluminum. Both the spheres were located in the center region by adjusting the diameter and gap between electrodes. Two spheres were precisely arranged with their vertical axes parallel to the applied electric field. In the experiments, the attractive force between the two spheres was measured. This software provides a wide range of simulation applications for controlling the complexity of both modeling and analysis of a system. Similarly, the desired level of accuracy required and associated computational time requirements can be managed simultaneously to the address of most engineering applications. Finite element method allows entire designs to be constructed, optimized, and refined before the design is manufactured. The 2D and 3D effects of electric field also discovered in this scenario. This method is helpful for draw the line plots between different parameters. Line plots changes with respect to the place of the electric field between the sphere electrodes.

4.3.1. Simulation of Electric Field

The simulation of electric fields in three different configuration is observed using COMSOL Multi-physics software [11]. In electrostatics, Maxwell's equations and constitutive equation reduce to the following form

$$\nabla \times E = 0 \tag{4.7}$$

$$\nabla \cdot D = \rho \tag{4.8}$$

$$D = \varepsilon E \tag{4.9}$$

where, E is the electric field intensity, D is the electric displacement, ρ is the space charge density, ε is the dielectric permittivity of the material. Based on Eq. (4.7), electric field intensity is introduced by the negative gradient of the electric scalar potential V in following form

$$E = -\nabla . V \tag{4.10}$$

Substituting equations (4.8) and (4.9) in (4.7) Poisson's scalar equation is obtained as

$$-\nabla \cdot (\varepsilon \nabla V) = -\nabla \cdot (\varepsilon_0 \varepsilon_r \nabla V) = \rho \tag{4.11}$$

where, ε_0 is the permittivity of free space, $\varepsilon_r = \varepsilon_r(E, x, y, z)$ is the relative permittivity and ρ is the space charge density. If the permittivity ε is constant such as in the isotropic dielectrics, Eqn. (26) becomes

$$\Delta V = -\rho\ \varepsilon \tag{4.12}$$

For space charge free (ρ = 0) fields, field is expressed by Laplace's equation as ΔV = 0.
In this study, solution of the problem is obtained from solution of Laplace's equation in rectangular coordinates.

$$\nabla^2 V = \frac{\partial^2 V}{\partial^2 x} + \frac{\partial^2 V}{\partial^2 y} + \frac{\partial^2 V}{\partial^2 z} \tag{4.13}$$

V = Breakdown voltage on the upper electrode,
V = 0 Volt (ground) on the lower electrode,
∂V/∂n = 0 on all other outer boundaries and on the symmetry axis.

4.4 Effect of Humidity on Air Breakdown Voltage

Air breakdown voltage is influenced by the effect of the humidity. In air, increasing humidity increases the breakdown voltage. The effect is most perceptible in uniform field and less important in non-uniform gaps (such as sphere gaps where the gap is a large fraction of the sphere diameter or in needle or rod gaps). The effect was found to be maximum in some locations and minimum in some locations. The relation between breakdown voltage and humidity was practically linear for spacing less than that which gave the maximum humidity effect. Figure 6.10 shows the effect of humidity on the breakdown voltage of a 25 cm diameter sphere with spacing of 4 cm when AC voltages are applied. In this humidity effect AC breakdown voltage is slightly less than DC voltage and air breakdown voltage increases with the partial pressure of water vapour. Insulating liquids derive their dielectric strength from the much higher density compared to gases. The breakdown process expects the following impacts:

- Moisture delivers charge carriers and therefore decreases the dielectric withstand strength.
- Aging byproducts such as acids also deliver charge carriers through dissociation. Additionally they are surface-active, decreasing the surface tension. Thus they support bubble evolution following into a decreased dielectric strength.
- With increasing pressure the breakdown voltage should increase. For pressures below the atmospheric pressure the breakdown voltage should decrease.
- A decreased air breakdown voltage is expected of they are highly conductive or wet.

The humidity effect increases with the size of spheres and is largest for uniform field electrodes. Air breakdown voltage changes for a given humidity change increase with gap length. The increase in breakdown voltage with increase in partial pressure of water vapour and this increase in voltage with increase in gap length is due to the relative values of ionization coefficients in air. The water particles readily attach free electrons, forming negative ions. These ions therefore slow down and are unable to ionize neutral molecules under field conditions in which electrons will readily ionize. Humidity also influence on maximum electric field and humidity correction factor [13-14].

4.5 Measurement of Humidity Correction Factor

The breakdown voltage obtained in air will be affected by atmospheric condition such as temperature and absolute humidity. According to IEC 60052 (2002), the absolute humidity and relative air density are effects on air breakdown voltage in the standard sphere gap method. In this work determines the humidity correction factor. The gap configurations used in this present work were sphere-sphere gaps made of aluminum nickel coated with the diameter of 25 cm. The humidity correction factor was helpful to correct the breakdown voltage at each value of humidity.

In this work taken humidity range in between 0-32% and find the corresponding humidity factor. This work investigates the influence of humidity on the AC breakdown voltage and determines the humidity correction factor was suitable for application in all atmospheric conditions. In measurement of humidity correction factor the input parameters are temperature is 31.1^{0}C, pressure is 760 mm of hg and gap between sphere electrodes is 4cm taken.

Humidity correction factor of sphere-sphere gap

$$k = \left[1 + \left(0.002 \times \left(\frac{h}{\delta} - 8.5\right)\right)\right] \quad (4.14)$$

where, h is humidity of air and δ is the relative air density factor [8, 21,24].

CHAPTER -5

Results and Discussions

CHAPTER 5

RESULTS AND DISCUSSIONS

To simulate the performance characteristic of the air breakdown voltage (BDV) and maximum electric field between the conducting spheres, two standard sphere electrodes is taken into considered in this work using MATLAB simulation. The main focus of the analysis is variation of breakdown voltage versus electrode gap with different diameters. This characteristic provides significant information on the withstanding capacity of the insulation to sustain the high spark over voltage. The air breakdown voltage between the sphere electrodes are measured by conducting the air breakdown voltage in high voltage laboratory and corresponding electrical field strength and % of error BDV are calculated from the experimental, theoretical and simulation results which is depicted in Table 1.

TABLE-I

MEASUREMENT OF BREAKDOWN VOLTAGE AND ELECTRIC FIELD STRENGTH BETWEEN SPHERES

Sphere Gap (cm)	BDV Experiment (kV)	BDV Theory (kV)	BDV Simulation (kV)	Electric field Experiment (kV/cm)	Electric field Theory (kV/cm)	Electric field Simulation (kV/cm)	%Error (BDV)
1.0	19.5	21.92	33.65	19.50	21.92	33.65	11.0
1.5	30.0	32.17	40.32	20.00	21.44	26.88	6.7
2.0	37.0	41.71	53.12	18.50	20.85	26.56	11.2
2.5	49.0	51.40	59.27	19.60	20.56	23.70	4.6
3.0	58.0	60.81	65.25	19.34	20.27	21.75	4.6
3.5	65.0	70.00	71.07	18.57	20.00	20.30	7.1
4.0	74.0	79.19	76.74	18.50	19.79	19.18	6.5
4.5	82.0	88.38	82.26	18.23	19.64	18.28	7.2
5.0	85.0	97.58	87.63	17.00	19.51	17.52	12.8
5.5	97.0	99.77	92.86	17.63	19.41	16.88	9.1

*BDV=Breakdown Voltage

The performance characteristic of air breakdown voltage versus electrode gap for sphere electrodes of 25 cm diameter is shown in Fig.5.1. In this Fig the theoretical BDV [10] and simulation BDV for different electrode gap spacing are plotted with experimental results.

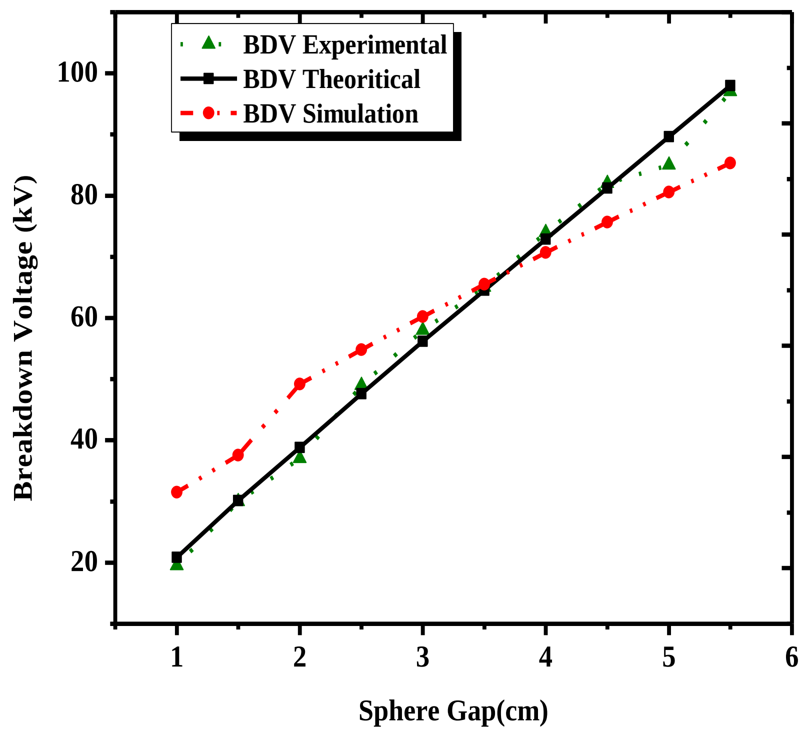

Fig.6.1. Comparison plot between sphere-gap and breakdown voltage in experimental, simulation and theoretical.

It is clear from the Fig.5.1 that the gap between the sphere electrode is varies in the wide range from 1 cm to 5.5 cm and the corresponding breakdown voltage is varies in the range from 19.5 kV to 99.77 kV. It is also observed that the increase of sphere gap the air breakdown voltage is also increases. Figure 5.2 shows that electric field distribution along the gap distance in between the sphere electrode. In this Fig. 5.2 the theoretical electric field and simulation electric field for different electrode gap spacing are plotted with experimental results.

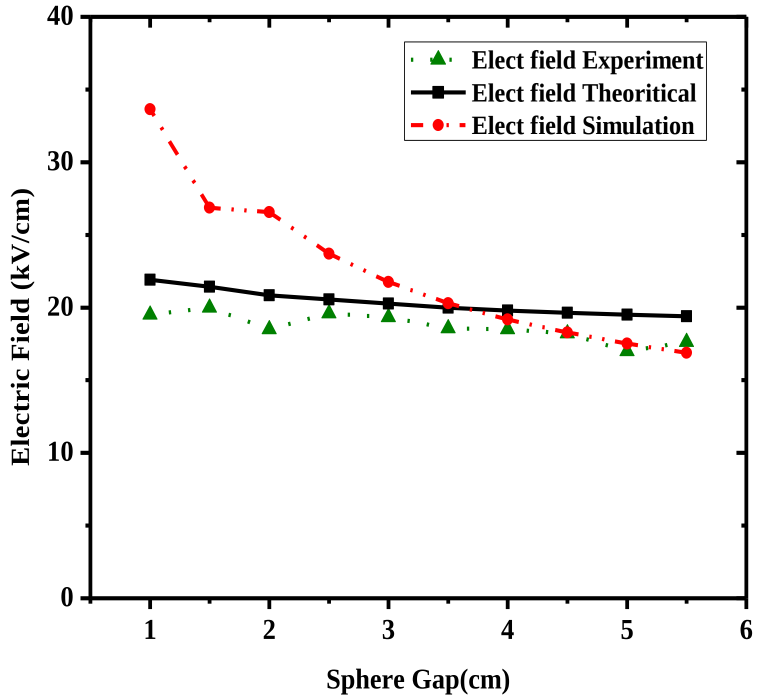

Fig.5.2. Comparison of experimental, theoretical and simulation results of electric field distribution for sphere-sphere (φ = 25 cm) electrode at different electrode gap.

While comparing with the experimental, theoretical and simulation results it is observed that the electric field decreases as the distance between electrodes increases. In addition, to find out the relation between the diameter of sphere electrode with the air breakdown voltage and the corresponding electric field, a theoretical as well as simulation study has been made in this work which is depicted in the Table 2.

TABLE-II

MEASUREMENT OF BREAKDOWN VOLTAGE AND ELECTRIC FIELD STRENGTH FOR DIFFERENT SPHERES

Sphere Radius (cm)	**Breakdown Voltage Theory (kV)**	**Breakdown Voltage Simulation (kV)**	**Electric field Theory (kV/cm)**	**Electric field Simulation (kV/cm)**	**%Error (Breakdown Voltage)**
2.5	32.2	32.0	22.76	22.62	0.6
5	31.6	31.9	22.34	22.55	0.9
7.5	31.3	31.5	22.13	22.27	0.6
12.5	31	30.9	21.92	21.84	0.3

As the air breakdown voltage and corresponding electrical field strength is depends on the geometric configuration of the sphere electrode, the theoretical and simulation work has been done in this work which shown in Fig.5.3 and Fig.5.4 respectively.

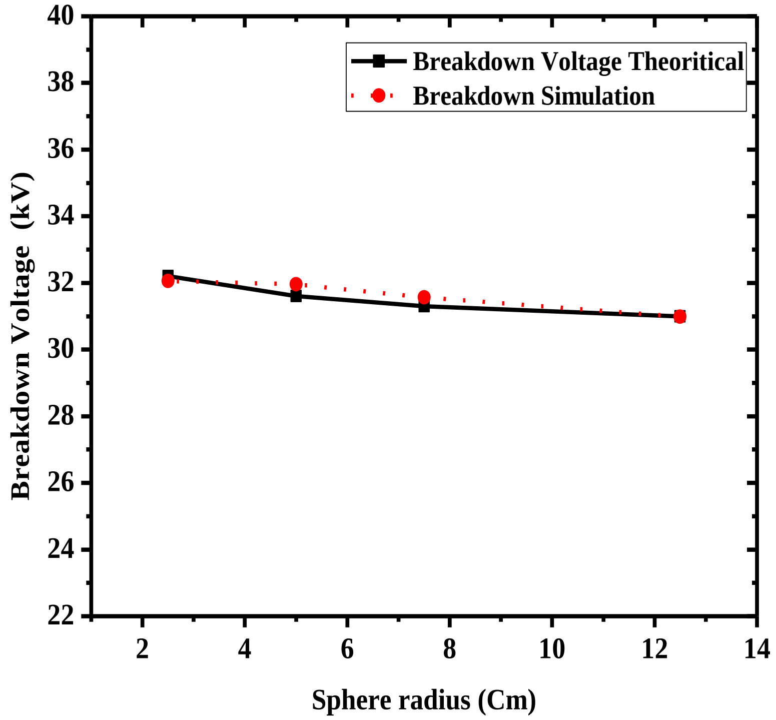

Fig.5.3. Comparison study with variation of sphere radius and air breakdown voltage.

From Fig.5.3 it is observed that air breakdown voltage decreases with the increase of the sphere radius in both the theoretical and the simulated results.

Figure 5.4 shows results between the electric field distributions with wide variation of the sphere diameter.

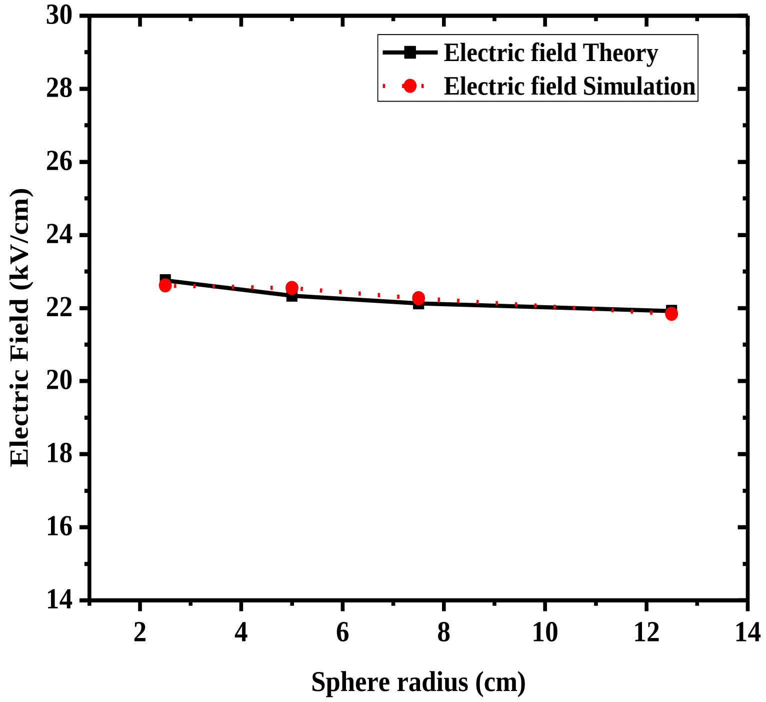

Fig.5.4. Comparison study with the variation of sphere radius and electric field distribution.

It is clear from the Fig.5.4 that with the increase of sphere radius electric field distribution between the sphere electrode decreases.

Atmosphere temperature effects on maximum electric field and relative air density factor. The maximum electric field and relative air density factor at each temperature's' are determined in simulation. These are given in Table 3. At these parameters, radius of the sphere electrodes is 12.5cm, sphere electrode material is aluminium and atmospheric pressure is 760 mm of Hg.

TABLE-III

MEASUREMENT OF RELATIVE AIR DENSITY FACTOR AND MAXIMUM ELECTRIC FIELD STRENGTH FOR DIFFERENT TEMPARATURES

Temperature (℃)	**Relative air density factor δ**	**Maximum Electric field (kV/cm)**
10	1.03	82.43
20	1	78.71
30	0.96	75.29
40	0.93	72.12
50	0.9	69.18
60	0.87	66.45
70	0.85	63.91
80	0.83	61.54

Figure 5.5 contains the characteristics between temperature and relative air density factor by simulated results are plotted for different temperature‘t’.

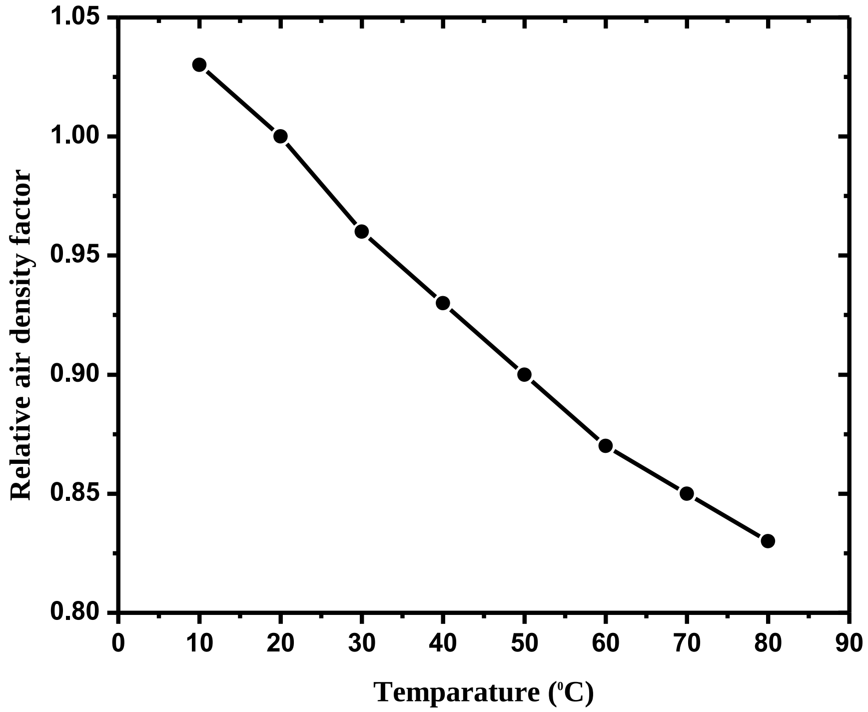

Fig.5.5. Performance plot between temperature and relative air density factor in simulation.

From Fig.5.5 it is observed that relative air density factor decreases with the increase of the temperature of atmosphere in the simulated results. Figure 5.6 contains the performance plot between temperature and maximum electric field. In this simulation maximum electric field is measured for different temperature‘t’.

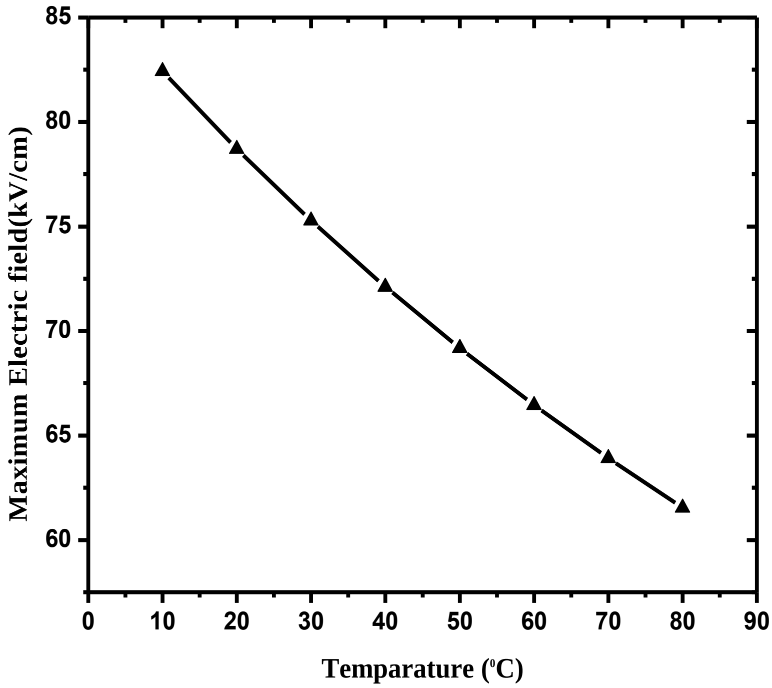

Fig.5.6. Performance plot between temperature and maximum electric field in simulation.

It is clear from the Fig. 5.6 that with the increase of sphere radius electric field distribution between the sphere electrode decreases.

In addition to find the maximum electric field at different negative temperature‘t’ is determined in simulation. These quantities are given in Table 4. These are finding at constant parameters those are specified in earlier.

TABLE-IV

MEASUREMENT OF MAXIMUM ELECTRIC FIELD FOR NEGITIVE TEMPARATURE

Sl. No.	Temperature (^{0}C)	Maximum electric field (kV/cm)
1	-10	90.87
2	-20	95.69
3	-30	100.99
4	-40	106.83
5	-50	113.3
6	-60	120.5
7	-70	128.56
8	-80	137.62

The response for present work is shown in Fig.5.7. It contains the response between negative temperature and maximum electric field.

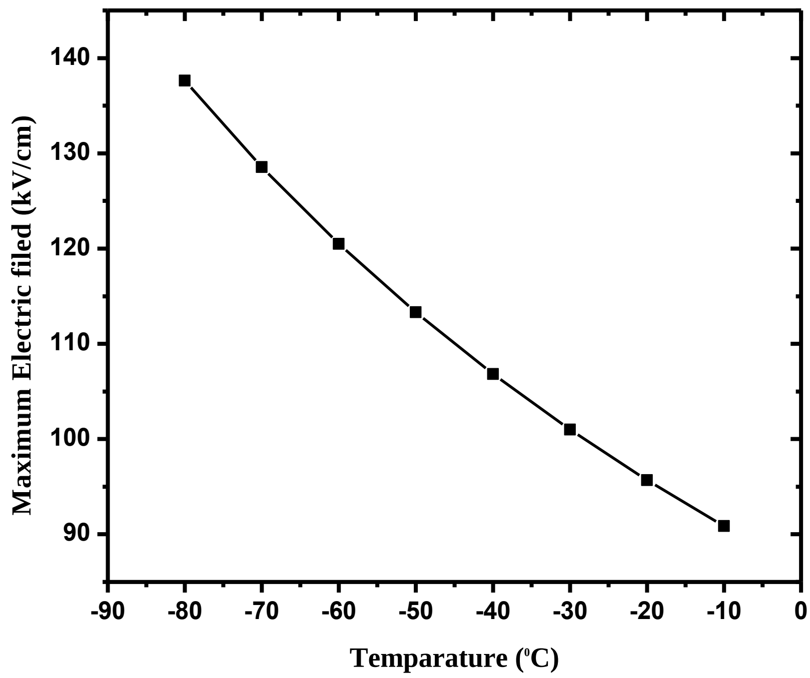

Fig.5.7. Response between negative temperature and maximum electric field.

It is observed from the above graph when temperature is increases then the corresponding maximum electric field decreases. Negative temperature is taken for observe the maximum electric field in cold countries.

The maximum electric field and relative air density factor at each pressure ‘P’ are determined in simulation. These are depicted in Table 5. At these parameters, radius of the sphere electrodes is 12.5cm, sphere electrode material is copper and room temperature is 20^0C.

TABLE-V

MEASUREMENT OF RELATIVE AIR DENSITY FACTOR AND MAXIMUM ELECTRIC FIELD STRENGTH FOR DIFFERENT PRESSURES

Pressure torr	Relative air density factor (δ)	Maximum electric field (kV/cm)
710	0.93	71.93
720	0.94	73.27
730	0.96	74.62
740	0.97	75.98
750	0.98	77.34
760	1	78.71
770	1.01	80.09
780	1.02	81.47

As the relative air density factor and corresponding maximum electrical field is depends on the atmospheric pressure and simulation work has been done in this work which shown in Fig. 5.8 and Fig. 5.9 respectively.

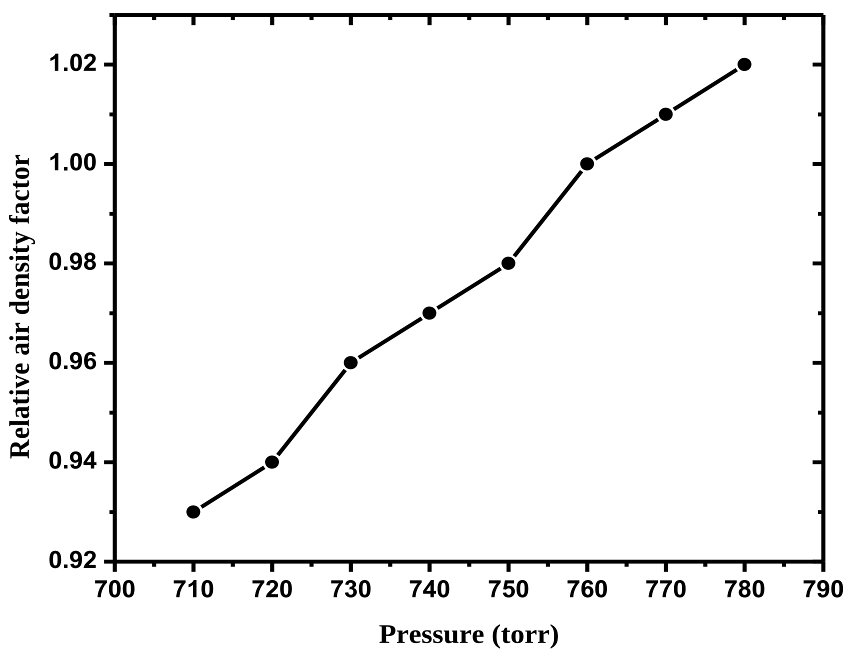

Fig.5.8. Response plot between pressure and relative air density factor in simulation.

From the above Fig.5.8 it is understand that the pressure is varies wide range from 710-780 torr and the corresponding relative air density factor is varies in the range from 0.93-1.02. It is also observed that pressure of atmosphere is increase then the corresponding relative air density factor is decreases.

The performance plot between pressure and maximum electric field is shown in Fig.5.9.

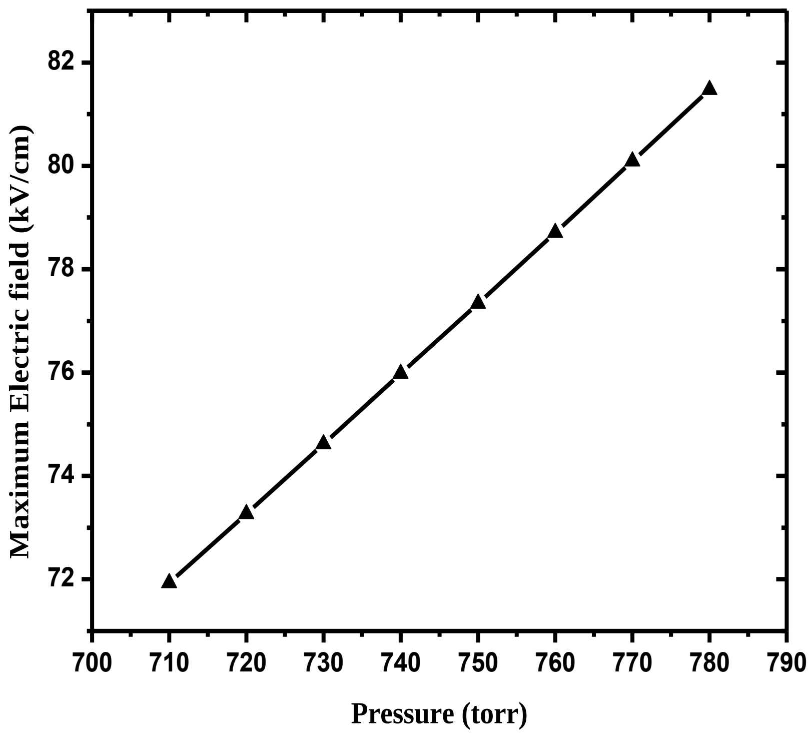

Fig.5.9. Performance plot between pressure and maximum electric field in simulation.

It is clear from Fig.5.9 atmosphere pressure is linearly proportional to maximum electric field.

It is studied that humidity is one of the major factor affecting the air breakdown voltage between the sphere electrodes. The characteristics breakdown voltages of the air at different humidity have been also investigated. It is observed that air breakdown voltage is the function of the humidity presence in the air. As the humidity for a particular day is more or less constant so the different humidity value will not appear during the practical experiment which can be affect the air breakdown voltage between the sphere electrodes. To implement the above, a computer simulation has been done in this work considering the practical value and it is found that air breakdown varies with the humidity which is shown in Table 6.

TABLE-VI

MEASUREMENT OF BREAKDOWN VOLTAGE FOR DIFFERENT HUMIDITIES FOR SPHERE ELECTRODE OF DIAMETER 25 CM

Sl. No.	**Humidity (%)**	**Breakdown Voltage (kV)**
1	2	76.077
2	4	76.386
3	6	76.694
4	8	77.002
5	10	77.311
6	12	77.619
7	**14**	**77.927**
8	16	78.236
9	20	78.852
10	24	79.469
11	28	80.086
12	30	80.394
13	32	80.700

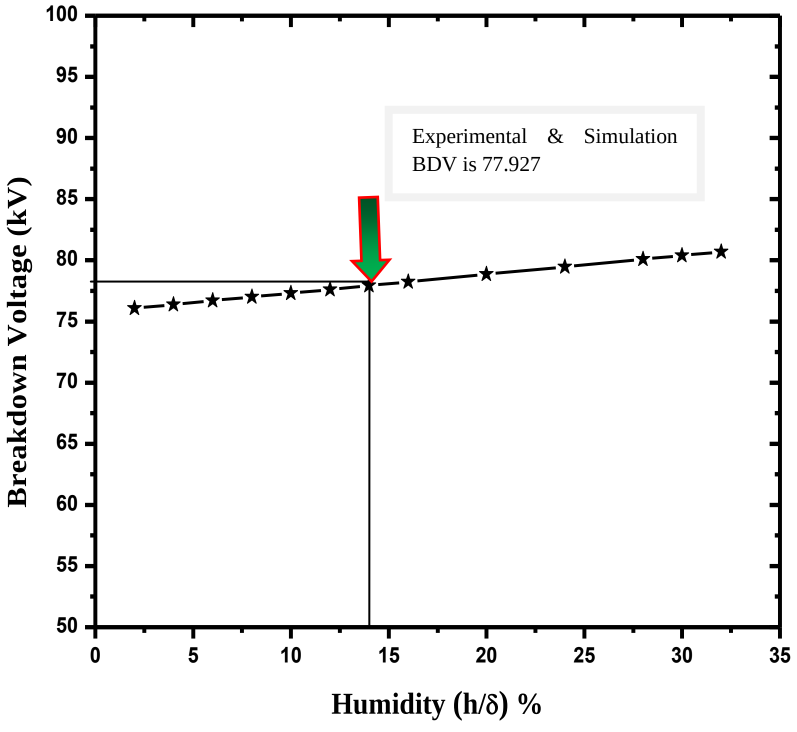

Fig.5.10. Variation of the air breakdown voltage with humidity considering practical value of humidity of 14%.

It is observed from Fig.5.10 that the air breakdown voltage is increases from 76.07 to 80.70 while humidity changes from 2% to 32% keeping the electrode gap spacing of 4 cm. During the study of air breakdown voltage, it is also observed that air breakdown voltage due to 14 % humidity presence in the air is 77.92 kV.

In addition, to find out the relation between the humidity with the humidity correction factor, a simulation study has been made in this work which is depicted in the Table 7.

TABLE-VII

MEASUREMENT OF HUMIDTY CORRECTION FACTOR FOR DIFFERENT HUMIDITIES

Sl. No.	Humidity (%)	Humidity Correction Factor (K)
1	0	0.983
2	2	0.987
3	4	0.991
4	6	0.995
5	8	0.999
6	10	1.003
7	12	1.007
8	14	1.012
9	16	1.016
10	20	1.024
11	24	1.032
12	28	1.041
13	30	1.045
14	32	1.049

Another plot for present work is also done it is shown in Fig.5.11. It contains the response between humidity and humidity correction factor.

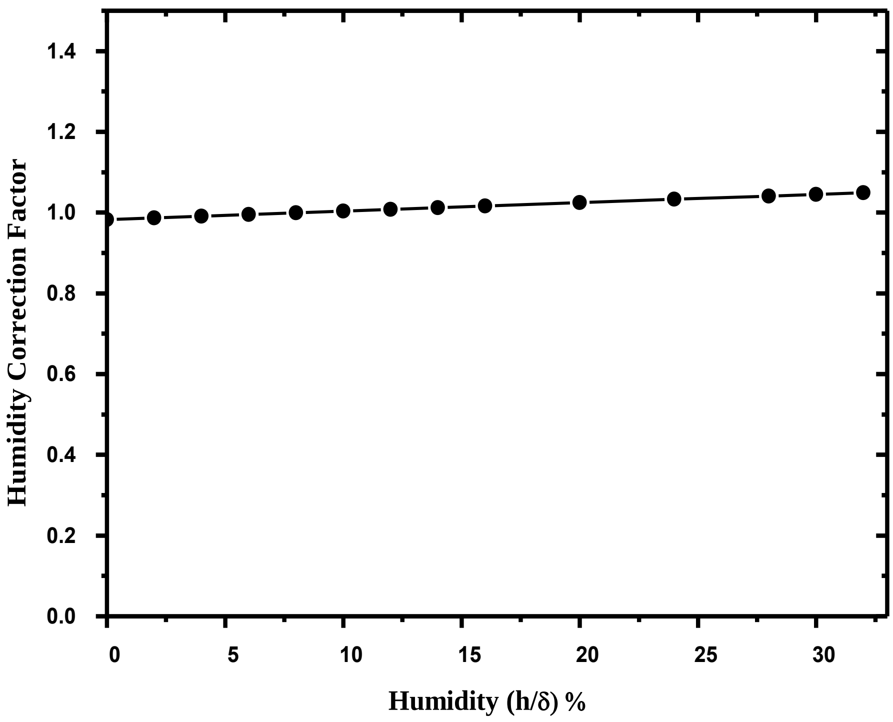

Fig.5.11. Performance plot between humidity and humidity correction factor.

It is observed from Fig.5.11 the humidity correction factor maintains almost constant with the corresponding humidity. Humidity correction factor helps for maintain breakdown voltage constant.

In this work the finite element method is also used for finding the maximum electric field between the sphere electrode arrangements. This method is done in COMSOL software which is used to solve the electrical field distribution and its analysis problems and modeling of high voltage equipments. In this method the input parameters are sphere radius is 12.5 cm, sphere is made up of with aluminium, gap between the sphere electrodes is 1 cm and normal temperature and pressure is taken into consideration. The atmospheric air is taken as an insulating medium for this method. Figure 5.12 show the maximum electric field between the sphere electrodes in the standard sphere gap method.

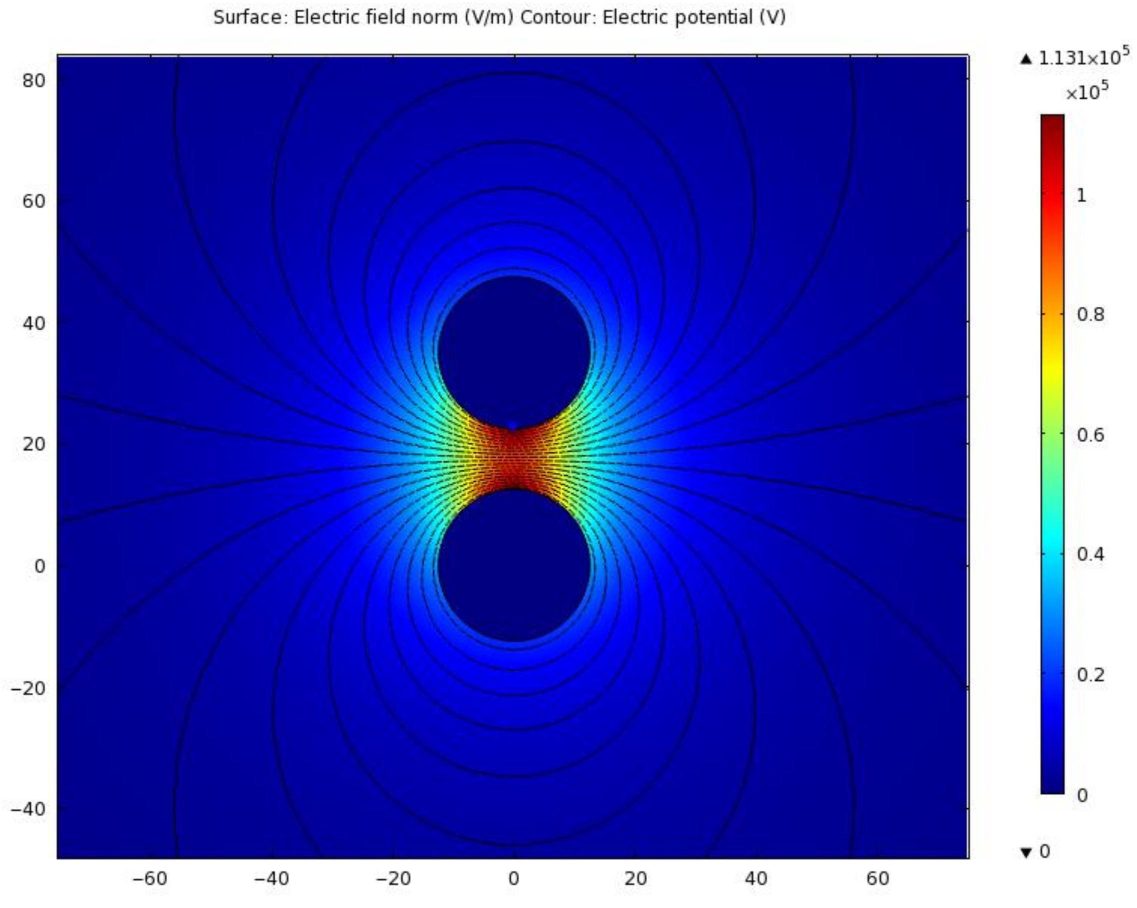

Fig.5.12. Maximum electric field between the sphere electrodes using finite element method.

It is observed from Fig.5.12 the electric field is maximum in vertical axis where the curvatures of the sphere electrodes more or less uniform and it is decreasing gradually in non uniform fields. From Fig. 5.12 it is observed that the electric field distribution is non-uniform for sphere-sphere electrode arrangement. The electric field is non-uniform in the y-axis. The line plot for finite element method is shown in Fig. 5.13.

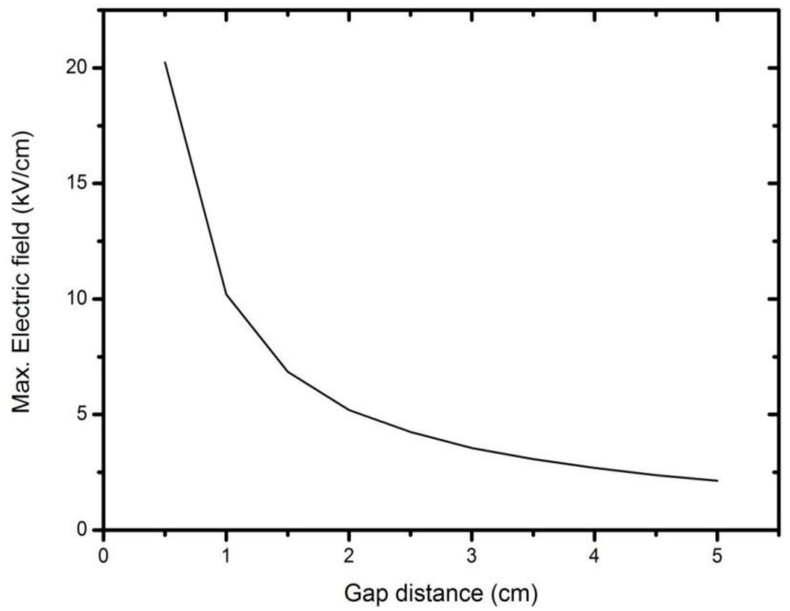

Fig.5.13. Maximum electric field (E_{max}) kV/cm vs. gap distance (cm).

Figure 5.13 shows that the maximum electric field decreases with the increase in the gap distance. In the beginning there is sharp drop in the maximum electric field but it gradually saturates with increase in the gap distance.

CHAPTER -6

Conclusion

&

Future Scope of the Work

CHAPTER-6

CONCLUSIONS & FUTURE SCOPE OF THE WORK

6.1 Conclusions

In electrical power system, high voltage (HV) power equipments are mainly subjected with spark over voltage. These over voltage which may causes by the lighting strokes, switching action, determine the safe clearance required for proper insulation level. Normally, the standard sphere gaps are widely used for protective device in such electrical power equipments. The sphere gaps are filled up with insulating medium such as liquid insulation (transformer oil), solid insulation and gas insulation (SF_6, N_2, etc). Generally, air medium is widely use as an insulating medium in different electrical power equipments as its breakdown strength is 30 kV/cm. In this study the performance characteristics of air breakdown voltages and electric field behaviors are studied theoretically as well as experimentally by using the standard sphere gap method. The air breakdown characteristics between the sphere-sphere electrodes are observed with variations in electrode arrangements, both in size and spacing. 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. Maximum electric field and relative air density factor characteristics are derived with different temperature and pressure. It is concluded that with increase of temperature the maximum electric field and relative air density factor are decreased and with increase of pressure the maximum electric field and relative air density factor are increased.

In addition, as the humidity is one of the important factors for measurement of the air breakdown characteristic and it is not changeable during the experiment, a simulation work has been carried out with different humidity condition through MATLAB environment. Humidity factor is also calculated for different humidity of atmosphere in simulation. The maximum electric field also observed in finite element method and it concludes that the curvatures of electrodes are uniform then electric field in gap between electrodes is more.

6.2 Future scope of the work

The research focused on the experimental validation of the breakdown characteristics in high voltage test laboratory and ac thorough comparison is made with the theoretical calculations.

The complete analysis provides an analytical framework for designing the withstand capacity of the high voltage insulation systems. This study can be extended for analyzing breakdown and pre-breakdown strength including other mediums such as vacuum, SF_6 and N_2 to assess the performance characteristics for measuring AC, DC and impulse voltages. This work is also gives the future work opportunity using different types of electrodes (i.e., needle-plate, plate-plate, needle-sphere, rod-rod etc.). The indigenously developed module for air breakdown voltage test by using MATLAB/COMSOL software is to be explored for utilization of all properties of this software in the field of remote access of such HV power apparatus.

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List of Publications

List of Publications

Research Paper Presented in National/International Conferences

[1] **P. B. Sankar** and S. Karmakar, "An Experimental Study of Air Breakdown Voltage and Electric Field using Standard Sphere Gap Method", *International Conference on Emerging Trends in Electrical Engineering(ICETE-2011)*, pp. 551-555, Karnataka, India, 4th-5th May, 2011.

List of Publication in International Reviewed Journal

[1] S. Karmakar and **P. B. Sankar**, "An Experimental Study of Air Breakdown Voltage and its Effects on Solid Insulation", ***communicated***.