Measurement of Air Breakdown Voltage and Electric Field Using Standard Sphere Gap Method

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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 (polystyrene, paper) and gas insulation (SF6, N2, CO2, CCl2F2 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.

Keywords: Air, Breakdown Mechanism, Corona, Sphere gap, Humidity correction, Air density.

I. 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 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 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 JNTUKakinada 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...
II. Literature Review

Different topologies are developed for measure the air breakdown voltage, maximum field and humidity correction factor by using standard sphere gap method. 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 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/\delta lower than 13 g/m³ in 2008 [8]. The humidity effect on breakdown voltage is observed by the reference of P. N. Mikropoulos, C. A. Stasinopoulos 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.

III. 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, and liquids.

IV. 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.

V. 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/cm². 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 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. Photo ionization occurs when the amount of radiation energy absorbed by an atom or molecule exceeds its ionization energy and is represented as A + hv \rightarrow A^+ + e where A represents a neutral atom or molecule in the gas and hv 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 N2, CO2, CCIF2 (Freon) and SF6 (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.

\[
AB + e \rightarrow AB^- \quad (1)
\]

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

\[
AB + e \rightarrow A^+ + B^- \quad (2)
\]

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 sculpture 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 SF6, N2, CO2, CCIF2 etc [4, 10]

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**VI. 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 is 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 circuit. 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

(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 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.

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 2\( D \) 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 1.5\( D \) above the (presumably) grounded floor. Figure 2.2 indicates horizontal sphere gap arrangement.

Horizontal gaps are much the same as vertical gaps, except that both electrodes are insulated. The insulators should be longer, at least 2\( D \) long (putting the sparking point at least 4\( D \) from the supports: 2\( D \) for the insulator, 1\( D \) for the shank, 1\( D \) 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]. 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].

![Fig.1. Vertical sphere gap schematic diagram](image1)

![Fig.2. Horizontal sphere gap schematic diagram](image2)

![Fig.3. Sphere-Sphere electrode arrangement.](image3)
(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

$$E_{\text{max}} = 0.9\frac{V}{x} a + x/a$$

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.

![Fig.4. Sphere-Plate electrode arrangement](image)

VII. 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

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. The main function of the control panel is to control all equipment under test.

![Fig.5. Control panel used for conducting the air breakdown test](image)

(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.

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.

![Image of High Voltage Transformer](image)

**Fig.6 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.

(f) **Sphere-sphere gap arrangement**

230V Power frequency is applied to the Low Voltage side by a Auto Transformer. Slowly raise the voltage till faint hissing audible sound is heard. This is the beginning of corona. Hence the Corona Inception Voltage is appeared. Raise the Voltage further till such time there is a faint visible glow at the high voltage electrode. This is the Visible Corona Inception level. Then slowly reduce voltage further till such time the hissing sound subside i.e., dies down or becomes extinct. This voltage is called Corona Extinction Voltage. Once again raises the voltage till such time there is a Breakdown. This voltage is called Breakdown Voltage. Then the measured voltage has been corrected by the Air density correction factor and Humidity Correction factor. Reduce the voltage completely and open the circuit breaker. Then furtherer breakdown has been obtained for different gap distances.

**VIII. EXPERIMENTAL RESULTS**

The test circuit is shown in Fig. 6. It consists of AC voltage source 230 V, Auto Transformer 400V/1000KV transformer, water resistor (RW) =560 kΩ along with filter.
The main focus of the analysis is variation of breakdown voltage versus electrode gap with different diameters. This characteristic provides significant information on the withstand 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 theoretical and experimental results which are depicted

**Table-I: Sphere-sphere Measured and Corrected value with respect to gap distances.**

<table>
<thead>
<tr>
<th>Sphere Gap (cm)</th>
<th>BDV Experiment (kV)</th>
<th>BDV Theory (kV)</th>
<th>BDV Simulation (kV)</th>
<th>Electric Field Experiment (kV/cm)</th>
<th>Electric Field Theory (kV/cm)</th>
<th>%Error (BDV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>19.5</td>
<td>21.9</td>
<td>20.0</td>
<td>19.0</td>
<td>19.3</td>
<td>1.55</td>
</tr>
<tr>
<td>1.5</td>
<td>30.0</td>
<td>32.1</td>
<td>30.0</td>
<td>30.0</td>
<td>30.6</td>
<td>2.00</td>
</tr>
<tr>
<td>2.0</td>
<td>41.0</td>
<td>43.8</td>
<td>35.0</td>
<td>40.0</td>
<td>40.6</td>
<td>1.50</td>
</tr>
<tr>
<td>3.0</td>
<td>52.0</td>
<td>55.2</td>
<td>50.0</td>
<td>45.0</td>
<td>45.6</td>
<td>1.33</td>
</tr>
<tr>
<td>4.0</td>
<td>65.0</td>
<td>68.2</td>
<td>60.0</td>
<td>55.0</td>
<td>55.6</td>
<td>1.11</td>
</tr>
<tr>
<td>5.0</td>
<td>79.0</td>
<td>82.2</td>
<td>75.0</td>
<td>65.0</td>
<td>65.6</td>
<td>1.51</td>
</tr>
<tr>
<td>6.0</td>
<td>94.0</td>
<td>98.2</td>
<td>90.0</td>
<td>80.0</td>
<td>80.6</td>
<td>1.50</td>
</tr>
<tr>
<td>7.0</td>
<td>110.0</td>
<td>114.2</td>
<td>105.0</td>
<td>95.0</td>
<td>95.6</td>
<td>1.38</td>
</tr>
<tr>
<td>8.0</td>
<td>125.0</td>
<td>129.2</td>
<td>120.0</td>
<td>110.0</td>
<td>110.6</td>
<td>1.18</td>
</tr>
</tbody>
</table>

*BDV=Breakdown Voltage

**Table-II: Measurement of breakdown voltage and electric field strength for different spheres.**

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

**CONCLUSION**

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 (SF6, N2, 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.

**Reference:**


