1984

Composite insulation surface flashover study.

Mahesh K. S. Rao

University of Windsor

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LA THÈSE A ÉTÉ MICROFILMÉE TELLE QUE NOUS L'AVONS RÉCEVE
COMPOSITE INSULATION - SURFACE FLASHOVER STUDY.

by

Mahesh Rao.K.S

A thesis
presented to the University of Windsor
in partial fulfillment of the
requirements for the degree of
Master of Applied Science
in
The Department of Electrical Engineering

Windsor, Ontario, 1984

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ABSTRACT

This thesis describes experimental measurements of the flashover voltage of solid-gas composite insulation systems under uniform field conditions, using DC (both polarities) and impulse voltages. The solid insulator used in the present investigation was either Plexiglass or Glass-ceramic and the gaseous insulation was Air, N₂, or SF₆. Experiments were conducted in the pressure range of 1 to 5 bar and the diameter as well as the thickness of the solid dielectric along with the total separation distance between the electrodes, were varied over a wide range. Measurements of total time to breakdown under impulse voltages were also carried out.

The measured flashover values were compared with the values of capacitive voltage distributions and were found not to agree with those values. A modification to the formula was made which incorporated the diameter of the solid dielectric and the conductor, and was found to be in better agreement over the range of values compared. The effects of solid insulator diameter, thickness and dielectric constant along with the pressure and type of gaseous insulation on flashover voltage of composite insulation are presented. Also, the effect of pressure,
solid insulator diameter and percentage of overvoltage on time to breakdown of such composite insulation system are reported.
ACKNOWLEDGEMENTS

It is my great pleasure to sincerely acknowledge my supervisors of this project, Dr. Reuben Hackam and Dr. G.R. Govinda Raju, for their valuable guidance, encouragement and constructive criticism during the course of this work and of course for their tireless reading of this thesis in manuscript.

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Finally, I would like to express my profound gratitude to my parents for their moral support in furthering my career.
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Chapter I

INTRODUCTION

1.1 PREAMBLE

The term "Composite Insulation" designates, in general, the presence of two or more insulating materials between two conductors in a high voltage system. In the earlier days of electrical power distribution, the problem of insulation seldom arose, as the insulators used gave more satisfactory performance than the rest of the equipment used in generation and distribution. However, with increased voltages and transmission distances, for economic reasons, problems connected with insulation failure have become more important.

In power apparatus such as high voltage switches, cables, protection equipment, etc., solid insulators are used to bridge the gap between two conductors. It is a well known fact that the withstand voltage of a gap containing a solid insulator is considerably lower than that of an identical gap without the solid insulator or lower than the volume dielectric strength of the solid insulator(1-2).

However, the reduction in the withstand voltage depends upon the type and presence of the gas surrounding the insulator(3), along with other factors like the geometric
shape and surface condition of the insulator and the conductor(4), etc. Thus, in general, the insulating surface constitutes the weakest section of the insulation.

In practical insulating systems, small air gaps may be present between the conductor and the insulating support due to improper cohesion, or because of specific design considerations, in some equipment larger air gaps may be present(5). Also, thin air films or bubbles are often entrapped in the solid insulation used in coils, cables and other electrical apparatus(6).

It is of great practical importance to be able to predict the behaviour of these air films, bubbles or gaps and the voltages at which their breakdown occurs. The breakdown of this air bubble, film or gap may not cause immediate rupture or damage of the solid insulator; it may result, however, in gradual deterioration of the insulator(7) for the following reasons:—

1. Heating due to losses in corona,
2. Chemical action due to the formation of Ozone and Nitric acid,
3. Mechanical action due to the rapid movement of streamers and
4. The formation of conducting paths by the chemical action and carbonization.

For these reasons, the surface flashover study of composite insulation systems, is considered to be very
useful. Also, understanding the behaviour of the flashover voltages for composite insulation system would eventually lead to the easy detection of any flaws on the walls of the insulator bridging the gap or at the contacts of the solid insulator and the conductor.

1.2 REVIEW OF THE LITERATURE

Surface flashover along a gas/solid interface is an important factor for the withstand voltage and the reliability of high voltage equipment. Creepage length, end effects, sheds, and contamination are the typical terms often heard in relation to the solid support insulators. They reflect practical experience gained from the development of many electrical devices and apparatus such as spark gaps, transformers, compressed gas insulated power equipment, etc. The solid support, and the gas/solid interface which results, are inevitable in gaseous insulation[8]. The need to have surfaces and the fact that they are often the limiting factor to lower withstand voltages and to the reliability at the operating voltages has been a strong motivation for much of the work described in the extensive literature concerning surface flashover. A flashover event involves an expanding plasma-like process which develops rapidly in time and space, and releases unknown constituents from the surface.
There is an extra degree of complexity involved in the case of Composite Insulation systems, mainly because of the charges accumulated on the dielectric surface, on the air side, and hence the withstand voltage of the system will either increase or decrease depending upon the polarity of these charges and the applied voltage\(^{(9)}\).

Most of the scant literature on this subject is limited in many ways such as the magnitude of the applied voltage, the type and polarity of the applied voltage, the type of the solid insulator along with many others. In addition, substantial variation in the results of the past researchers can be noticed. This section aims at reviewing briefly the investigations carried out by the earlier researchers and their limitations, in this field of composite insulation systems.

Trump and Andrias\(^{(1)}\) have studied the influence of surface irregularities on the surface flashover voltage along with the effect of surface bound charges, the end effects and the effect of corrugations. However the calculation of capacitive distribution of voltages (Appendix-I) was first made by Halleck\(^{(10)}\), who has concluded from the investigations that:

1. The corona starting voltages are predictable in air-solid dielectric systems (later described as composite insulation systems) when the thickness and the dielectric constant of the solid dielectric or
dielectrics are known. The accuracy is within 10 to 15 percent, depending upon the thickness and the type of insulation used.

2. The corona starting voltage can be determined for two or more dielectrics in series with one air gap and the accuracy is approximately the same as with one solid dielectric.

However, his investigations were limited in terms of the thickness of the solid dielectric and the type of applied voltage. Trum and Andrias(1) however have concluded that, even though the electric field-intensity acting on the gaseous portion of the gap of the solid-dielectric system may be approximated by the equation of the capacitive voltage distribution, this approximation gets strongly influenced by the surface bound charges.

Helene Bertein(11) has successfully measured and photographed such charge sites on insulator surfaces and calculation of energy of the first negative direct discharges was made. Naidu et al. (12) have shown that the capacitive distribution of voltages, does not hold good exactly in a nonuniform field. They used a point plane electrode configuration and measured the corona inception voltage for different thickness of the solid dielectric sample. They have fitted a semi-empirical formula to their measured values and have attributed the difference between the estimated and the measured values to the space charge.
effect at the point electrode. Hussain and Nema (13) have made an attempt to explain these deviations between the measured and the estimated values of inception voltage on the basis of the Townsend mechanism by evaluating the values of primary ionization and secondary ionization co-efficients using the air gap fields obtained from the measured discharge inception voltage values. The values of $\gamma$ obtained by them were an order of magnitude higher than that reported for metal electrodes by Raja Rao and Govinda Raju (14). As the nature of the curves are the same, they have concluded that the higher values of $\gamma$ are due to the insulating surfaces having higher secondary ionization co-efficient by the usual positive ion bombardment or photoelectric action or field enhancements than the metal surfaces. Also they have shown that for both surface and internal discharges, Paschen's minimum shifts to the right of its usual minimum value.

Recently, Maller and Srivastava (3, 15-16), have shown that in uniform fields with insulating supports, the field due to surface charge on the insulator surface increases the air gap stress significantly, resulting in lower values of discharge inception voltages than those estimated by assuming a capacitive field distribution. In the case of non uniform field with an insulating support, they have reported that, even though the corona inception voltage decreases significantly, a considerable increase in the
breakdown voltage of the gap is observed. They calculated the secondary ionization co-efficient values and have concluded that the difference in corona inception and breakdown phenomena was due to surface charges, which they have measured and was not due to the $\gamma$ values. Again, the above investigations were limited in terms of various parameters like the type and polarity of the applied voltage, etc.

The following conclusions can be drawn from the review presented above.

1. Measured and estimated values of breakdown voltage for a composite insulation system differ significantly.

2. Even though the difference has been attributed to different factors, such as space charges near the dielectric, surface bound charges or the secondary ionization co-efficient values, the conclusions of different researchers are quite conflicting.

3. The investigations were greatly limited by many factors, such as the polarity and type of the applied voltage, type of gaseous gap, thickness of the solid insulator, diameter of the solid insulator, length of the gaseous gaps, etc.
1.3 OBJECTIVES OF THIS RESEARCH

Recognizing the importance of providing adequate insulation strength to high voltage equipment, it is essential to have an accurate knowledge of the withstand voltage of such insulation. This knowledge is essential in establishing healthier EHV and UHV systems, which are in turn essential to cope up with the fast progressing and rapidly expanding energy needs of today's world.

The purpose of this thesis is therefore to study the surface flashover of composite insulation over a wide range of parameters such as: polarity of the applied voltage along with the type of the applied voltage, types of gaseous and solid dielectric gaps, different dimensions of the solid dielectrics, etc. Also, the time to breakdown (t_d) of these composite insulations systems under impulse voltages are measured.

The major aspects of the present investigations by the author are, briefly:

1. surface flashover voltage measurements are made in Air, Nitrogen, SF_6 in the pressure range of 1-5 bars;

2. the thickness of the solid dielectric as well as the air gap are varied over a wide range; also two types of solid dielectric materials are tested;

3. different diameters of solid dielectric material are used:
4. DC (both polarities) and Impulse (1.2/50 wave) voltages are applied for measurements.

5. Measurement of total time to breakdown under impulse voltages at different pressures, with different diameters of solid dielectrics and with different percentage overvoltages are carried out.

1.4 ORGANIZATION OF THESIS

Chapter I summarizes the previous studies which are relevant to the investigations described in this thesis.

Chapter II gives a detailed and thorough description of the experimental system and the measuring techniques employed in the study of surface flashover of Composite Insulation Systems, under different types of applied voltages. The precautions to be taken in making such measurements along with the accuracy with which the measurements are performed, are presented and conclusions have been derived.

In Chapter III, the measured values of surface flashover voltages using positive and negative polarity DC voltages in different cases are presented. The effect of various parameters on the surface flashover voltages have been analysed through different graphs. Also, these measured values of flashover voltage are compared with the estimated flashover voltage values using the capacitive voltage distribution and an analysis of the results is made. A
modification to this capacitive voltage distribution formula is presented which takes into account the diameter of the solid dielectric and the results are discussed.

Chapter IV devotes to Impulse flashover measurements. The results are compared with the DC (both polarities) voltages. The total time to breakdown \( t_d \) under impulse voltages are reported and the effect of pressure, the dimensions of the solid insulator and the \% of overvoltage on time to breakdown is analysed.

In Chapter V important conclusions are presented and suggestions are made for the extension of this work.
Chapter II

EXPERIMENTAL SYSTEM AND TECHNIQUES

The experimental system used in the present studies can be divided into three main parts: breakdown chamber, insulators and electrodes, and the high voltage source together with the measuring circuits.

2.1 BREAKDOWN CHAMBER

A sectional view of the pressure vessel used in this experimental work is shown in figure 2.1 and figure 2.2 depicts a photograph of the breakdown chamber with the viewing ports, gas inlets, measuring gauges; etc. The cylindrical wall of the pressure vessel, which has a volume of 80 liters, has two sections. The upper section (#1), is made of 0.375 inch thick carbon steel and the lower section (#9), is made of 0.25 inch thick steel. The upper section serves as an extension to accommodate the high voltage bushing, which is capable of withstanding a working voltage of over 500 kV, when pressurized with SF₆, to about 2 bars. Actually this high voltage bushing consists of two porcelain cylinders (#8) and (#7), two end plates, a mounting plate and a hollow conductor (#6). The space between the above two porcelain cylinders and the end plates are sealed from the atmosphere and from the pressure vessel.
FIGURE 2-1 PRESSURE VESSEL AND ELECTRODE ASSEMBLY
FIGURE 2-2  PHOTOGRAPH OF THE BREAKDOWN CHAMBER.
One of the four ports (#10) was utilized as a gas inlet port and out of the other three, two ports served as viewing ports and the fourth was completely sealed. The windows of these viewing ports were made of quartz discs, 50 mm in diameter and 35 mm in thickness. A gas outlet or the gas discharge vacuum port (#12) was located in the base plate. The high voltage electrode was connected to the hollow conductor of the bushing using a spring contact system (#2). The bottom electrode which was movable and grounded, was connected to the base plate through a connecting rod which in turn was connected to a screw mechanism (#14) with a dial gauge (#13); with the help of this mechanism the low voltage electrode could be moved to an accuracy of 0.01 mm. This lower movable electrode was grounded using a copper strip (#4), through the base plate of the vessel. Great care was taken to see that the electrodes are perfectly aligned and are parallel as explained in (17).

The breakdown chamber was cleaned thoroughly and was checked for leakage. A rubber gasket was used to keep the leakage rate to less than 0.5% per day (24 hrs.). A calibrated pressure gauge, which had a resolution of 1 p.s.i in a 300 p.s.i. range, was used for measuring the pressure and was checked earlier with a test gauge of an accuracy of 0.25%. The other two gauges seen in fig. 2.2 are vacuum gauges in the range of 0-50 mbar and 0-25 mbar respectively, and are used in measuring the chamber pressure before starting the experiments.
Precautions were taken to see that lint and other contaminants do not enter the system. Usually the gas in use was passed through a 0.03 micron filter and then through a gas purifier containing a dessicant which kept the dew point of the gas below -100°F. Also, crystals of Copper Sulphate and activated alumina were placed inside the chamber prior to the starting of the experiment, in order to remove any corrosive gas compounds which may result from the electrical breakdown of the gas.

2.2 **INSULATORS AND ELECTRODES**

2.2.1 **Solid Insulators**

Polymethylmethacrylate, commercially known as Plexiglass along with Macor glass ceramic, having relative dielectric constants of 3.2 and 5.8, respectively, in the form of cylindrical rods are used in the present investigations as the solid dielectric materials. They are cut to the required size from stock in standard sizes of rods and are machined to a very smooth finish and are polished using 600 grit sand paper. The earlier investigation shows that these materials have very good electrical properties. However, the dielectric properties of the insulator vary in accordance with the particular composition used and the techniques employed in the manufacturing process (18-19).
Macor glass ceramic of 10 mm thickness and 25.0 mm diameter, Plexiglass of 5 mm, 10 mm and 15 mm thickness and 13.1, 25.0, 51.0 and 64.0 mm diameters have been used in order to find the effect of insulator diameter and thickness on the flashover performance, in the present study. These solid insulators are cleaned thoroughly using acetone and distilled water and are dried completely before installing in the system.

2.2.2 Gaseous insulation

Nitrogen, Air and Sulfur-hexafluoride were used as the gaseous gaps in the present study. Nitrogen is the most abundant permanent gas in the atmosphere, comprising about 80% of the earth's atmosphere. Its dielectric strength has been measured by some of the earliest investigators, as reported in the classic volumes of Thompson and Thompson(20) and Townsend(21). Although air is a mixture of about 80% of Nitrogen, 18% of Oxygen and the remaining consisting of other gases like Hydrogen, Carbon-Di-oxide, etc., it constitutes a natural electrically insulating medium and, probably for this reason, has been the object of many investigations. These reasons have lead to the use of air and nitrogen in the present investigations.

\[ \text{SF}_6 \] was first obtained from Fluorine and Sulphur in 1900 by Moissan and Lebeau(22). In the following years a great deal of attention was focused on the chemical
stability of this gas when subjected to electrical discharges. In the early fifties technical interest in the gas as insulating material for high voltage technology became evident. SF₆ gas since found a wide variety of applications in the field of high voltage engineering. It is used as an:

1. arc quenching medium in circuit-breakers,
2. insulating medium in instruments and equipment.

As an insulating medium in High Voltage Technology it has already been used in the following fields:

1. SF₆ insulated and cooled transformers,
2. measuring capacitors for extremely high voltages,
3. electrostatic generators,
4. X-ray equipment,
5. SF₆ insulated substations, etc.

SF₆ is an electronegative or electron attaching gas, which means that free electrons are readily removed from a discharge by the formation of negative ions through processes by which a free electron is attached to a neutral gas molecule. This attachment may occur in several ways(23), for example, as direct attachment

\[ \text{SF}_6 + e^- \rightarrow \text{SF}_6^- \quad (2.1) \]

or as dissociative attachment

\[ \text{SF}_6 + e^- \rightarrow \text{SF}_6 + \text{F}^- \quad (2.2) \]
Highly mobile electrons which may ionize by the collision process in the gas are in both cases replaced by heavy and relatively immobile negative ions which do not ionize in the gas. The result of these processes is a tendency to prevent or quench the formation of electron avalanches which otherwise might have led to a breakdown. Due to these excellent insulating qualities, $Sp^+$ (99.8% minimum) manufactured by The Matheson Inc, was employed in the present investigations.

2.2.3 Electrodes

When the breakdown characteristics of uniform field electrodes are required, great care must be taken in preparing the electrodes in order to avoid edge effects. Near the edge of the plane electrodes the radius of curvature must be decreased very gradually so that at no point does the field become greater than it is in the center of the plane portion (24). Using the extension of Maxwell's (25) analysis of electrostatic field due to afinite plane plate parallel to an infinite plane plate, satisfactory electrode profiles may be obtained. In the present investigations Bruce profile, brass electrodes of 115 mm diameter was used.

The emission of electrons from the surfaces due to irradiation and positive ion bombardment, and particularly the coefficient $\gamma$, are greatly affected by the condition of
the electrode surface. Therefore, it is not surprising that the spark breakdown voltage is affected by the presence of impurities on the cathode surface such as oil, finger prints, oxide films, dust and other insulating particles, as well as adsorbed gases. Hence, the electrodes were carefully polished, to minimize the effects of sharp points, using 600-grit sand paper and then were given a mirror polish. It was cleaned of impurities and of dust and grease by washing it with acetone and then with distilled water, before installing into the system. However, nothing has been done about the adsorbed gas content of electrodes.

2.3 HIGH VOLTAGE SOURCE AND MEASURING CIRCUIT

Surface flashover measurements of composite insulation were performed using:

1. Negative polarity DC voltages,

2. Positive polarity DC voltages and

3. 1,2/50 microsecond Impulse voltages

Let us consider the electrical circuit of all the above mentioned voltages.

2.3.1 Negative polarity DC

The high voltage bushing of the pressure vessel was connected to the HVDC generator through a 3" diameter copper pipe and a 250 k Ohms wire wound resistor which was located at the top of the bushing.
The output voltage of the DC generator was variable from 0-1000 kV. This DC generator made by Deltaray Corporation (model M-1000) runs on a primary power supply of 208/240 Volts, 60 Hz, single-phase, 8 kVA supply and can deliver 1 million volts in air at 2mA. The variations in this DC generator output voltage due to ripple and regulation were within 0.01%. This supply consists of Cockroft-Walton voltage multiplier circuits and a stack of 20 identical voltage producing decks, driven by an 81 kHz source, in an insulating busaing.

The output voltage of this negative polarity DC generator was measured with an RC voltage divider of ratio of about 10^6:1 and a digital voltmeter of accuracy of ± 0.05%. The divider ratio was calibrated with an electrostatic voltmeter within an accuracy of 0.5% of the applied voltage up to a voltage range of 50 kV. It was calibrated (from 50 kV onwards) with a 25 cm sphere-gap up to a voltage of 270 kV. This calibration assured an accuracy in the measurement of gap voltage within ± 2% (2σ) for the range of voltages applied.

2.3.2 Positive polarity DC

Figure 2.3(a) shows the block diagram representation of the circuit used. An A.C. power supply, using an input of 208/230 Volts, single-phase, 50/60 Hz with a power capacity of about 3 kVA, which delivers 0-150 kV (rms) at 14 mA.
maximum) was used in conjunction with a full-wave diode rectifier and a doubler circuit to obtain the required 0-300 kV DC voltages with positive polarity. The maximum ripple was kept at less than 0.11%.

Measurements were performed using a calibrated resistance divider of ratio 9915:1. This resistance divider was oil immersed with ±1% accuracy. A calibrated digital voltmeter of reading accuracy of ±0.05% was connected to the low voltage arm of the resistance divider when flashover measurements were carried out.

2.3.3 Impulse voltages

Surges produced by lightning or switching or by other causes can have a variety of wave shapes. However in most practical impulse testing laboratories it has become a practice to use, for general purposes, an impulse voltage wave shape, which corresponds to the usual form of travelling waves encountered on transmission lines. Occasionally other wave shapes of more extreme characteristics are used (27).

The usual form of impulse voltage used in the laboratory is one having a rapid rise followed by a less rapid decay to zero, given by

\[ V = V_0 \left\{ \exp(-at) - \exp(-bt) \right\} \]  \hspace{1cm} (2.3)

Where,
\[ V_0 = \text{maximum voltage (at } t=0) \]

\[ V = \text{peak value of the impulse wave,} \]

\[ a \text{ and } b \text{ are constants and } t \text{ is the time in micro seconds.} \]

A wave is referred to as \( t_1 / t_2 \) wave. \( t_1 \) is the time occupied by the impulse voltage wave in rising from zero to its peak value and \( t_2 \) is the total time occupied by the impulse wave in rising to its peak value and decaying therefrom to one-half the peak value.

The standard wave shape is 1,2/50 i.e., wave front of 1.2 micro seconds and a 50 micro seconds wave tail. A tolerance of not more than 30% is allowed on the wave front and of 20% on the wave tail.

The impulse voltage test circuit is shown in figure 2.3(b). Using this 8-stage "Marx-generator" capable of delivering about 800 kVolts, a 1,3/45 micro seconds negative polarity impulse voltages as shown in figure 2.4 was obtained. The ringing observed at the peak of the impulse wave was kept at a level less than 6.5%. The stage capacitance consisted of two 0.2 \( \mu \)F capacitors connected in series and were charged through 100 k\( \Omega \) resistors. The maximum charging voltage of each capacitor unit was 50 kV, thus limiting each stage charging voltage to a maximum of 100 kV. Working details of this Marx generator, except for its 8-stages, resembles that explained in (26).
POSITIVE D.C. CIRCUIT.

FIGURE 2.3a SCHEMATIC OF POSITIVE POLARITY D.C. CIRCUIT.

IMPULSE CIRCUIT
(Marx generator).

FIGURE 2.3b SCHEMATIC OF IMPULSE TEST CIRCUIT.
X-axis: 10 micro-secs/division.
Y-axis: 20 Volts/division.

Figure 2.4 Oscillogram of the Impulse Waveform.
The charging voltage of the first stage was measured by using a resistance divider, consisting of 600 MΩ and 60 kΩ, coupled to a digital voltmeter. This divider was then calibrated using an electrostatic voltmeter within an accuracy of 0.5% of the applied voltage. The output of the generator was calibrated with respect to the charging voltage against a 25 cm diameter sphere gap within an accuracy of ± 2%.

In the case of impulse voltage applications, measurements of total time to breakdown \( t_d \) reveals a great deal of information about the flashover. So time lag studies were conducted using a 549 Tektronix storage oscilloscope with a 1A1 plug-in unit in conjunction with a capacitance voltage divider. The high voltage arm of this divider had a capacitance of 1370 pF, whereas the low voltage arm consisted of a capacitor of 4.23 μF. The divider ratio was thus 1.23/0.001370 = 898. It was necessary to terminate the cable with its characteristic impedance of 50 Ohms. This eliminated the distortions of the waveform which reflections at the cable terminations would otherwise introduce.
2.4 **ACCURACY OF FLASHOVER MEASUREMENT**

In any practical experimental setup, naturally errors get introduced into the measured data through different ways like the instrumentation error, parallax or measuring error, source error, etc. Thus the total error should be kept within tolerable limits. In order to analyze the magnitude of error or in other terms the quality of the measured data, flashover voltage measurements using plane, parallel, Bruce profile brass electrodes were determined and the results were compared with the values readily available in the literature (26-29).

Figures 2.5(a) through 2.5(c) give the measured breakdown or flashover voltage of the gas, i.e., air, N₂, and SF₆ respectively, at different pressures, represented by the numbers on the curves, and for varying gap length or separation distance of electrodes. It was found that the flashover measurements presented here lie within a maximum of 5% of those values reported in (26-29). Thus the above analysis ensured that the experimental system used in the present investigation was reliable over the range.

All the results were reported at a temperature of 20°C. Any fluctuations in the laboratory temperature were compensated by multiplying the measured flashover voltage by a factor of \((273+T)/293\), where T was the recorded laboratory temperature during the experiment, in °C.
FIGURE 2.5a  BREAKDOWN VOLTAGE AT DIFFERENT PRESSURE
AND AT DIFFERENT GAP DISTANCES.
**Figure 2.5b**  
Breakdown voltage at different pressures and at different gap distances.

Gas: N₂  
20°C
Chapter III
DIRECT CURRENT FLASHOVER MEASUREMENTS

3.1 GENERAL

A flashover is characterized by the rapid transition of an insulating medium or an insulator from a poor electrical conductor of very high resistivity to a relatively good electrical conductor. The voltage at which this transition takes place is referred to as the 'flashover voltage'.

This chapter describes the results of flashover voltage tests of composite insulation using both positive and negative polarity direct voltages. Three different thicknesses of solid dielectric materials were used and their effect on flashover voltage have been studied. Also, four different diameters of the solid dielectric material have been used. Air, Nitrogen and Sulfur Hexafluoride were used as the gaseous insulation, whereas glass ceramic ($\varepsilon_r=5.8$) and plexi-glass ($\varepsilon_r=3.2$) were used as solid insulators in the present investigations.
3.2 ESTIMATION OF FLASHOVER VOLTAGE

Figure 3.1 shows the experimental set-up used. Basically it was a very simple set-up. A high voltage, high value resistor was used in series with the extra high voltage source, and the experimental set-up, for the purpose of limiting short circuit current.

A composite insulation system has been a subject of many researchers in the past. They have represented such a system by two capacitors in series. If two capacitors having very high volume resistivity compared to their capacitive reactances were connected in series, then the voltage will be distributed between these capacitors in accordance with the thickness and the dielectric constant of each capacitor, represented as,

\[ V_b(\text{estimated}) = \frac{V_b(\text{of gas at } d_1)}{1 + \frac{d_2}{(\varepsilon_2 I d_1)}} \]  \hspace{1cm} \hspace{1cm} \hspace{1cm} (3.1)

Where,

\[ d_1 = \text{distance between the top electrode and the solid dielectric,} \]

\[ d_2 = \text{thickness of the solid dielectric and} \]

\[ \varepsilon_2 = \text{permittivity of the solid dielectric.} \]
FIGURE 3-1  EXPERIMENTAL SET-UP.
Appendix-I explains the details about the development of this expression (3.1). A comparison between the measured flashover or breakdown values of the composite insulation system using the earlier explained experimental set up (fig. 3.1), with the estimated values of breakdown voltage using the above said capacitive voltage distribution has been presented.

We have used the "percentage deviation", defined as the difference between the measured and the estimated value of breakdown voltages with respect to the estimated values of breakdown voltage, under identical experimental conditions, given by,

\[
\text{% deviation} = \frac{V_b(\text{measured}) - V_b(\text{estimated})}{V_b(\text{estimated})} \times 100 \quad \ldots(3.2)
\]

as a performance criterion.

3.3 FLASHOVER MEASUREMENTS

In the case of negative polarity DC voltages, as explained earlier, 0-1000 kV DC generator was used. The output voltage of this HVDC generator was controlled by a ten turn potentiometer. The rate of rise of output voltage was proportional to the angular velocity of the potentiometer rotation. The voltage was controlled manually and this posed a limitation on the change in output voltage
to a rate which should eliminate the possibility of influencing the test results. This statement is based on the experience gained through these experiments. In view of this an arbitrary rate of rise of about 20 kV/3-4 min. was adopted for all the flashover tests. However, when the flashover voltages were higher than 200 kV, for the purposes of reducing the time involved in making measurements, the applied voltage was raised swiftly to about 60% of the expected flashover voltage and then was increased gradually, as explained earlier.

Before setting up the apparatus for the measurement of flashover voltage of the composite insulation, care was taken to see that the electrodes were properly conditioned, thus eliminating the conditioning effects on the measured results. At each experimental set-up the average value of the ten flashover voltage applications was taken as the flashover voltage. The vertical bars in figs. 3.2(a-e) and 3.3 show the spread of these ten flashover voltage applications at that particular set up and the numbers on these curves indicate the pressure.

3.3.1 **Effect of pressure and electrode separation**

Figure 3.2(a) shows the negative polarity DC flashover voltage-total separation distance 'd' relation for a composite insulation system where N₂ was the gaseous medium and a 5mm thickness and 51mm diameter of plexiglass was the
solid dielectric material. Broken lines indicate the estimated values of flashover voltage using capacitive voltage distribution. We observe that the estimated values of flashover voltages were lower than the measured flashover voltage values, the percentage difference being highly predominant at shorter gaseous gap distances or at smaller values of total separation distance 'd'. The curves are for the pressure range from 1 to 4 bars and the total separation 'd' was varied over the range of 6mm to 35mm in this case.

Figures 3.2(b) through (e) depict similar graphs of composite insulation flashover voltage against total separation distance 'd'. In figs 3.2(b) and (c), the thickness of solid insulator, plexiglass, was 10mm and diameter was 51mm, the gaseous insulation was air and SF₆ respectively, whereas in figs 3.2(d) and (e), the solid dielectric thickness was 15mm and 51mm was the diameter and the gaseous dielectric was air and nitrogen respectively. Again, in all these figures the estimated values of flashover voltage were represented by broken lines.

In all these graphs of flashover voltage-Vs-total separation distance 'd', for the negative polarity DC applied voltages, a stereo-type behaviour was observed - i.e., the measured values of flashover voltages were much higher than the estimated values of flashover voltages using the earlier explained capacitive voltage distribution, the difference being more predominant at shorter gaseous gaps and at medium pressures (1-3 bars) in comparison with
FIGURE 3.2a FLASHOVER VOLTAGE - 'd' FOR PLEXI GLASS
UNDER NEGATIVE POLARITY D.C.

gas: N₂, d=d₁+d₂, d₂=5 mm
--- ESTIMATED
--- MEASURED

\[ V_b (kV) \]

\[ d \text{ in mm} \]
Figure 3.2b  Flashover Voltage 'd' for PLEXIGLASS

Under Negative Polarity D.C.

Gas: AIR, d=d1+d2,
d2=10 mm, \( \xi_2=3.2 \),

- - - - ESTIMATED

MEASURED

\( v_b \) (kV) vs. \( d \) in mm.
FIGURE 3.2c  FLASHOVER VOLTAGE- 'd' FOR PLEXI GLASS
UNDER NEGATIVE POLARITY D.C.

gas: SF₆, d=d₁+d₂, d₂=10 mm,

- ESTIMATED,
- MEASURED.
Figure 3.2d Flashover Voltage - 'd' for Plexiglass Under Negative Polarity D.C.
Figure 3.2e: Flashover Voltage - 'd' for Plexi Glass under Negative Polarity D.C.

Gas: N₂, \( d = d_1 + d_2 \),
\( d_2 = 15 \) mm, \( \epsilon_2 = 3.2 \),
--- ESTIMATED,
--- MEASURED.

\[ V_b (kV) \]
\[ d \text{ in mm.} \]
larger values of total separation distances (say, \(d = 25\text{mm and above}\)).

Even in the case of positive polarity DC voltages which were obtained using 0-150 kV, 60 Hz, A.C. supply, as explained in section 2.3.2, the flashover voltage as a function of the total separation distance, shown in figure 3.3, depicts the same behaviour. In this figure, the thickness of the plexiglass, of 51mm diameter, was 10 and 15 mm and the pressure range and other details can be visualized through the graph.

The reasons for the discrepancy between the measured and estimated values of flashover voltage at shorter gap distances may be attributed to the approximations employed in arriving at this estimated value of flashover using the capacitive voltage distribution. However the fact that the mechanisms involved in the flashover event of such composite insulation system will have sufficient bearing on the flashover voltage value can not be neglected. This has been discussed in detail at the end of this chapter.

Figures 3.4(a) and (b) show the percentage deviation (performance criterion) for various separation distances. In fig. 3.4(a), the thickness of the solid dielectric was 5mm and its diameter was 51mm with air being the gaseous insulant, whereas in fig. 3.4(b) nitrogen was the gaseous insulant and the thickness of the solid insulator, plexiglass, was 15mm.
Figure 3.3: Flashover Voltage - 'd' for Flexi Glass (positive D.C.)

\[ V_b(kV) \]

- \( d = d_1 + d_2; \) AIR, \( \epsilon_r = 3.2, \) positive D.C., \( D_1 = 51 \text{ mm}, \)
- Estimated,
- Measured,
- \( d_2 = 10 \text{ mm}, \)
- \( d_2 = 15 \text{ mm}. \)
Figure 3.4a: Percentage Deviation (P.d.) - d for Plexiglass under negative polarity D.C.

Gas: Air, d = d1 + d2,
d2 = 5 mm, 20°C.
气体: $N_2$, $d=d_1+d_2$, $d_2=15$ mm, 20°C.

图3.4b 电晕电位（P.d.）- $d$ 对于柔性玻璃在负极性直流下的百分比偏差
This performance criterion, given by (3.2), decreases to considerably low values at larger gap distances and at higher pressures, as expected. This was because of the fact that the magnitude of the estimated flashover value was higher at higher pressures and at larger gap distances. In the expression (3.2), the difference between the estimated and measured flashover value gets divided by the estimated value and hence as the magnitude of the estimated value becomes higher, values of percentage deviation become considerably lower, as can be seen through the graphs 3.4(a) and (b).

3.3.2 Effect of gaseous insulation

A comparison between the flashover voltages of Air, Nitrogen and Sulfur Hexafluoride as the gaseous insulating media of these composite insulation systems can be visualized through figure 3.5. Under identical experimental conditions, for negative polarity DC voltages, the flashover voltage of Air lies between that of N₂ and SF₆, thus indicating that the flashover voltage of composite insulation systems vary with the electronegativity of the gas medium(11). Air has about 18% of Oxygen, a more attaching gas with respect to N₂, and about 80% of nitrogen thus resulting in slightly higher values of flashover voltages. However, at higher pressures and at larger values of gap distances, the variation in flashover voltage becomes
**FIGURE 3.5** EFFECT OF GASEOUS INSULATION ON FLASHOVER (−ve D.C.).

\[ d = d_1 + d_2; \quad d_2 = 10 \text{ mm}, \]
\[ \varepsilon_2 = 3.2, 20^\circ \text{C}, \]
\[ b_1 = 51 \text{ mm}. \]
more predominant. SF₆, a highly attaching or electronegative gas, which has a relative withstand strength of about 2.5 times that of air, under identical experimental conditions, results in higher values of flashover voltages.

3.3.3 **Effect of solid insulator diameter**

A decrease in flashover voltage of the order of 30% was observed when the diameter of the solid dielectric in a composite insulation was increased by about five fold. Figures 3.6(a) through (d) show this effect. In fig. 3.6(a) and 3.6(b), flashover voltage was plotted against the total separation distance for various diameters of a 15mm thickness of solid dielectric, plexiglass, in air and nitrogen respectively, whereas, in fig. 3.6(c) and (d), flashover voltage was plotted against the diameter of the dielectric for various constant separation distances. The broken lines in the last two figures indicate 2 bar pressure.

It is a well known fact that the electric field necessary to produce electric breakdown (flashover) falls as the area of the electrodes or the solid/gas interface is increased (30). Actually by increasing the diameter of the dielectric, the surface area of the dielectric in contact with the electrode or the conductor (i.e., the triple point junction) increases, thus increasing both the probability.
**FIGURE 3.6a** EFFECT OF SOLID INSULATOR DIAMETER ON FLASHOVER UNDER NEGATIVE POLARITY D.C.

- **gas:** AIR, $d = d_1 + d_2$, $d_2 = 15\, \text{mm}$, $\varepsilon_2 = 3.2$, $20^\circ\text{C}$.

- **Estimated:** dashed line.
- **Measured:** solid line.

$d$ in mm

$V_d$(kV)
**Figure 3.6b** EFFECT OF SOLID INSULATOR DIAMETER ON FLASHOVER UNDER NEGATIVE POLARITY D.C.

Gas: $N_2$, $d = d_1 + d_2$, $d_2 = 15$ mm, $\mathcal{E}_2 = 3.2$, 20°C,

- --- ESTIMATED,
- --- MEASURED.
FIGURE 3.6c EFFECT OF SOLID INSULATOR DIAMETER ON FLASHOVER UNDER NEGATIVE POLARITY D.C.
FIGURE 3.6d  EFFECT OF SOLID INSULATOR DIAMETER ON FLASHOVER UNDER NEGATIVE POLARITY D.C.

gas: \( N_2 \), \( d=d_1+d_2 \),
\( d_2=15 \text{ mm}, \varepsilon_2=3.2 \),

--- 1 bar; --- 2 bar.
and the rate of initiation of electrons and in turn resulting in the increase in electric stress or the decrease in flashover strength or the breakdown voltage of the insulation.

3.3.4 Effect of dielectric thickness

If a need arises to double the electric stress in any solid/gas interface system, then by doubling the length of the solid/gas interface, it can not be achieved, unless other parameters like geometrical shape of the insulator, pressure or the contact area of the solid dielectric with the conductor are suitably modified [1]. Figure 3.7 depicts the surface flashover voltage against the total separation distance, 'd', for various pressure and solid dielectric thickness in air. The solid dielectric material was plexiglass of diameter 51mm.

We observe that at large values of 'd', or at higher pressures, flashover values with 5mm thickness of solid dielectric material seems to be higher than that of 15mm thickness of solid dielectric. The flashover voltage of a gaseous gap almost doubles with a two fold increase in the gap length, whereas, for a gap bridged by a solid dielectric, flashover voltage increases by a factor of about 1.6 for a two fold increase in gap length. Hence in the above fig. 3.7, at a total separation distance 'd' of 20mm, at 3 bar pressure, a 15mm gaseous gap exists in the
FIGURE 3.7 EFFECT OF INSULATOR THICKNESS ON FLASHOVER (–ve D.C.).

gas: AIR; 20°C,
d = d1 + d2;
D1 = 51 mm; ε2 = 3.2.
case of a 5mm thickness of solid dielectric compared to only a 5mm gaseous gap in the case of 15mm thickness of solid dielectric. Resulting, apparently in an increase in flashover voltage of 40 kV, for the earlier case as expected.

3.3.5 Effect of dielectric constant

Flashover voltage of a gap bridged by a solid insulator gets influenced to a great extent by the chemical composition of the insulating material, the relative permittivity of the solid dielectric along with many other factors like the resistivity of the material, geometric shape of the dielectric, field enhancements at the triple point junctions, etc.

Figure 3.8, compares the flashover voltage of composite insulation for different values of dielectric constant of the solid dielectric of thickness 10mm. Flashover voltage of plexiglass with a relative permittivity of 3.2 was compared with that of glass ceramic having a relative permittivity of 5.8, both of 25mm diameter discs, for various separation distances 'd', when nitrogen and air were used as gaseous insulating media. The flashover voltage values of plexiglass (εr=3.2) was found to be higher than that of glass ceramic (εr=5.8) under the identical experimental conditions, the difference being more predominant at higher pressures, as expected, in a composite insulation system.
FIGURE 3.8 EFFECT OF DIELECTRIC CONSTANT ON FLASHOVER (-ve. D.C.)
The difference in flashover values being attributed to the field enhancements resulting at the triple point junctions due to the increase in dielectric constant [31]. However, it should be noted that the flashover voltage does not vary linearly with the dielectric constant of the material.

We have plotted the percentage deviation given by expression (3.2) against the total separation distance 'd', for this 25mm diameter glass ceramic disc of 10 mm thickness in air and in \( N_2 \) in fig. 3.9. It can be readily seen that the graph looks similar to the ones explained earlier, i.e., fig. 3.4(a) and (b).

3.4 RESULTS AND DISCUSSIONS

The important observation made through the various graphs presented earlier in this chapter, was that the estimated flashover voltage of these composite insulation systems for various pressures, gap distances and diameters of solid dielectric do not agree with the measured values of flashover voltage. This difference can be attributed partly to the approximations made in arriving at the estimated values of the flashover voltage using the capacitive voltage distribution. But the fact that the increase in the diameter of the solid dielectric resulted in lower flashover voltages indicates that if the electrode surface were to be completely covered by the solid dielectric, then the estimated flashover voltage values,
FIGURE 3.9  PERCENTAGE DEVIATION (P.d) - 'd'

FOR GLASS CERAMIC (neg. D.C.)
given by expression (3.1), would result in better approximations.

Hence, a new approximation was made which takes into account the diameter of the solid dielectric. This equation can be written as,

\[
V_{b, \text{new}} = \frac{4A(1+d_2/d_1) + \pi D_1^2 (\varepsilon - 1)}{4A + \pi D_1^2 (\varepsilon - 1)} \cdot V_b \text{ (of gas at } d_1) \quad \ldots (3.3)
\]

Where,

- \( A \) = area of the electrodes in \( cm^2 \),
- \( d_1 \) = distance between the top electrode and the solid dielectric in \( cm \),
- \( d_2 \) = thickness of the solid dielectric in \( cm \),
- \( D_1 \) = diameter of the solid dielectric in \( cm \),
- \( \varepsilon_r \) = permittivity of the solid dielectric,

\( V_{b, \text{new}} \) = new approximation for the flashover voltage using the capacitive distribution of voltages.

Appendix-II explains the details about the development of this expression (3.3).

Tables 3.1 through 3.4 present a comparison between the measured flashover values for negative polarity DC voltages.
with the expression (3.3) for various parameters. The agreement seems to be very good over the range of values presented, thus indicating that the diameter of the solid dielectric material does have a predominant effect on the estimation of the flashover voltages in composite-insulation system.

However, even in this approximation, it was found that the deviation of the measured and estimated flashover values using equation (3.3) were higher, at shorter gaseous gaps (< 2 mm) compared to larger gaseous gaps. Also, this difference between the measured and estimated values was predominant in the case of a solid insulator with a diameter of 13.1 mm compared to that of 64 mm. For values of flashover voltage higher than 150 kV, the deviation between the measured and estimated flashover values seems to be higher.

The above deviation of the measured flashover voltage from the estimated values using expression (3.3) can be attributed to the effect of stray capacitance existing between the electrodes and the edge of the solid insulator along with many other factors like the surface bound charges, non-uniform surface leakage (32), etc.

Thus, in general, the estimated flashover voltage values using the new expression (3.3) are in better agreement with the measured flashover voltage values, compared with the values obtained using expression (3.1). So, it indicates that, the flashover voltages are predictable, to a certain
degree of accuracy in gas-solid dielectric systems when the thickness of the solid dielectric, dielectric constant, and the conductor and solid dielectric diameters are known. However, the accuracy seems to mainly depend upon the length of the gaseous gap between the solid dielectric surface and the conductor along with the magnitude of the applied voltage.
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<th>Pressure in bars</th>
<th>Total Separation Distance in mm</th>
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**TABLE 3.1** A comparison of the measured flashover voltage with the estimated values, in kV, using the expression (3.3) in air and N₂, for plexiglass.
<table>
<thead>
<tr>
<th>Pressure in bar (AIR)</th>
<th>Total Separation 'd' in mm</th>
<th>DIFFERENT VALUES OF $d_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5 mm</td>
</tr>
<tr>
<td></td>
<td>Measured</td>
<td>Estimated</td>
</tr>
<tr>
<td>1</td>
<td>13</td>
<td>31.0</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>37.0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>50.5</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>65.0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>80.0</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>97.3</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>60.5</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>71.0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>101.0</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>128.0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>152.5</td>
</tr>
</tbody>
</table>

**TABLE 3.2** A comparison of the measured flashover voltage with the estimated values, in kV, using expression (3.3) for different dielectric thickness (plexiglass, $D_i = 51$ mm)
<table>
<thead>
<tr>
<th>Pressure in bars</th>
<th>Total Separation Distance 'd' in mm</th>
<th>FLASHOVER VOLTAGE, kV, VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AIR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measured</td>
</tr>
<tr>
<td>1</td>
<td>13</td>
<td>37.5</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>43.5</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>57.0</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>66.0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>77.0</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>63.0</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>75.0</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>94.0</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>122.5</td>
</tr>
</tbody>
</table>

TABLE 3.3 A comparison of the measured flashover voltage with the estimated values, using expression (3.3) for different gases (D₁ = 51 mm, plexiglass, d₂ = 10 mm)
<table>
<thead>
<tr>
<th>Pressure in bar</th>
<th>Total Separation Distance in mm.</th>
<th>FLASHOVER VOLTAGE IN kV</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>AIR</td>
<td>Measured</td>
<td>Estimated</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>39.0</td>
<td>38.1</td>
<td>36.5</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>49.0</td>
<td>48.5</td>
<td>45.5</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>64.0</td>
<td>63.3</td>
<td>59.0</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>77.0</td>
<td>78.8</td>
<td>73.5</td>
</tr>
<tr>
<td>36</td>
<td></td>
<td>89.5</td>
<td>95.9</td>
<td>76.0</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>55.5</td>
<td>60.9</td>
<td>51.5</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>70.5</td>
<td>68.9</td>
<td>63.5</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>87.5</td>
<td>108.0</td>
<td>80.5</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>112.0</td>
<td>137.4</td>
<td>98.5</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>134.0</td>
<td>165.4</td>
<td>122.0</td>
</tr>
<tr>
<td>35</td>
<td></td>
<td>152.0</td>
<td>188.3</td>
<td>146.0</td>
</tr>
</tbody>
</table>

TABLE 3.4 A comparison of the measured flashover voltage with the estimated values, in kV, using expression (3.3) for glass ceramic. (Di = 25 mm, d2 = 10 mm)
Chapter IV

IMPULSE FLASHOVER AND TIME LAG STUDIES

4.1 GENERAL

With the great increase in transmission of electric power by overhead lines, which get exposed to all kinds of weather conditions, the lightning hazards have become of prime concern. Lightning currents in general rise rapidly to a maximum value in a few microseconds and then fall to a low value in a period approaching 100 microseconds. Though the current-time characteristic referred to as a "wave" or "wave shape", may be irregular and may contain reversal of polarity, for test purposes aperiodic waves of 1,2/50 microsecond are used. Whenever lightning strikes a transmission line, a voltage wave similar to the lightning current wave travels along the line in both directions, thus subjecting the equipment connected to the line to this lightning impulse.

So it is important to study the effect of impulse flashover on insulation systems and hence in this chapter, an attempt has been made to study the flashover characteristics of composite insulation to impulse applications. Also, the total time to breakdown of these insulation systems were measured.
4.2 IMPULSE FLASHOVER MEASUREMENT

Insulators usually break down by flashover due to the application of sufficient magnitude of voltage across them. In the case of impulse voltage applications, the rise in the peak value of the applied voltage changes the probability of an impulse causing a flashover from zero to one. But this transition takes place very gradually, giving an "S" shaped curve, which follows the "Gaussian-probability distribution", with the extremities of the changeover being ill defined. For making quantitative measurements of flashover voltage, usually 'the 50% flashover' voltages were determined, which, in practice can be obtained with some precision if about 70-80 impulses were applied under identical experimental conditions. The results were plotted on arithmetic probability paper, an example of which is shown in figure 4.1.

Figure 4.2 depicts the 50% negative polarity impulse flashover values against the total separation distance for a composite insulation system, consisting of air and plexiglass of 10mm thickness and 51mm diameter as the insulating media. Estimated values of flashover voltage were represented by broken lines. As in the case of DC voltages, the estimated values of flashover for impulse voltages were also lower than that of measured flashover voltages, under identical experimental conditions.
FIGURE 4.1 AN EXAMPLE OF AIR-THEMIC PROBABILITY OF FLASHOVER.
Figure 4.2: Flashover voltage - 'd' for impulse voltages.

- $d = d_1 + d_2$; $d_2 = 10$ mm, $\varepsilon_0 = 3.2$.
- $D_1 = 51$ mm, gas: AIR.

- Estimated.
- Measured.
- '-' D.C.
- '+' D.C.
- $1.2/50$ impulse.
A comparison between negative polarity impulse and the positive and negative polarity DC flashover voltages can be seen in Table 4.1. The gaseous insulation was air at 2 bar and the solid dielectric was plexiglass of 10mm thickness and 51mm diameter.

Flashover strength of the composite insulation system for negative polarity DC and the impulse voltages were almost the same, whereas for positive polarity DC, lower values of flashover voltages were observed. This can be easily explained by referring to Fig.3.1. When a positive polarity voltage was applied to the top high voltage, fixed electrode, the lower grounded electrode which was a movable one, became the cathode. The solid insulator was placed on this electrode for all experiments, and hence, the 'triple point junction' (conductor-insulator-gas junction) lies on this electrode. The fact that this triple point junction acts as the weakest section of any insulation system and the fact that it lies on the cathode under positive polarity voltages seems to influence the flashover voltage to a great extent. However, when the applied voltage was of negative polarity, this triple point junction was on the anode and hence the flashover voltage of positive polarity DC voltages were lower, as expected, than that of negative polarity DC voltages.
<table>
<thead>
<tr>
<th>Pressure in bars</th>
<th>Total separation distance 'd' in mm</th>
<th>Flashover voltage in kV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>+VE DC</td>
</tr>
<tr>
<td>1</td>
<td>13</td>
<td>29.5</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>41.5</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>57.0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>72.0</td>
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<tr>
<td></td>
<td>35</td>
<td>85.0</td>
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<tr>
<td>2</td>
<td>13</td>
<td>58.5</td>
</tr>
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<td></td>
<td>15</td>
<td>69.0</td>
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<td>73.0</td>
</tr>
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<td></td>
<td>15</td>
<td>99.5</td>
</tr>
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<td></td>
<td>20</td>
<td>130.5</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>167.5</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>209.0</td>
</tr>
</tbody>
</table>

**TABLE 4.1** FLASHOVER VOLTAGE FOR DC

(Both polarity) and impulse at various pressures and gap distances.
4.3 TIME-LAG STUDIES

There are two conditions which must be simultaneously satisfied in order that an electrical discharge can occur across a gap. First, there must be at least one suitably located free electron in the gap to initiate the avalanche, and secondly the electric field must be of sufficient strength and duration to ensure that this electron produces a sequence of avalanches which lead to a flashover (34). With slowly rising voltages there are usually sufficient initiatory electrons created by cosmic rays or due to the naturally occurring radioactive sources. Under surge voltages and pulses of short duration, unless the initiatory electrons are ensured, the flashover of the gap may not take place as the voltage reaches the peak, thus resulting in an elapse of time between the application of a surge voltage and the flashover event (26). This time, which elapses between the application of a sufficient voltage and the flashover or breakdown of a gap and the breakdown is called the time to breakdown \((t_d)\) or the time lag. It is well known that this time lag for breakdown consists of two components: the "statistical time lag" \((t_s)\) which quantifies the time required for an initiatory electron to appear in the gap at a most suitable point and the "formative time lag" \((t_f)\) which quantifies the time required to complete the breakdown process, once initiated.
The statistical time lag mainly depends on the amount of pre-ionization present in the gap. This in turn depends upon the size of the gap and the radiation producing the primary electrons. The appearance of such electrons is usually statistically distributed. The formative time lag depends essentially on the mechanisms of spark growth. In cases when the secondary electrons arise entirely from the electron emission at the cathode by positive ion impact, the transit time \( t_i \) of the positive ions from the anode to cathode will be the dominant factor, determining the formative time lag.

In experimental studies of the initiatory and formative time lags it is always the total time or the time to breakdown \( t_d \) which is measured. From the measured time lags, the statistical time lag \( t_s \) and the formative time lag \( t_f \) components can be separated using the Von-Laue equation (35):

\[
n_i = n_0 \exp(-t/\lambda) \quad \quad \quad \quad \quad (4.1)
\]

Where,

- \( n_0 \) = total number of breakdown experiments,
- \( n_i \) = number of breakdowns with time lags greater than \( t \),
- \( \lambda \) = mean time lag.

Then the observed time lag corresponding to \( n_i / n_0 \neq 1 \) is the formative time lag for breakdown.
The above analysis was done by applying 100 negative
polarity impulses in succession, allowing a sufficient time
interval between successive shots, keeping all other
parameters like pressure, peak value of applied voltage,
total separation distance, etc., constant.

Figure 4.3 gives the Laue plots for different diameters
of solid dielectric, plexiglass, of 10 mm thickness at 2 bar
pressure in air when the total separation distance was 13 mm.
The effect of insulator diameter on time to breakdown can be
easily visualized. The reduction in insulator diameter
results in an increase in time to breakdown in a composite
insulation system, thus indicating that the surface area of
the solid dielectric or the area of contact of solid
dielectric with the conductor has a pronounced effect or
influence on the total time to breakdown. Also, due to the
fact that the breakdown voltage increases with the decrease
in diameter of the solid dielectric seems to have some
effect on time to breakdown in this case.

Figures 4.4(a) and (b) depict the actual pictures taken
using a polaroid camera for 51 mm and 13.1 mm diameter of
solid dielectric, for which the Laue plots were
drawn (fig. 4.3).

In figure 4.5, the time to breakdown for different
values of applied voltages or over voltage factors, for a
gap separation of 13 mm, with a 10 mm thickness of solid
dielectric of 51 mm diameter, at 2 bar in air has been
plotted.
FIGURE 4.3 TIME TO BREAKDOWN (td) - DIFFERENT INSULATOR DIAMETER.

Applied voltage = 81.2 kV.
d = 13 mm. d2 = 10 mm.
plexiglass material.
1: 13.1 mm diameter.
2: 51 mm diameter.
diameter of dielectric = 51 mm.

diameter of dielectric = 13.1 mm.

FIGURE 4.4 OSCILLOGRAMS SHOWING TYPICAL TIME LAGS.
FIGURE 4.5  EFFECT OF OVERVOLTAGE ON TIME TO BREAKDOWN (td).
Formative time lags were found to decrease considerably with the increase in applied voltage or in other terms, the slope of the plots increased with increase in voltage(35). When the applied voltage to a gap increases, the electrons in the gap get more energy and hence their drift velocity increases, thus reducing the transit time and hence lowering the time to breakdown.

The formative time lag or the time to breakdown, was plotted for different pressures in figure 4.6. As the applied voltage and the total separation distance 'd' were kept constant, with increase in the pressure, E/p ratio decreases, resulting in a decrease in the electron energy of the gap. Hence, as the pressure increases, time to breakdown should increase, as can be seen in figure 4.6.

The presence of the insulator reduces the average breakdown time, under identical experimental conditions. This seems to indicate that the discharge initiation mechanism gets influenced significantly by the presence of the dielectric surface. The reduction in flashover time may possibly be due to the production of electrons from the insulating surface, and/or due to the localized high field sites created by the surface charges(36). Figure 4.7 shows Laue plots with and without an insulator in a 10mm, 2 bar pressure air gap. However, the overvoltage factor for the air gap was only 1.05 whereas for the insulator it was about 1.9 and that might have affected the time to breakdown to
Applied voltage = 95 kV, \( d = 13 \text{ mm}, \) \( d_2 = 10 \text{ mm}, \) plexiglass material.

FIGURE 4.6 EFFECT OF PRESSURE ON TIME TO BREAKDOWN (td).
Applied voltage = 62.4 kV.
1: without insulator.
2: with insulator.
Pressure: 2 bar in AIR.

Figure 4.7 Effect of Insulator on Time to Breakdown (td).
a greater extent, as the energy in the gap increases in the latter case, resulting in a reduction in transit time $t_1$ of the electrons.

However, the time to breakdown $t_d$ of the order of only a few microseconds (with in a maximum of 5 microseconds) were recorded in the present investigations using the experimental set up shown in fig. (3.1).
Chapter V
CONCLUSIONS

5.1 GENERAL

In any practical high voltage system, determination of flashover voltage or the insulating ability of the system, which is essential for the healthier operation of the system, needs an accurate knowledge of various other parameters like, type and polarity of the applied voltage, type of insulation in use, field distribution in and around the system of interest, etc. Even though, the measured flashover voltage data from a laboratory clean system, may seem to be of less importance for practical purposes, it does give an idea of the general behaviour of the system for that particular type of applied voltages. Hence, the flashover voltages measured and presented through this work can also be used to understand the general behaviour of such composite insulation systems.

This chapter presents the conclusions of the studies conducted in the present work on the flashover of composite insulation systems. The most significant result of the present work is that in the case of composite insulation systems, where the solid dielectric does not cover the entire conductor surface (as can be seen from fig. 3.1), the
estimation of surface flashover voltage using the capacitive voltage distribution should take into account the diameter of the solid dielectric, under uniform field conditions.

5.2 CONCLUSIONS

The following conclusions are derived from the present work presented in this thesis:

1. Under uniform field conditions, estimation of flashover voltages using the capacitive voltage distribution (given by expression (3.1)) does not agree with the measured flashover values, unless, the effect of solid insulator diameter on the capacitive voltage distribution is taken in to account, as in expression (3.3).

Thus the flashover voltages are predictable, to a certain degree of accuracy, in gas-solid dielectric systems when the thickness, diameter, dielectric constant of the solid dielectric along with the diameter of the conductor are known. Though the accuracy depends upon the magnitude of the applied voltage and the length of the gaseous gap, it is found to lie within tolerable limits over most of the range of parameters presented.

2. The flashover voltage of composite insulation varies with the electronegativity of the gaseous insulation, as well as, the dielectric constant of the solid insulator.
Under identical experimental conditions, flashover voltage of air, as a gaseous insulant of a composite insulation, is found to lie between that of \( N_2 \) and \( SF_6 \). Also, the flashover voltage for glass ceramic \((\varepsilon_r=5.8)\), in composite insulation, is less than that of plexi-glass \((\varepsilon_r=3.2)\).

3. The decrease in diameter of solid insulator results in an increase in flashover voltage of the composite insulation for the same values of total separation distance \( 'd' \) and the thickness of the solid insulator.

   An increase in flashover voltage of the order of 30% was observed for about a five fold decrease in solid insulator diameter, under identical experimental conditions.

4. At higher pressures or for larger values of gap separation distance \( 'd' \), a decrease in solid insulator thickness results in an increased flashover voltage.

5. The reduction in insulator diameter results in an increase in time to breakdown in a composite insulation system. Also, the presence of the insulator reduces the average breakdown time, under identical experimental conditions.

6. The time to breakdown decreases with increase in applied voltage, indicating that under identical
experimental conditions, an increase in applied voltage increases the $E/p$ ratio, thus reducing the transit time of the electrons. Similarly, under identical experimental conditions, an increase in pressure reduces the time to breakdown $t_d$.

7. The flashover voltage of composite insulation is lower for positive polarity DC voltages compared to that of negative polarity DC or the 1.2/50 microseconds, negative polarity impulse voltages.

Thus, the polarity of the applied voltage does have a pronounced effect on the flashover of composite insulation, as it determines whether the triple point junction lies on the anode or the cathode, in the system.

5.3 **SUGGESTIONS**

It must not be overlooked that the present study examines only a few aspects of the properties or behaviour of a composite insulation system in power apparatus. The whole electrical aspect itself is one of the many which must be taken into account in electrical insulation equipment design and fabrication. Keeping this in mind, the following suggestions can be made for the continuation of this work:

1. It is of practical interest to know how the surface bound charges on the insulator surface affect the flashover of a composite insulation system. Hence, it
wil be usefull to measure the magnitude and the 
polarity of the charges by some technique after, as 
well as, just before the flashover event, in these 
composite insulation systems.

2. Also, the time-resolved photography of the flashover 
event may give additional information, about the 
processes by which a flashover event has taken place.
APPENDIX - I

Development of Equation 3.1

If a voltage $V$ is applied to two capacitors in series, as shown in Fig. A-I (a), the voltage will be divided between the two capacitors

$$V = V_1 + V_2 \quad \text{(A-I.1)}$$

where,

$V_1 =$ voltage across capacitor $C_1$

$V_2 =$ voltage across capacitor $C_2$

The voltage gradient across each capacitor is $E_1 = V_1/d_1$ and $E_2 = V_2/d_2 \quad \text{(A-I.2)}$

We know that

$$E_1 \epsilon_1 = E_2 \epsilon_2$$

If $C_1$ is the capacitance of a gaseous gap of thickness $d_1$ and dielectric constant of 1 and $C_2$ is the capacitance of the dielectric material of thickness $d_2$ and dielectric constant $\epsilon_2$, then,

$$E_2 = E_1/\epsilon_2 \quad \text{(A-I.3)}$$

Substituting in (A-I.1),

$$V = E_1 d_1 + E_2 d_2 = E_1 d_1 \left[1 + \frac{d_2}{d_1 \epsilon_2} \right]$$

So $V_b$ (estimated) = $V_b$ (of gas at $d_1$) $\left[1 + \frac{d_2}{\epsilon_2 d_1} \right] \quad \text{(3.1)}$
APPENDIX - II

Development of Equation 3.3:

We can observe from the Fig. 3.1. that the solid dielectric does not cover the entire surface of the lower conductor. Thus, the capacitance \( C_2 \) of Fig. A-I(a) consists of, actually, two capacitors, \( C_d \) the capacitance of the solid dielectric material and \( C_g \) the capacitance of the surrounding medium, as shown in Fig. A-II(a).

\[
\begin{align*}
C_1 &= \varepsilon_0 \frac{A}{d_1}, \\
C_d &= \varepsilon_0 \varepsilon_r A_d / d_2 = \varepsilon_0 \varepsilon_r \pi D_1^2 / 4d_2.
\end{align*}
\]

Neglecting fringing effects,

\[
C_g = \varepsilon_0 \frac{(A - A_d)}{d_1}
\]

and \( A \) = Area of the electrodes = \( \pi (11.5)^2 / 4 \)

so, the equivalent capacitance \( C_2 = C_d + C_g \)

\[
C_2 = \varepsilon_0 \left[ (A - A_d) + \varepsilon_r A_d \right] / d_2
\]

\[
= \varepsilon_0 \left[ A + A_d (\varepsilon_0 - 1) \right] / d_2
\]

Now, as the same current flows through these two capacitors connected in series, as shown in Fig. A-II(b), we have,

\[
C_1 V_1 = C_2 V_2
\]

Also,

\[
V_2 = (V_{b\text{ new}} - V_1)
\]
so \( C_1 V_1 = C_2 (V_{b,new} - V_1) \)

or \( V_1 (C_1 + C_2) = V_{b,new} C_2 \)

or \( V_{b,new} = \frac{C_1 + C_2}{C_2} V_1 \)

\[
= \frac{\varepsilon_0 A/d_1 + \varepsilon_0 [\varepsilon + (\varepsilon_r - 1) A_d]/d_2}{\varepsilon_0 [\varepsilon + (\varepsilon_r - 1) A_d]/d_2}
\]

Multiplying by a factor of \( 4d_2 \) and simplifying, we get,

\[
V_{b,new} = \frac{4A (1 + d_2/d_1) + \pi D_1^2 (\varepsilon_r - 1)}{4A + \pi D_1^2 (\varepsilon_r - 1)} \cdot V_b \text{ (of gas at } d_1) \]
This appendix contains the graphs of the flashover voltage against the total separation distance for the values presented in the tables 3.1 through 3.4.
FIGURE A-III(1). Comparison of measured and estimated flashover voltages in AIR.
FIGURE A-III(2). Comparison of measured and estimated flashover voltages in $\text{N}_2$. 

- ESTIMATED
- MEASURED

$D_1 = 64 \text{ mm}$
$D_1 = 51 \text{ mm}$
$D_1 = 25 \text{ mm}$
$D_1 = 13.1 \text{ mm}$
FIGURE A-III(3). Comparison of measured and estimated flashover voltage.

$V_b$ (kV)

$d$ in mm
FIGURE A-III(4). Comparison of measured and estimated flashover voltage.
FIGURE A-III(5). Comparison of measured and estimated flashover voltage.
REFERENCES.


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