SURFACE ELECTRIC STRENGTH OF PROCESSED PRESSBOARD UNDER SUPERIMPOSED dc AND SURGE VOLTAGES

By

Ge Zhang

A thesis
presented to the University of Manitoba
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
the Department of Electrical Engineering

Winnipeg, Manitoba

ISBN 0-315-63300-X

SURFACE ELECTRIC STRENGTH OF PROCESSED PRESSBOARD UNDER SUPERIMPOSED dc AND SURGE VOLTAGES

BY

GE ZHANG

A thesis submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

MASTER OF SCIENCE

Acknowledgements

The author wishes to express his sincere and deep gratitude to his thesis supervisor, Professor M.R. Raghuveer, for his valuable guidance and encouragement during the course of study and investigation.

The author would also like to thank Mr. J. Kendall and Mr. G. Toole for their cooperation and help in developing and constructing the testing apparatus.

Grant support from the Manitoba High Voltage Direct Current Research Center which made this investigation possible is greatly appreciated. Also, many thanks are due to Mr. W. McDermid of Manitoba Hydro for his help in procuring the aged transformer oil.

Abstract

The surface electric strength of cylindrical shaped processed pressboard immersed in mineral oil under the application of dc voltage superimposed on standard lightning and switching impulse voltages has been determined experimentally at room temperature. The surface electric strength of the pressboard-oil insulation has also been investigated with the pressboard samples impregnated in aged mineral oil in order to determine the influence of aging of transformer oil on the surface electric strength of this insulation system. For the unaged oil study three gaps in the range 5 - 10 mm and two dc levels were employed while for the aged oil study, the same gap lengths were used but only one dc level was employed. In the investigation to determine the electric surface strength of pressboard-oil insulation under dc voltage superimposed on lightning impulse voltages, positive dc and negative lightning impulse voltages were used. For the dc voltage plus switching impulse voltage study, negative dc and positive switching impulses were employed.

It has been found that the surface electric strength of the pressboard-oil insulation is lower when the stresses are positive dc plus negative lightning impulse voltages or negative dc plus positive switching impulses compared to that obtained under the application of pure lightning or switching impulses, respectively. It has also been found that with an increase in the dc component of the composite stress of dc plus impulse voltages, the surface breakdown voltage is increased. The change of dc component of the composite stress, in other words, has little effect on the impulse component needed to cause surface breakdown

of the insulation system except for a gap length of 10 mm under dc plus lightning impulse voltages.

As far as aged mineral oil is concerned, the surface strength of the pressboard-oil (aged) insulation is lower than that when unaged oil is used.

Table of Contents

List of Figures

Chapter 1

Introduction

1.1 Pressboard and Oil Impregnated Pressboard Insulation

Pressboard, which is dried resin impregnated compressed paper, is one of the main constituents of solid insulation in large power transformers and electric machines due to its excellent electrical, mechanical and thermal properties. Since these apparati represent extremely important components of an electric power system, their successful design from the point of view of satisfactory life expectancy presupposes a thorough knowledge of how processed pressboard behaves under various types of electric stresses which might appear in a power system.

Oil impregnated paper has been the traditional insulating material used in transformers, bushings and other high voltage power apparati. Processed oil impregnated paper insulation is economical and easy to apply. It is able to withstand a high operating stress, exhibit low dielectric loss and show a reasonably slow rate of deterioration in service. This kind of composite system is also used to minimize insulation distance while ensuring adequate cooling capacity. Since the composite system of pressboard and oil forms the main insulation of power transformers which represent an important part of an electric power system, it is essential to know the behavior of this insulation under various types of electric stresses which might appear in the system in order to ensure satisfactory operation of the power system. Considerable work has been carried out to gain a thorough knowledge of the behavior of pressboard-oil insulation under various types of stresses that may appear in a power system.

In [1-7], the puncture dielectric strength of pressboard-oil insulation under the application of ac, dc, lightning, switching and steep front impulse voltages, combined ac and dc voltages and ac voltage superimposed on lightning impulse voltages was experimentally studied with the electric field perpendicular to the solid-liquid interface. Also, the surface electric strength of pressboard-oil insulation under dc and ac voltages has also been experimentally determined by some researchers with the interface parallel to the electric field [8-11, 16, 19]. Similarly, the impulse voltage surface strength of a solid-liquid interface parallel to the electric field has been investigated by a number of researchers by using various models and electrode configurations [12-22]. Also, data on the surface electric strength of mineral oil impregnated pressboard insulation under the application of dc voltage with ripple are available [23].

1.2 The Importance and Scope of the Present Investigation

The insulation of converter transformers and reactors in HVDC systems is similar to that employed in power transformers in ac systems. However, the stresses experienced in the former case are quite different.

For HVDC systems, it is inevitable that the pressboard-oil insulation is subjected to overvoltages such as lightning and switching impulse type voltages while the major parts of the HVDC system such as converter transformers, smoothing reactors and auxiliary power apparatus have to operate under a superimposed dc bias. Therefore, it is extremely important to understand how the pressboard-oil insulation behaves under dc voltage superimposed on lightning and switching impulse voltages. Some work has already been done concerning the simultaneous application of dc voltage and impulse type voltages [24-29].

The effect of a composite waveform arising out of simultaneous application of standard lightning surges and dc voltages has been considered [24] in the determination of the dielectric strength of laminated paper and composite dielectrics. The peculiar voltage stresses in HVDC converter transformers and the voltage distribution in the insulation structure resulting from the dc potential on the valve windings are discussed in [25]. In the same reference the effects of dc voltage with superimposed impulse or ac voltage on the dielectric breakdown strength is also reviewed. Proposals are made for a high voltage acceptance test including, particularly, dc tests with reference to a multibridge transmission system. In [26], the authors considered the relevance of superimposed surge and dc stresses in testing converter transformers. The criteria of dielectric strength of major oil-barrier insulation under dc voltage and impulse superimposed on the dc voltage are discussed in [27]. Here the electric strength investigations were performed on small-scale insulation models simulating the middle and end parts of a transformer winding. Results of the study of the electrical characteristics of oil and pressboard under dc voltages are also given. In reference [28], a laboratory investigation involving tests on models and on full-sized cables has been carried out into the behavior of oil-impregnated paper insulation under the simultaneous action of a pre-stressing direct voltage and a voltage surge of either the same or opposite polarity. It was found that the dielectric strength does not depend on the level or polarity of the prestressing direct voltage or on the duration of the surge, except when a series of reversed polarity surges is applied at intervals of a few seconds, progressively increasing the level until breakdown occurs. In [29], Lokhanin and co-workers reported the results of an investigation concerning the design and testing of large capacity converter transformers and smoothing reactors for HVDC transmission. The effect of simultaneous application of dc and lightning or switching type surges on oil barrier insulation is considered. Results of insulation studies and dynamic tests at the factory and test station are given.

From the above description, one can see that previous work concerning simultaneous application of dc voltage superimposed on surge voltages is limited in that it concerns the determination of the puncture dielectric strength of the pressboard-oil insulation. Data concerning the surface electric strength of pressboard-oil insulation under dc and superposed surges does not exist in current literature.

There are several references concerning the mechanism underlying the propagation of the surface discharge along a solid-liquid interface under impulse voltages only [12, 13, 17]. Also, a variety of mechanisms are postulated to explain the lowered electric strength of a solid-liquid insulation system because of introduction of an interface which touches both electrodes and is oriented parallel to the electric field under ac and dc voltages [9, 30, 31]. In [32-34], an explanation of interfacial breakdown has also been proposed. The model proposed attributes the reduction of breakdown voltage at the interface to an electrohydrodynamic phenomenon. This phenomenon and its role in liquid breakdown as well as its contribution to the breakdown across a dielectric spacer in oil are discussed in [35].

From the above description, it can be seen that considerable effort has been expended to gain a better understanding of the behavior of a solid-liquid insulation under different electrical stresses and in different conditions and the breakdown mechanism involved.

However, data concerning the surface electric strength of pressboard-oil insulation under the effect of dc voltage superimposed on surge voltages has not been reported even though it is of great interest to HVDC systems and utilities. It is understood that the determination of the surface strength for practical configurations is very important because the allowable longitudinal or parallel gradient is lower than the gradient which can be tolerated in a direction perpendicular to the insulation, i.e. surface discharges require lower initiating stresses. Therefore it is essential to gain a thorough knowledge of the surface strength of processed pressboard in mineral oil under the application of dc voltage with superimposed surge voltages.

The present investigation deals with the experimental determination of the surface electric strength of pressboard-oil insulation under the application of dc voltage superimposed on standard lightning and switching impulse voltages. The pressboard is tested in a cylindrical configuration with ring shaped electrodes fitted snugly around it. Three gap spacings of 5, 7.5 and 10 mm are used and all the tests are conducted at room temperature. Two levels of the dc voltage component of the composite stress have been chosen in order to determine the influence of dc component of the composite stress on the surface electric strength of pressboard-oil insulation. Hitherto, all the previous investigations have used unaged mineral oil to form the paper-oil insulation system. However, since the oil, an important part of pressboard-oil insulation, ages while the power apparatus are in service, it is essential to determine the surface electric strength of the pressboard using aged oil. This has been done in the present investigation by impregnating the pressboard samples with aged oil procured from transformers operating in the field. Only one dc level was used in these tests.

1.3 Organization of the Thesis

The details and results of this investigation are presented in the following chapters. Explanations have been offered regarding the breakdown phenomenon of the pressboard-oil insulation.

In Chapter 2, some previous work concerning the puncture dielectric strength and surface electric strength of the pressboard-oil insulation under various electrical stresses is reviewed and the major work of this investigation is outlined. Some basic ideas and considerations about this investigation are also advanced.

In Chapter 3, the test equipment used in the tests of dc voltage plus impulse voltages, the experimental techniques employed in the study and the experimental procedures are described.

Chapter 4 presents the test results from the experiments and compares the results under different stresses in different conditions.

Chapter 5 deals with the discussions and explanations of the test results.

Finally, in Chapter 6, conclusions of this investigation are drawn and some suggestions for further work are made.

Chapter 2

Review of Previous Work and Basic Considerations of Present Investigation

2.1 Review of Previous Work

2.1.1 Puncture dielectric strength of pressboard-oil insulation under ac, dc and impulse voltages

The puncture dielectric strength of pressboard-oil insulation has been the subject of several studies [1-7]. In [1], the impulse strength of lapped impregnated paper dielectric has been investigated by using model cables. Some basic characteristics of the behavior of the combination of pressboard of 1 mm or 2 mm thickness immersed in mineral oil and stressed in a rod-plane gap with either impulse voltages of standard 1.2/50 μs waveshape (of both polarities) or alternating voltages of 50 Hz has been reported in [2]. A description of the mechanism of the discharge development, up to the breakdown of the test object under both types of test voltages is also given. The dielectric behavior of the pressboard-oil insulation under switching impulse voltage is reported in [3] where the influence of the temperature of oil on the partial discharges has also been examined. In [4], the partial discharge characteristics of oil-immersed insulation under combined ac-dc voltage and polarity reversal of dc voltages were made clear by experiments. In reference [5], the electrical breakdown strength of paper-oil insulation samples was measured under pulsating voltage. The pulsating voltage was obtained by superimposing ac voltage upon dc voltage. This test provides an attractive method for a simultaneous testing and assessment of the state of insulation of the various parts of HV apparatus in service. Furthermore, the 50 Hz ac partial discharge characteristics triggered by standard lightning impulse voltage and breakdown characteristics under superimposed voltage condition including all combinations of both polarities at the peak point of ac voltage are studied for several models of oil-immersed transformer insulation, representing the typical combination of mineral oil and oil-impregnated paper [6]. In [7], the authors study the dielectric breakdown of oil-impregnated paper insulation by using fast-front voltages and standard lightning impulse voltages.

2.1.2 Surface electric strength of pressboard-oil insulation under ac, dc, impulse and pulsating voltages

Researchers have also been interested in determining the surface electrical strength of pressboard-oil insulation under the application of various stresses with the electric field parallel to the solid-liquid interface by using various methods and electrodes configurations [8-23].

In [8-11, 16, 19], the surface strength of a solid-liquid interface parallel to the electric field has been experimentally determined under ac and dc voltages at various temperatures lying in the range from room temperature to 150°C. In reference [8] the surface strength has been experimentally studied for cylindrical shaped specimens under dc and ac stresses. This study shows that the surface strength is greater under dc voltages than under ac voltages. When the applied voltage is ac, most breakdowns occurred away from the interface. The presence of the interface lowers the breakdown voltage in the ac case; however, it does not affect the breakdown voltage in the dc case. The influence of pressboard on ac breakdown voltages in oil gaps is studied in [9]. A variety of mechanisms have been postulated to explain the phenomenon of the lowering of electric strength. In [16], the locations of electrical breakdown in a composite paper-oil insulating system have been measured under ac stresses. The data indicate that, in a carefully prepared system, the breakdown will not necessarily occur at the interface. In addition, it was found that breakdown voltages were not significantly lower for those breakdowns which occurred at the interface than for those which did not. It was noted that if the paper was not dried or if many gaseous voids were left in or on the paper, the breakdown regularly occurred at the interface and at a lower voltage. In [19], the author has studied the 60 Hz flashover voltages of various pressboards, polyethylene and polypropylene in transformer oil. It is concluded that the difference between materials is due to different discharge propagation properties, and that the propagation is assisted by permittivity mismatch between liquid and solid. At 60 Hz the introduction of solid interfaces can increase the flashover voltages. Metal particles on the interface can reduce average values of the flashover voltage by at least 20% and minimum values even more. In [10] the measurement of the electrical breakdown location in the vicinity of an oil-paper interface under the application of dc and ac stresses, over the temperature range from room temperature to 150°C is presented. The data indicate that the electrical breakdown occurred at the interface for 15% to 43% of the time, depending upon the details of the particular set of measurements. In the test system used, the breakdown voltage is not reduced by the introduction of a paper interface parallel to the field and touching both electrodes. It is also demonstrated that the effects of the electric field enhancement, due to geometric factors and dielectric mismatch, can be accounted for in a straightforward manner. It is clear from this analysis that the breakdown location is influenced by the degree of field enhancement as well as the relative volume occupied by the enhanced field. Similar to the studies on pressboard-oil insulation, the results of investigations of interfacial breakdown on electrolytic surfaces is covered. It is believed that the formation of multiple discharges along with the main leading arc is behind the higher values of the measured critical voltages than previously predicted [11].

The impulse voltage surface strength of a solid-liquid interface parallel to the electric field has been experimentally determined by a number of researchers [12-21]. Most of them have used standard impulse voltages while others have employed other waveshapes such as 1/5 μs, 0.5/2 μs, impulses with front times up to 16 μs and ramp type shapes with breakdown occurring in 10-20 μs. In [12], a fundamental study of the mechanism of propagation of impulse creepage streamers over an insulating surface is reported. The mechanism is discussed in considerable detail for both positive and negative polarity of applied dc voltage. In [13], the progress of an investigation of the breakdown of solid and liquid dielectrics in combination is described, and generalizations are made about the effects of electrode shape, impulse duration and polarity on the puncture voltage of alternate layers of solid and liquid, and on the flashover voltage of a solid and liquid interface under various conditions of stress. The results of flashover in oil between electrodes mounted on pressboard sheets, flashover in the presence of stress normal to the pressboard surface, breakdown between covered conductors in contact, or separated by packing pieces, or separated by barrier sheets, and flashover between electrodes passing through bushings in a pressboard sheet are presented by the same authors [14]. This paper also contains comparative data on breakdown voltages at room temperature and at 90°C, for selected arrangements. From the test results, the authors conclude that the flashover voltage between electrodes mounted on a pressboard sheet is increased by increasing the height of the electrodes or by rounding the edges in contact with the sheet. Surface flashover voltage in the presence of normal stress due to a parallel conductor connected to one electrode is mainly a function of flashover distance and increases only slowly with insulation thickness. The flashover voltage between conductors passing through a dielectric sheet can be increased by the use of insulating bushings, but the possibility of a simple quantitative generalization seems unlikely. They also find that the surface flashover voltage is not lower at 90°C than at 20°C. In [15], the effect of permittivity matching on the flashover of solid-liquid interfaces is investigated. It is widely assumed that in many situations the interface between the solid and the liquid insulation is the point in a complex system at which breakdown would occur [30-33]. However, data reported in [16] do not support that conventional wisdom. From these data, which were taken using a carefully-prepared, paper-oil interface structure, it is concluded that the breakdown will not necessarily occur at the interface. Similarly, the voltage for breakdown at the interface is not necessarily lower than the voltage at which the breakdowns occur away from the interface. The work shows, however, that it is a relatively simple matter to force the breakdown to occur at the interface and at the same time reduce the breakdown voltage. It is likely that interfacial breakdown will occur if the paper is not carefully dried or if many gaseous voids are left in or on the paper. The impulse voltage used was (13-16 μs) /178 μs waveshape obtained using a conventional Marx generator. This pulse shape is approximately the same as used by Taylor [15] in an earlier study of interfacial breakdown. The paper, typical of that used in transformers, was clamped by the split electrodes and held parallel to the field. Plane electrodes with edge radii of 1.6, 3.2 and 7.4 mm, as well as hemispherical electrodes of radius 12.7 mm were used in the study. The concept " figure of surface discharges (FSD) is reported by Nikolopoulos and Sakkas [17]. By applying voltages lying between inception voltages of surface and volume discharges, the FSD is formed. In their investigation, the development of partial discharges in pressboard insulating plates of 1 or 2 mm, immersed in mineral oil and stressed with standard lightning impulse voltages of 1.2/50 μs is presented. The pressboard-oil combination formed the insulation of a rod-plane gap, the two electrodes of which were in contact with each one of the two sides of the pressboard plates. In [18], the creepage discharge propagation in transformer oil with impulse voltages was observed using an image converter camera to investigate various characteristics of the phenomenon although there have been some published papers on this matter [2, 12]. A belt-like back electrode of the rod-plane electrodes configuration was employed to control the creepage discharge for 1-dimensional propagation so that it could be photographed at a high speed in a streak mode. A needle electrode with a tip angle of 45 degrees was used as the rod electrode for easy start of discharge. All test voltages were impulse voltages with a wave-front of 1.2-2.2 μs and a wave-tail of 65-650 μs, which were generated by an impulse generator. The experimental results show that impulse creepage discharge in transformer oil propagates in steps on both polarities. It is also found that the creepage discharge can be classified into some propagation modes according to propagation velocities and step pulse currents. Using two different electrode configurations, Anker investigated the lightning impulse flashover voltages of various pressboards, polyethylene and polypropylene in transformer oil [19]. The effect of permittivity matching and metal particles on the flashover voltage is also studied. In the rod-plane setup, which is one of the two configurations employed in the investigation, there is a substantial normal component of the field, and the electrodes are bare. In the other arrangement, the field is approximately parallel to the interface, and the electrodes are insulated and have a Rogowski profile. It is concluded that the difference between materials is due to different discharge propagation properties, and that the propagation is assisted by permittivity mismatch between liquid and solid. Surface structure can also affect the flashover voltage. Copper particles resting on the solid dielectric surface can greatly reduce the flashover voltage. Reductions of about 20% in average values were observed. Minimum values were reduced by up to 50%. In [20], creepage flashover characteristics in transformer oil under positive impulse voltage were studied by using models in which the electric field distribution was equivalent to that of actual transformers. In the experiments, some geometrical parameters concerning creepage flashover and the model scale were varied. The coaxial electrode system employed in the study consisted of a ring-type high voltage electrode located outside a pressboard insulation cylinder, a plane grounded electrode, and a back-side electrode (for grounding potential) located inside the pressboard cylinder. The high voltage and back-side electrodes can be slid axially to enable surface gap and back-side electrode lengths to be determined optionally. The test procedure was common to the standard and the scale effect model tests. The applied voltage was a 1.2/50 μs positive impulse voltage raised in 20 kV steps from 50-80% of the expected flashover voltage. It is concluded that the flashover voltage characteristics are determined by electric field strength of the high voltage electrode surface and stressed oil volume. The scale effect of the creepage flashover was found to be the power of 0.7 of the model scale. By using a similar electrode configuration, the surface strength of pressboard-oil insulation under the application of standard lightning and switching impulse voltages was studied [21, 22]. The pressboard was tested in a cylindrical configuration with ring shaped electrodes fitted around it. Gap lengths of 5, 10 and 15 mm have been considered and all the tests were conducted at room temperature. Standard lightning and switching voltages were of shapes of 1.4/47 μs and 300/1750 μs. Positive polarity was used in the tests. In the report, data on the surface electric strength under lightning and switching impulse voltages are presented. Also, data regarding the lightning and switching impulse strength are presented. The results show that the difference between the lightning and switching surface strength increases with gap length with the former being greater than the later. The presence of the interface lowers the breakdown strength. The decrease is larger under switching impulse voltages. If the sample has been degassed thoroughly, breakdowns on the surface do not permanently lower the strength of the gap. Similar to the investigation described above, data on the surface electric strength of oil impregnated pressboard insulation under the application of dc voltage with ripple is reported in [23]. In this case, three surface gaps of 5, 10 and 25 mm were tested under a composite waveform in the range of ripple from 0.3 to 2.8. It is shown that the breakdown voltage increases with increasing ripple and the peak value of the breakdown voltage under pulsating voltage does not always lie between the ac and dc breakdown values.

2.1.3 Puncture dielectric strength of pressboard-oil insulation under simultaneous application of dc and impulse voltages

As far as the simultaneous application of dc and impulse voltages is concerned, some work has already been done [24-29]. In [24], the effect of a composite waveform arising out of simultaneous application of standard lightning surges and dc voltages has been considered in the determination of the dielectric strength of laminated paper and composite dielectrics. Simple models were used to carry out tests on the main insulating materials including oil, oil impregnated paper and transformer board using specific voltages similar to those which occur in the converter transformers and smoothing reactors in HVDC stations. The peculiar voltage stresses in HVDC converter transformers and the voltage distribution in the insulation structure resulting from the dc potential on the valve windings are discussed in [25]. The effects of dc voltage with superimposed impulse or ac voltage on the dielectric breakdown strength is reviewed. Although it was difficult to perform impulse and switching surge tests with a superimposed dc voltage due to test equipment limitations at that time, the possible reduction in impulse or switching surge strength in the presence of a dc voltage was suggested. In [26], the authors considered the relevance of superimposed surge and dc stresses in testing converter transformers. It is found that the stress in the cellulose materials such as pressboard is much high than in the oil. The voltage drop in the oil is low and the oil therefore works as a close fitting earth sleeve around the winding. The barriers used in HVDC insulation systems therefore have an important additional function, namely to transfer dc voltage drop in the oil. It is, however, important to check that the stress in the barrier surface is tolerable. With increasing temperature and with increasing moisture content the resistivities of the oil as well as of the cellulose decrease in such a way that the span between oil and cellulose becomes reduced. This means that in service the dielectric stress distribution tends to be more uniform than that during the test condition. The dc voltage drop in the oil will increase. There is, however, no risk of overstressing the oil in the steady state as the oil ducts are designed to take a considerably larger voltage drop during surges and transient voltage conditions. In [27], Beletsky and co-workers reported the investigation of the main insulation characteristics of HVDC converter transformers. Results of the investigation on the electrical characteristics of oil and pressboard under dc voltage are given. The criteria of dielectric strength of major oil-barrier insulation under dc voltage and impulse superimposed on the dc voltage are determined. The electric strength investigations were performed on small-scale insulation models of the middle part and edge of the winding. A laboratory study involving tests on models and on full-sized cables has been carried out into the behavior of oil-impregnated paper insulation under the simultaneous action of a pre-stressing direct voltage and a voltage surge of either the same or opposite polarity [28]. It has been found that the dielectric strength does not depend on the level or polarity of the pre-stressing direct voltage or on the duration of the surge, except when a series of reversed polarity surges is applied at intervals of a few seconds, progressively increasing the level until breakdown occurs. In the study, both flat plate and cylindrical cable models were employed. In reference [29], Lokhanin and co-workers have reported the results of an investigation concerning the design and testing of large capacity converter transformers and smoothing reactors for HVDC transmission. The effect of simultaneous application of dc voltage with lightning and switching impulse type surges on oil barrier insulation is considered. Results of insulation studies and dynamic tests at the factory and test station are also given.

Although considerable work has been done concerning pressboard-oil insulation, the surface electric strength of such insulation under the application of dc voltage with superimposed surge voltages has not been reported.

2.2 Basic Considerations of the Present Investigation

In the present investigation, the pressboard-oil insulation is tested under the application of dc voltage superimposed on lightning and switching impulse voltages. There exist in total four possible combinations of application of the above composite stresses i.e. positive dc plus positive impulses; positive dc plus negative impulses; negative dc plus positive impulses and negative dc plus negative impulses. If all four possibilities have to be considered, the volume of experimental work becomes very large. Because of the symmetrical arrangement of the test gap, positive dc voltage superimposed on positive impulse voltage is equivalent to negative dc voltage superimposed on negative impulse voltage. Similarly, positive dc voltage superimposed on negative impulse voltage is equivalent to negative dc voltage superimposed on positive impulse voltage. Therefore, out of four possible combinations, only two need to be considered and the total volume of work is halved. Harrison [25] has pointed out that when negative dc voltage is superposed on positive impulse voltage the impulse breakdown strength increases with increasing negative dc voltage (i.e. suppose the +ve impulse breakdown voltage is V_1 without dc bias. In the presence of -ve dc bias larger impulse breakdown voltage V_2 is obtained, $V_2 > V_1$). Therefore, there is no need to consider the dc bias in this case. In the present investigation, as the electrode arrangement is symmetrical and there is no need to consider the following situations; negative dc voltage superposed on positive impulse and positive dc voltage superposed on negative impulse. Therefore, we need consider only those cases where the dc and impulse components of the composite stress are of the same polarity, i.e. positive dc voltage superimposed on positive impulse voltages or negative dc voltage superimposed on negative impulse voltages. It is understandable that in these cases the stresses are the strongest or the most powerful. Although the total work has been reduced by 75%, it is necessary to determine the waveform of the stresses that will be used in the tests. From the above discussion, we understand that either positive dc plus positive impulse voltages or negative dc plus negative impulse voltages can be employed for the tests. However, as we know, most lightning strokes are of negative polarity. Therefore, from a practical point of view, it is better to choose the -ve polarity lightning impulse. As far as switching surge is concerned, all the investigations show that for nearly all the gap configurations which are of practical interest, positive switching impulses result in lower flashover voltage than negative ones. The flashover behavior of external insulations with different configurations under positive switching impulse stress is therefore most important [36]. Therefore, negative lightning and positive switching surges have been employed in this investigation; the dc voltages chosen is of the same polarity of the impulse voltages. One important point that has to be clarified is that both the dc and impulse components of these composite voltages should be applied to one of the electrodes of the test gap while the other electrode is grounded.

Because of the complexity of the composite stress, i.e. both dc voltage and impulse surges are involved in the test, it is very important to consider the safety aspect of the test facilities in order to protect the dc and impulse generators from being damaged by overvoltages during the experiments. In previous studies concerning the simultaneous application of dc and impulse voltages, both the dc and impulse components of the composite stress of dc plus impulse voltages were applied to one of the two electrodes which formed the test gap while the other electrode was grounded. It is simpler to apply the composite voltage to the test gap in such a way that the impulse component is applied to one of the two electrodes while the dc component is applied to the other. In this case, neither electrode is grounded. The detailed arrangement will be described in Chapter 3. However, by using the above method of application of composite stresses to the test gap, the polarity of dc voltage has to be changed; this is because, now, the two components of the composite stress with opposite polarity give the maximum stress. Therefore positive dc voltage superimposed on standard negative lightning impulse voltages and negative dc voltage superimposed on standard positive switching impulse voltages were chosen for the present investigation.

Chapter 3

Test Setup, Sample Preparation and Test Procedures

3.1 Test Setup

3.1.1 Test equipment

The main equipment used in this study were test chamber, oil degassing system and dc and impulse generators.

3.1.1.1 Test chamber

The test chamber, as shown in Fig. 3.1, was a vacuum glass cylinder of 500 mm height and inner diameter 300 mm with wall thickness 7 mm. At both ends, the chamber was sealed with silicone "O" rings against chromed stainless plates. A rotary vacuum pump was connected to the chamber through the top plate. An end vacuum level of 3-5x10^{-2} Torr was produced within the chamber, as shown in Figs. 3.1 and 3.2.

In order to conduct the tests with composite voltage, the bottom plate was insulated from ground by means of teflon rods of 310 mm height and 50 mm diameter. Also, underneath the bottom plate, a ring shaped heater was attached for the purpose of vacuum drying of the drying of the samples. Both plates were connected with electrodes to apply the composite voltage to the test gap.

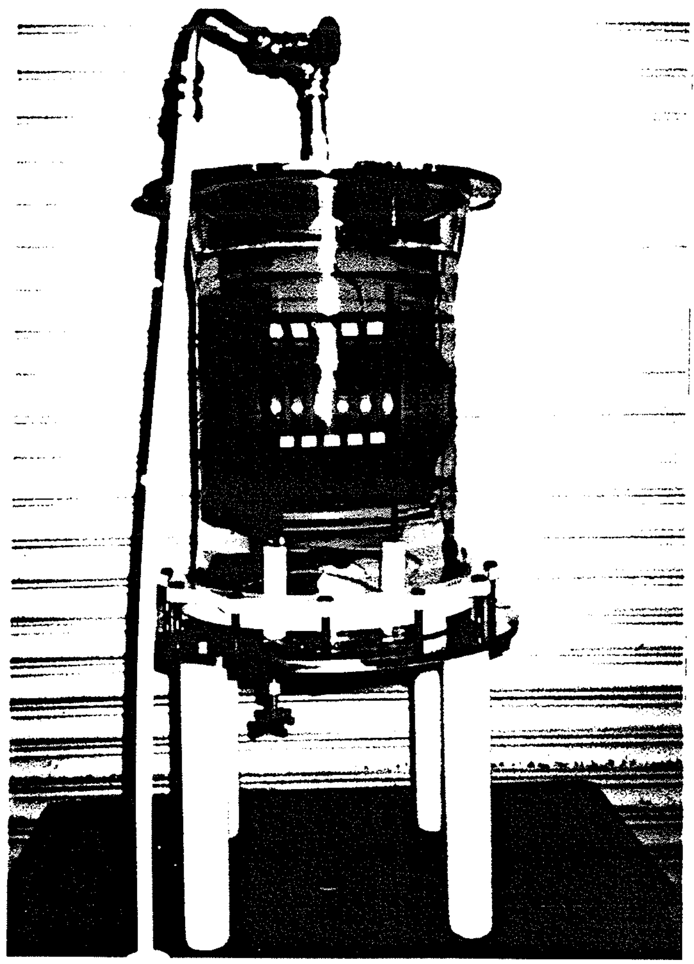

Figure 3.1: Test chamber.

Figure 3.2 shows the schematic diagram of the test chamber and the vacuum pump as well as the auxiliaries.

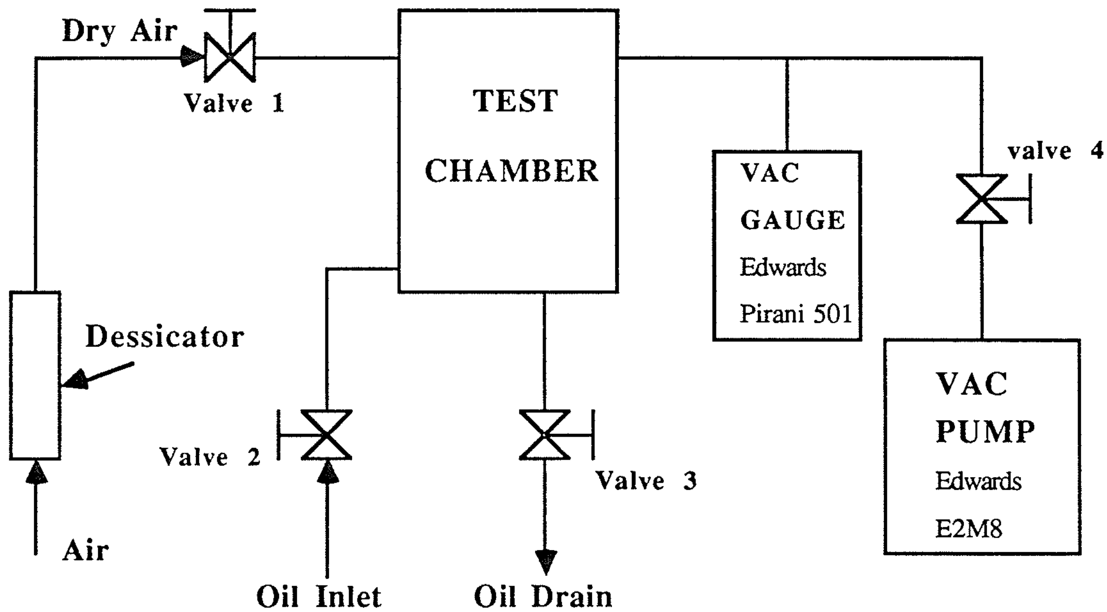

Figure 3.2: Schematic diagram of the test chamber.

3.1.1.2 Oil degassing system

As shown in Fig. 3.3, the oil degassing system was used to process the mineral oil which is one of the main components of the pressboard-oil composite insulation. It consisted of an oil tank of 32 litres capacity, a vacuum pump and an plastic oil vessel. On the outside wall of the tank, four heaters were installed to heat the oil tank when necessary.

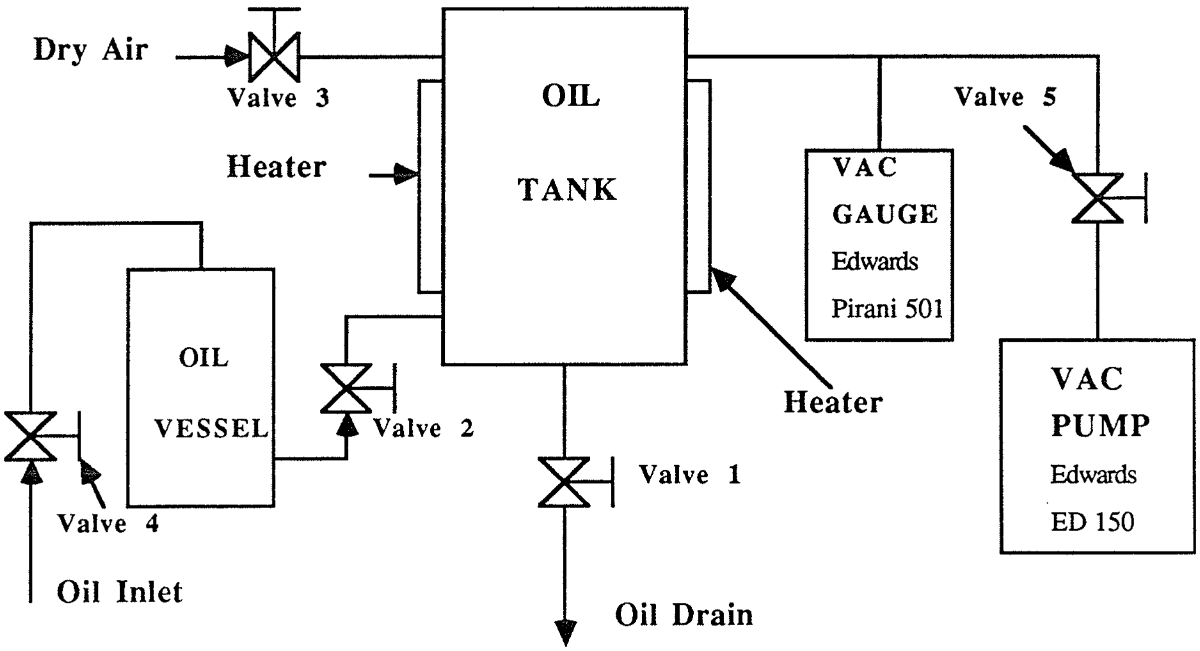

Figure 3.3: Schematic diagram of oil degassing system.

3.1.1.3 Vacuum system

The vacuum system is quite important to the test chamber and oil degassing system. In this investigation, the test chamber was evacuated by a two stage rotary pump (Edwards E2M8) with a nominal pumping speed 600 l / min and end vacuum 10^{-3} Torr. The oil degassing system was evacuated by an Edwards Speedivac ED 150 vacuum pump (approximately 150 l / min and end vacuum 10^{-1} Torr). The leakage rate of the vacuum system was determined with valves 1, 2 and 3 closed at a temperature of 25°C and pressure of approximately 10^{-1} Torr by using

$$N = V \times \Delta P / \Delta t$$

where N = leakage rate in Torr l / s

V = volume of the system

ΔP = increase in pressure due to evaporation of moisture and real leakage

Evacuation of the test chamber or oil tank continued until the leakage rate, N, settled to a steady value. At this point the increase in pressure in the chamber or oil tank with the pump disconnected is solely due to real leakage. The system leakage rate characteristics are shown in Fig. 3.4. From this curve the leakage rate can be determined. The steady state leakage rate is approximately 10^{-2} Torr l / s at a chamber temperature of 70°C.

3.1.1.4 Impulse and dc generators

Both the standard lightning and switching impulse voltages were generated from an 8 stage, 800 kV, 10kJ, 0.25 μF/stage impulse generator with appropriate waveshaping resistors. The dc generator was a 220 kV, 10 mA Ferranti dc supply. The dc voltage was measured by a resistive voltage divider.

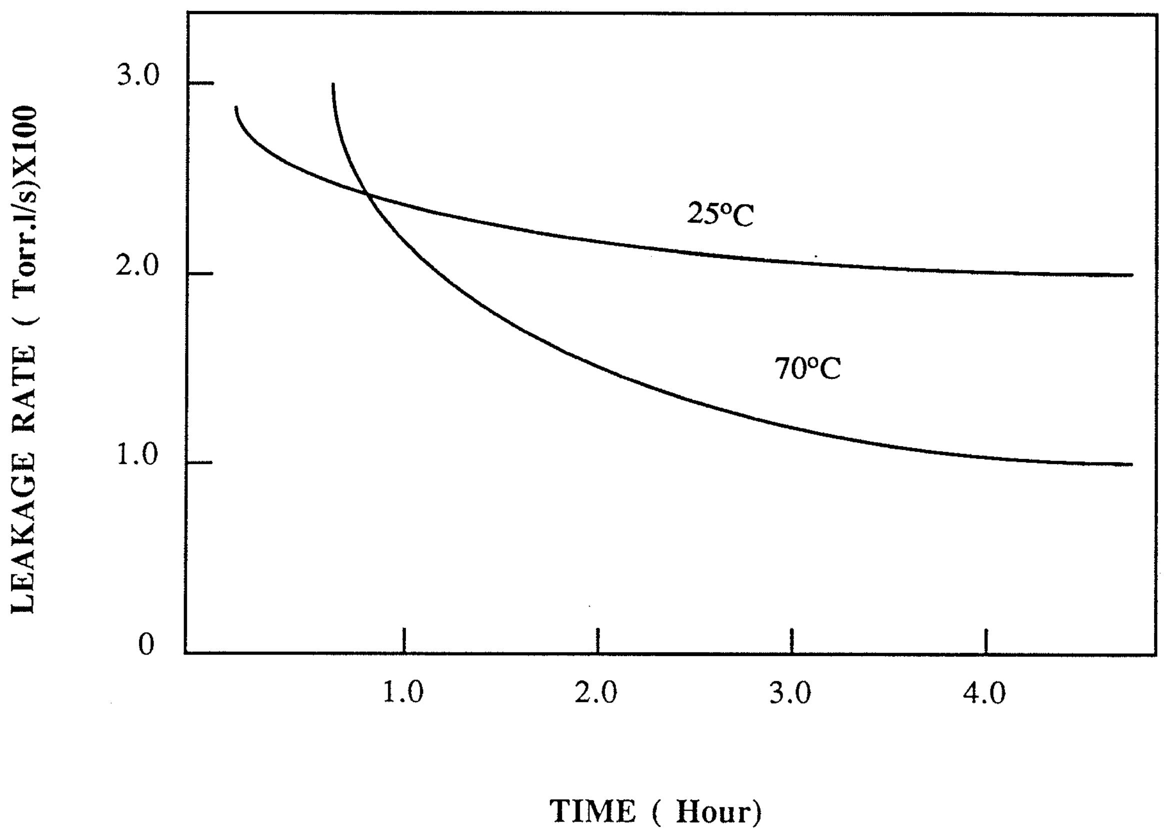

Figure 3.4: Vacuum system leakage rate characteristics.

3.1.2 Test circuits

In the tests employing superimposed voltages, two kinds of circuits were used. Figure 3.5 shows the circuit used to generate dc voltage with superimposed lightning voltages; the circuit used to generate dc voltage with superimposed switching impulse voltages is shown in Fig. 3.6.

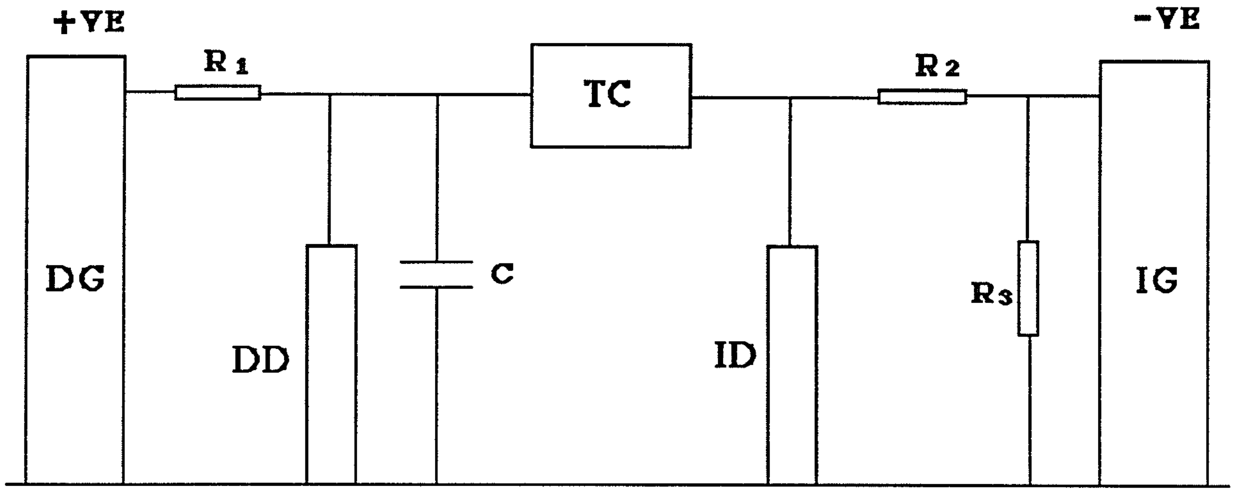

Figure 3.5: Circuit to generate +ve dc voltage superimposed on standard -ve lightning impulse voltages. DG - dc generator; IG - impulse generator; TC - test chamber; DD - dc voltage divider; ID - impulse voltage divider (ratio=2588); R_1, R_2, and R_3 - noninductive resistors; C - capacitor. R_1=2.3 MΩ; R_2=414.9 Ω; R_3=1643.6 Ω; C=0.5 μF.

Using the impulse generator with appropriate waveshaping elements as shown in Figs. 3.5 and 3.6, a lightning impulse voltage of 1.4/47 μs waveshape and a switching impulse voltage of 250/1800 μs waveshape was generated. Figures 3.7-3.10 show typical waveshapes of these surges.

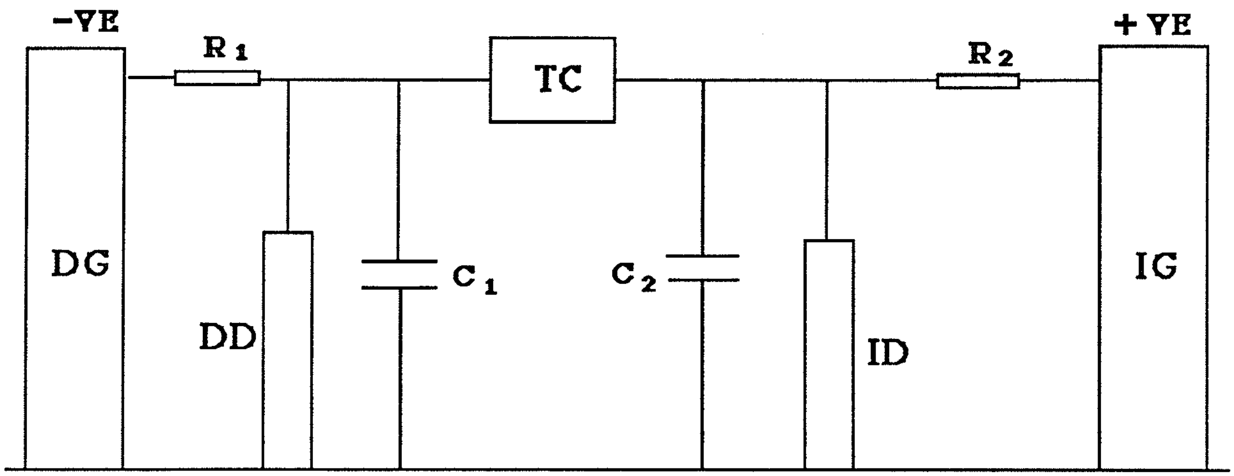

Figure 3.6: Circuit to generate -ve dc voltage superimposed on standard +ve switching impulse voltages. DG - dc generator; IG - impulse generator; TC - test chamber; DD - dc voltage divider; ID - impulse voltage divider (ratio=2588); R_1 and R_2 - noninductive resistors; C_1 and C_2 - capacitors. R_1=2.3 MΩ; R_2=24.74 kΩ; C_1=0.5 μF; C_2=5000 pF.

The composite waveforms of breakdown voltage of positive dc plus negative lightning and negative dc plus positive switching impulse voltages are shown in Figs. 3.11 and 3.12.

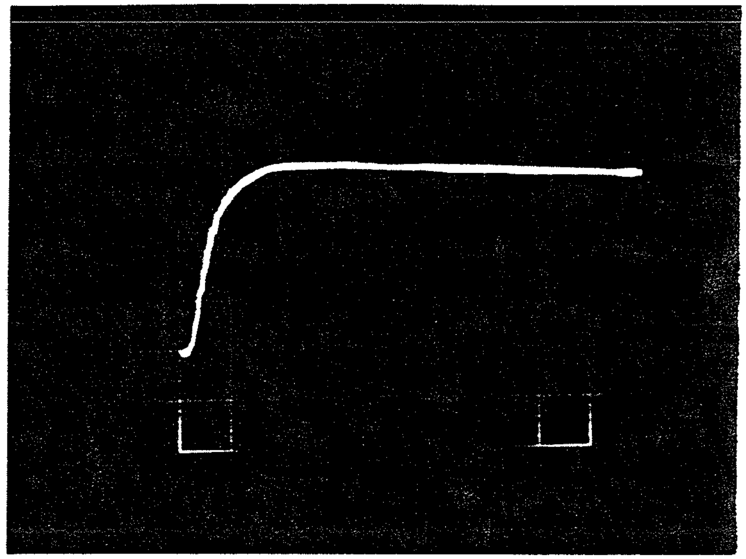

Figure 3.7: Lightning impulse: negative polarity. Time: 1 μs/cm. Volt.: 15 V/cm.

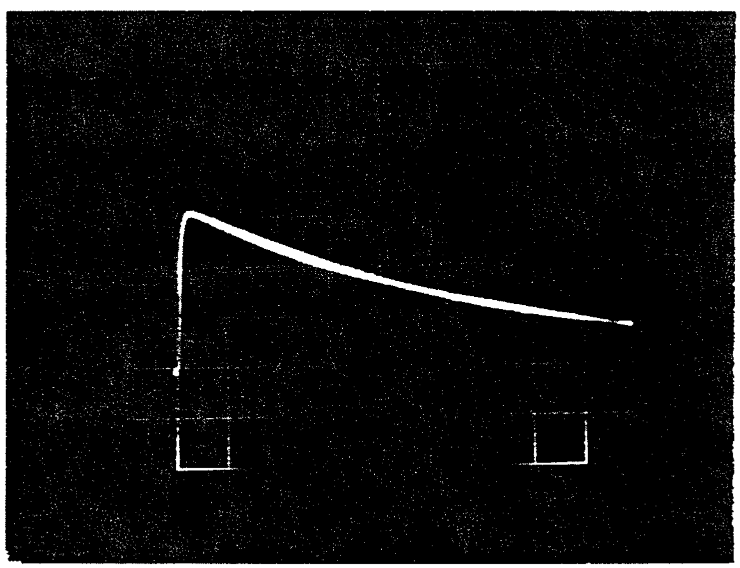

Figure 3.8: Lightning impulse: negative polarity. Time: 10 μs/cm. Volt.: 15 V/cm.

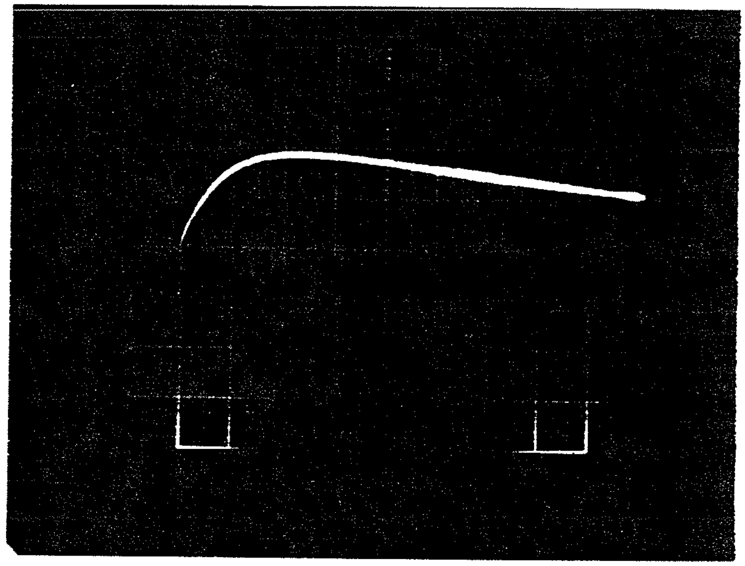

Figure 3.9: Switching impulse: positive polarity. Time: 100 μs/cm. Volt.: 15 V/cm.

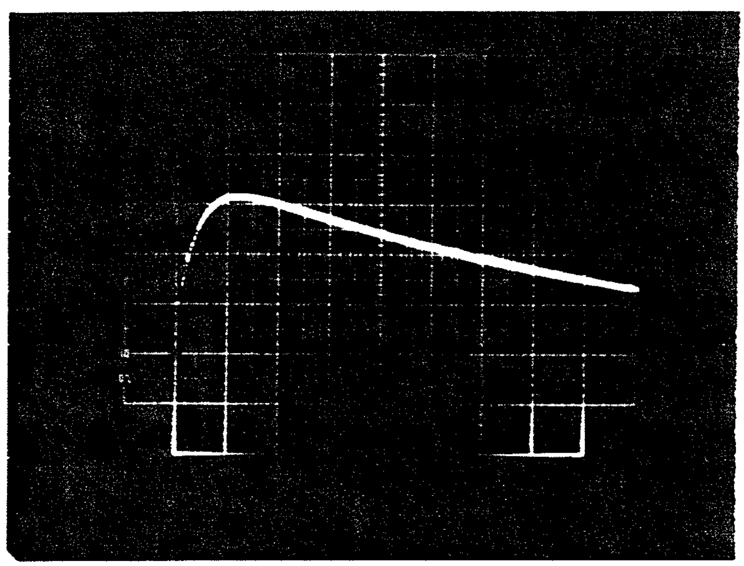

Figure 3.10: Switching impulse: positive polarity. Time: 200 μs/cm. Volt.: 15 V/cm.

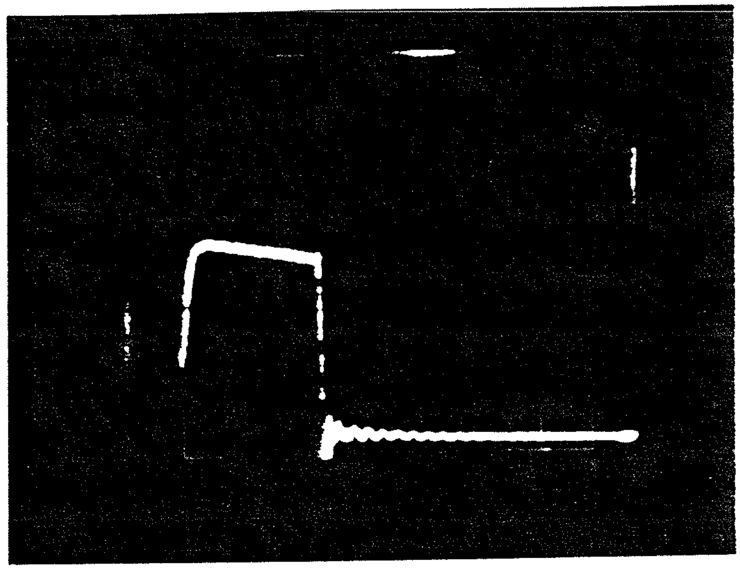

Figure 3.11: +ve dc plus -ve lightning impulse voltages at breakdown.

Time: 5 μs/cm. Volt.:10 V/cm.

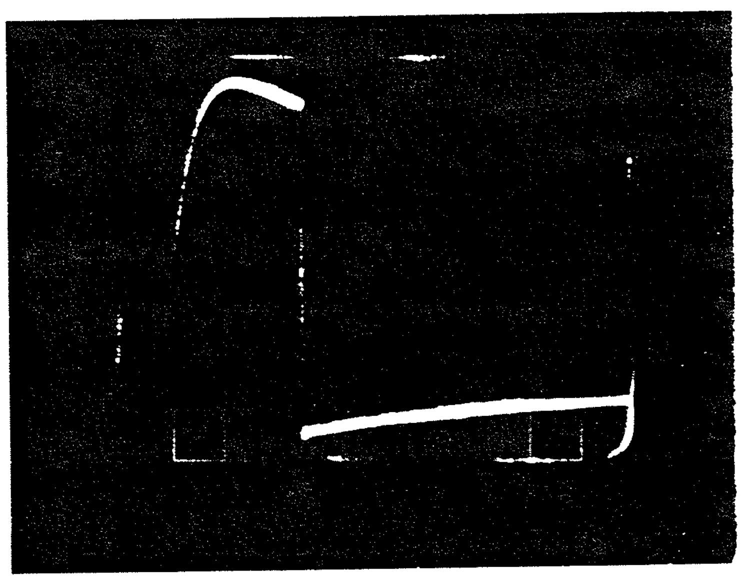

Figure 3.12: -ve dc plus +ve switching impulse voltage at breakdown.

Time: 200 μs/cm.Volt.: 7.5 V/cm.

The breakdown voltage oscillographs were recorded using a Tektronix type 466 storage oscilloscope together with a mixed parallel RC Haefely impulse voltage divider (ratio=2588). The breakdown voltage measured were the peak values. The times to breakdown were also noted.

3.2 Sample Preparation

3.2.1 Test specimens

Cylindrical pressboard samples were used in this study. It was of a precompressed grade known as type T IV and was supplied in cylindrical form by the E.H.V. Weidmann Company. It is normally used as insulating material in EHV power transformers.

3.2.2 Electrode configuration

Six ring shaped brass electrodes of outer diameter 199.2 mm, inner diameter 157.0 mm and of width 10.0 mm were fitted snugly around cylindrical pressboard samples and therefore formed 5 test gaps. The test gap spacing was fixed by three cylindrical teflon spacers of the same length, which were located symmetrically at the outer edge of the electrodes, as shown in Fig. 3.13. Three gap lengths were used in this investigation, i.e. 5 mm, 7.5 mm and 10 mm.

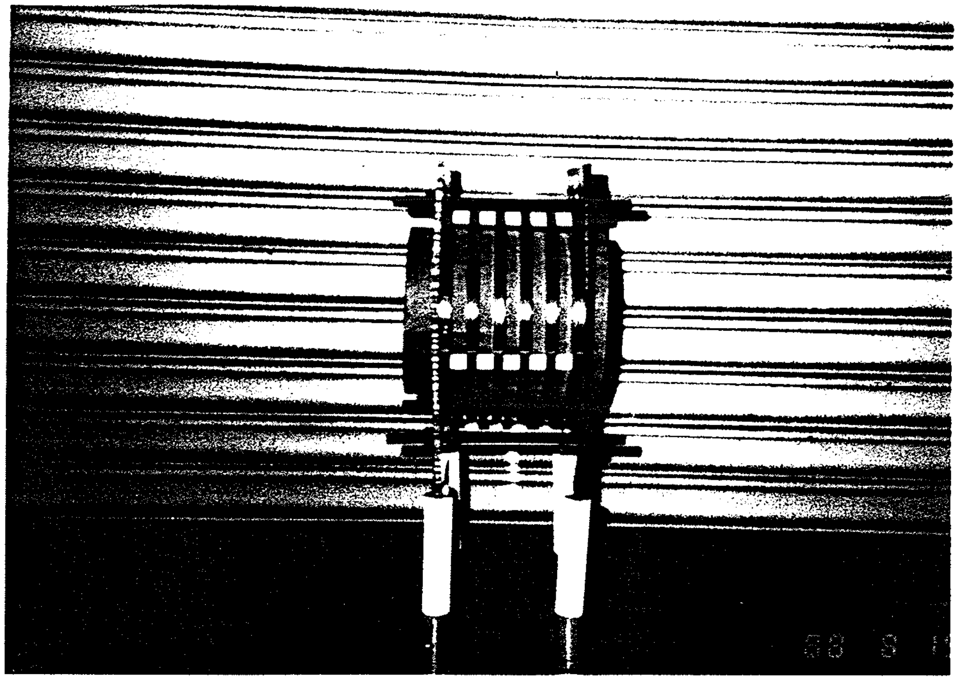

Figure 3.13: Configuration of electrodes with test sample.

The assembly consisting of the electrodes and spacers was held in place securely by means of permali holders.

Figure 3.14 shows the schematic diagram of the configuration of electrodes as well as the test sample.

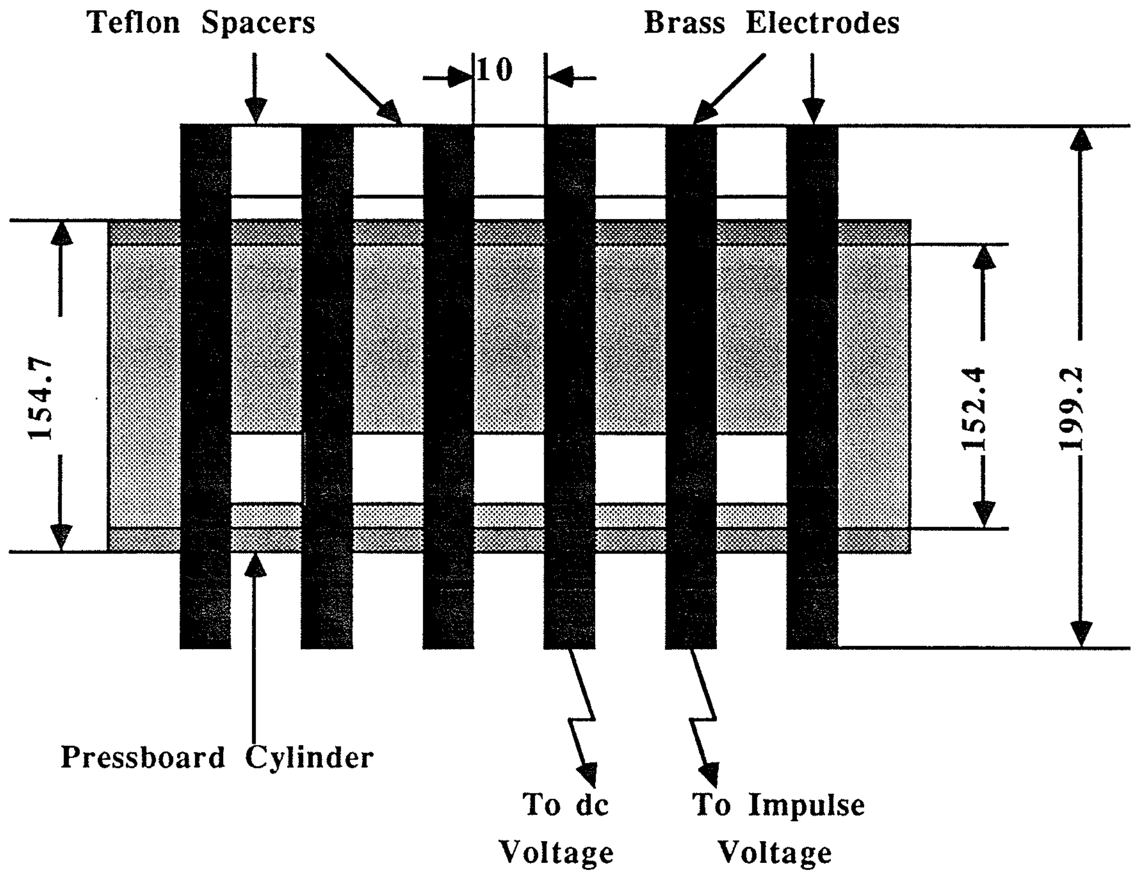

Figure 3.14: Schematic diagram of electrode configuration with sample. Unit of length: mm.

3.2.3 Oil degassing procedures

Refined mineral oil, VOLTESSO 35, was used as the impregnating insulant for fresh oil tests. For each test, 30 litres of oil were required. In order to remove the moisture in the oil, 30 litres of oil were degassed and dried in the oil storage tank (as shown in Fig. 3.3) in three stages lasting a total of 72 hours. In the first stage, 10 litres of oil were degassed and dried at a temperature of 30°C under a vacuum of 10^{-1} Torr for 24 hours. At the end of this stage, another 10 litres of oil were introduced into the tank and the second degassing stage started which also lasted 24 hours under the same temperature and vacuum level. Finally, 10 more litres of oil were introduced into the tank and processed in a similar way. The moisture content at the end of process was less than 10 ppm.

3.2.4 Drying and impregnating procedures

To ensure consistent results, all the electrodes, spacers and holders were thoroughly washed with methyl alcohol and the spacers were carefully and similarly situated for all the tests. In order to remove the moisture in the pressboard, four procedures were tried out to develop an acceptable drying technique. Circular samples of TIV pressboard of thickness 2.3 mm and diameter 150 mm were used. In the first procedure the sample was inserted in a test chamber and evacuated at room temperature for a period of 24 hours. In the second procedure the sample was preheated in an oven for 24 hours at 100°C prior to vacuum drying at room temperature for 24 hours. The third and fourth procedures were similar to the first and second procedures respectively except that the vacuum drying was carried out at 70°C. In all cases the end vacuum was between 3 and 5×10^{-2} Torr. The dissipation factor of the samples was measured by means of a low voltage Schering bridge at 1 KHz.

Figure 3.15 shows the variation of dissipation factor with time of evacuation for the four procedures. As expected, the dissipation factor decreased with vacuum application time. Also, the pressboard sample subject to the fourth drying procedure showed the lowest dissipation factor.

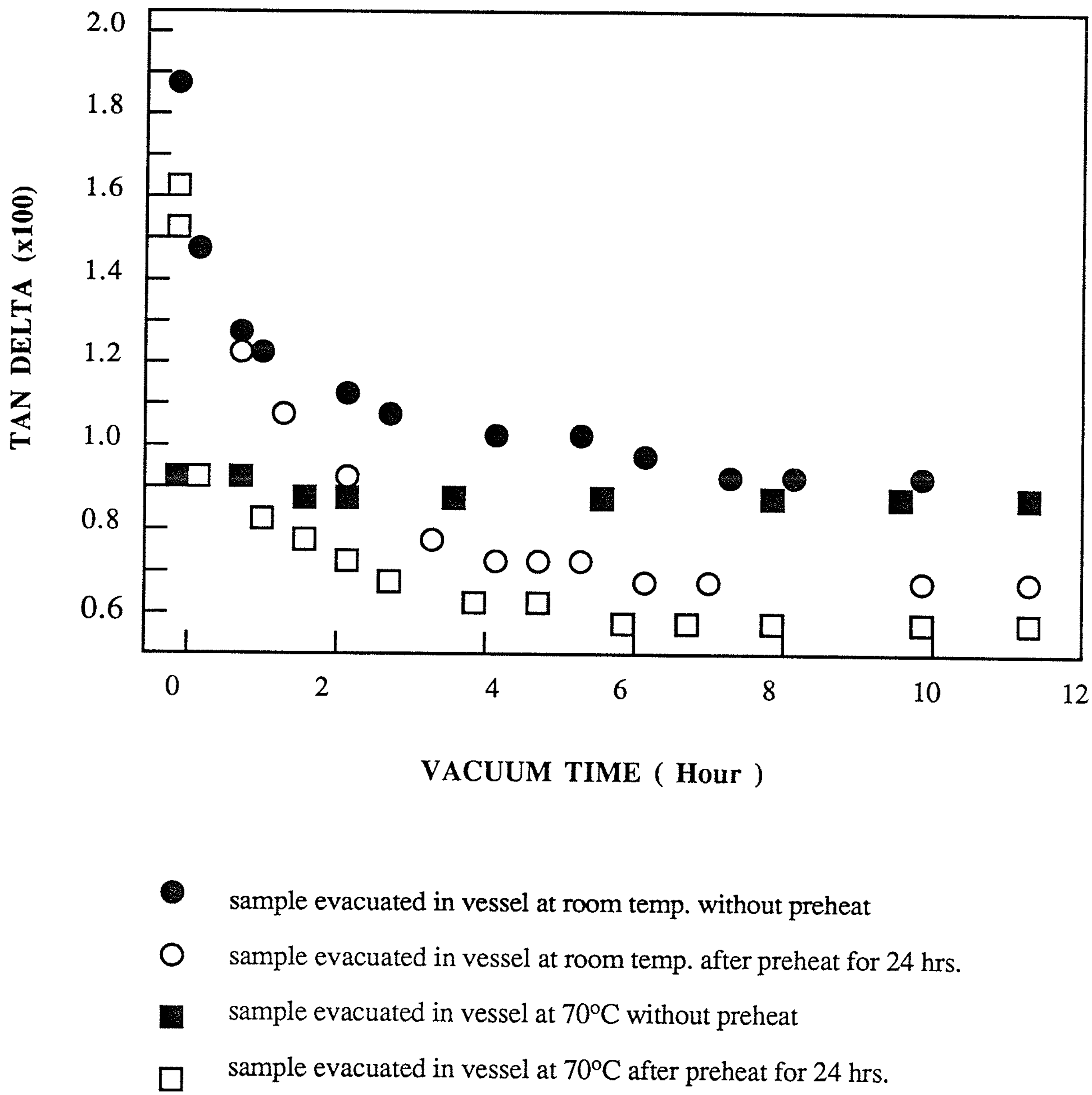

Figure 3.15: Variation of dissipation factor with evacuation time for four procedures considered.

Based on the above results the following drying and impregnating procedure was adopted:

The assembly consisting of sample and electrodes was placed in an oven and preheated for 24 hours at a temperature of 100°C. After preheating the assembly was transferred into the test chamber (as shown in Fig. 3.1) for vacuum drying for a further period of 24 hours at a temperature of 70°C. The end vacuum of this process was between $3x10^{-2}$ - $5x10^{-2}$ Torr. It was checked that for the volume of specimen used the vacuum drying time of 24 hours was more than sufficient to ensure a leakage rate of 10^{-2} Torr·l/s. Under this condition the amount of moisture by weight remaining in the paper is less than 0.5% [37]. After preheating and vacuum drying, the sample was vacuum impregnated slowly under a vacuum of less than 10^{-1} Torr with the oil at room temperature. This procedure usually took about an hour to complete and at the end of which the test chamber was filled with 30 litres of oil. During the process of impregnation, it was quite important to adjust the vacuum level in both oil tank and testing chamber to ensure the successful operation of impregnation. Then, the test chamber was fully evacuated for at least two hours until no bubbles could be observed. Just before testing, the pressure was returned to atmospheric value by admitting air into the chamber through the dessicator.

3.3 Test Procedures

Based on the considerations of section 2.2, negative polarity was chosen for lightning impulse voltages while positive polarity was chosen for switching impulse voltages during the investigation.

To conduct tests of positive dc plus negative lightning impulse voltages, a specific dc voltage was applied to one of the two electrodes of the testing gap first and then the impulse voltage was applied to the other electrode of the same gap. The applied impulse voltage was of such a value that it did not cause surface breakdown; next the impulse level was increased in steps until breakdown of the test gap occurred. Each increment in impulse voltage was less than 3% of the impulse magnitude employed in the previous step. The dc component of the composite stress was chosen as half of the lightning impulse component for the +ve dc plus -ve lightning impulse voltage test, i.e. dc voltage was approximately 1/3 of the total breakdown voltage. This is because for a typical HVDC system, e.g. $\pm$ 450 kV, the insulation level for lightning strokes of 1 μs front is 1550 kV. The dc voltage is approximately 1/3 of the insulation level. Similarly, since the switching impulse is usually 1.5 times the rated voltage of a power system, the dc voltage was chosen as 1/1.5 of the switching impulse component of the composite stress of -ve dc plus +ve switching impulse voltage, i.e. the dc component was 1/2.5 of the total breakdown voltage. After each breakdown, the test gap was carefully examined to ascertain the location of breakdown. If the breakdown occurred on the surface of the sample or spacers, the gap could not be used for further testing since the breakdown caused damage on the surface of the sample or spacer. Following surface damage a new gap was used for subsequent testing. If the breakdown occurred away from the interface, the same gap could be used for another test after application of vacuum to remove all the bubbles caused by the breakdown. In all cases the breakdown voltage (peak value), the time to breakdown and the location of the breakdown were noted. For each gap at least ten readings of breakdown voltage were obtained and the mean breakdown voltage was computed.

To conduct tests of dc plus switching impulse voltages, similar procedures were employed. However, the dc voltage was of negative polarity while the switching impulse was of positive polarity in this case.

Generally speaking, it took three to four days to prepare one test sample (5 gaps) and two to three days were needed to conduct experiments. Thus, it usually took one week to complete one test sample.

Chapter 4

Experimental Results

Test results of the surface electric strength of pressboard-oil insulation under the application of dc voltage superimposed on standard lightning and switching impulse voltages are presented in the following sections.

4.1 Surface Electric Strength of Pressboard-Oil Insulation under dc Voltage Superimposed on Standard Lightning Impulse Voltages

Figure 4.1 shows the total surface breakdown strength of the pressboard-oil insulation under the application of positive dc superimposed on standard negative lightning impulse voltages (i.e. +ve dc plus -ve lightning) at room temperature for test gaps of 5, 7.5 and 10 mm. The dc voltage applied to gaps of 5, 7.5 and 10 mm was 30, 45 and 60 kV, respectively. These voltages are referred to as dc "level 1".

Similarly, Fig. 4.2 shows the total surface breakdown voltage at different dc voltage level, "level 2", for the same three gaps. The "level 2" voltages are 36, 54 and 72 kV for 5, 7.5 and 10 mm gaps, respectively. It may be noted that these values are 20% higher than the "level 1" values

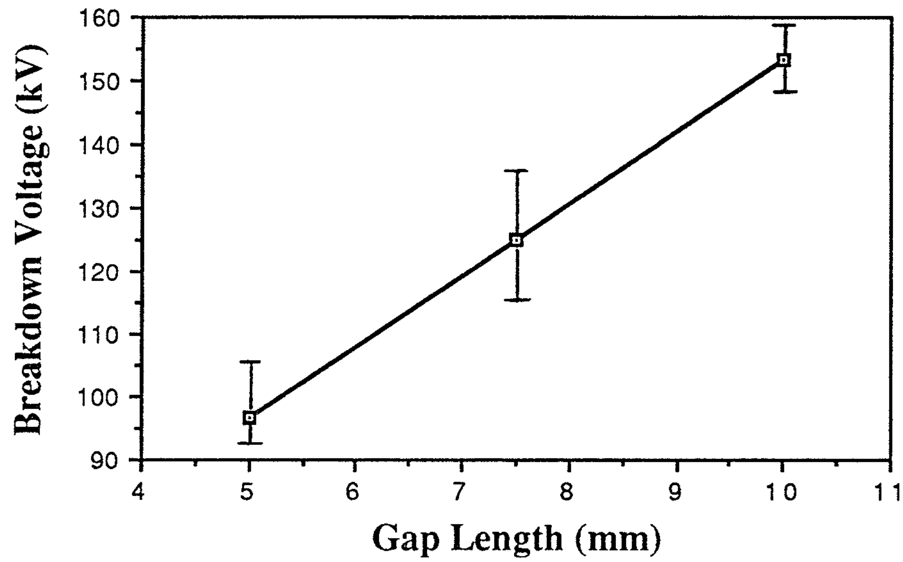

Figure 4.1: Dependance of total surface breakdown voltage on gap length.

+ve dc," level 1", plus corresponding -ve lightning impulse (LI 1)..

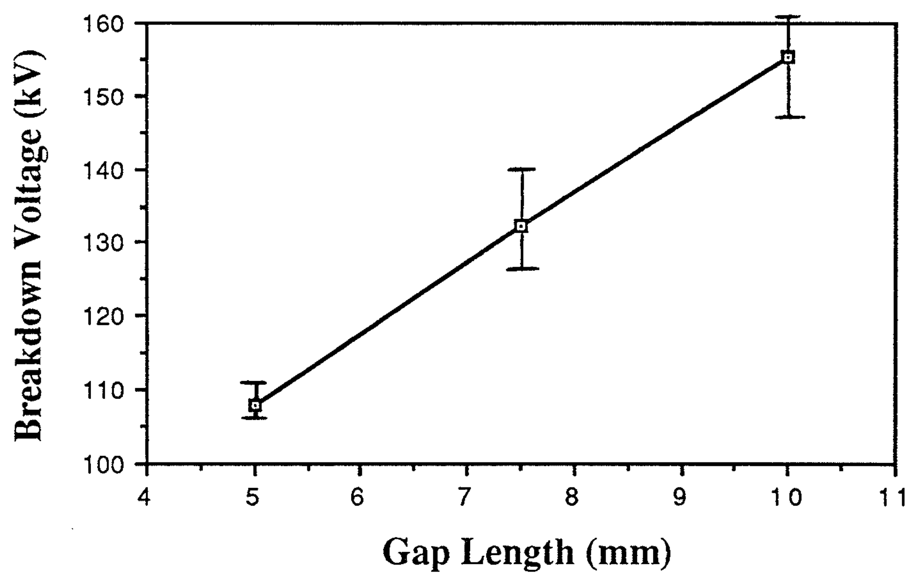

Figure 4.2: Dependance of total surface breakdown voltage on gap length.

+ve dc, "level 2", plus corresponding -ve lightning impulse (LI 2).

From Figs. 4.1 and 4.2, it can be seen that the electric strength-gap length relationships is almost linear under the application of dc plus lightning impulse voltages.

Figure 4.3 illustrates the typical surface damage under the application of positive dc voltage plus negative lightning impulse voltages.

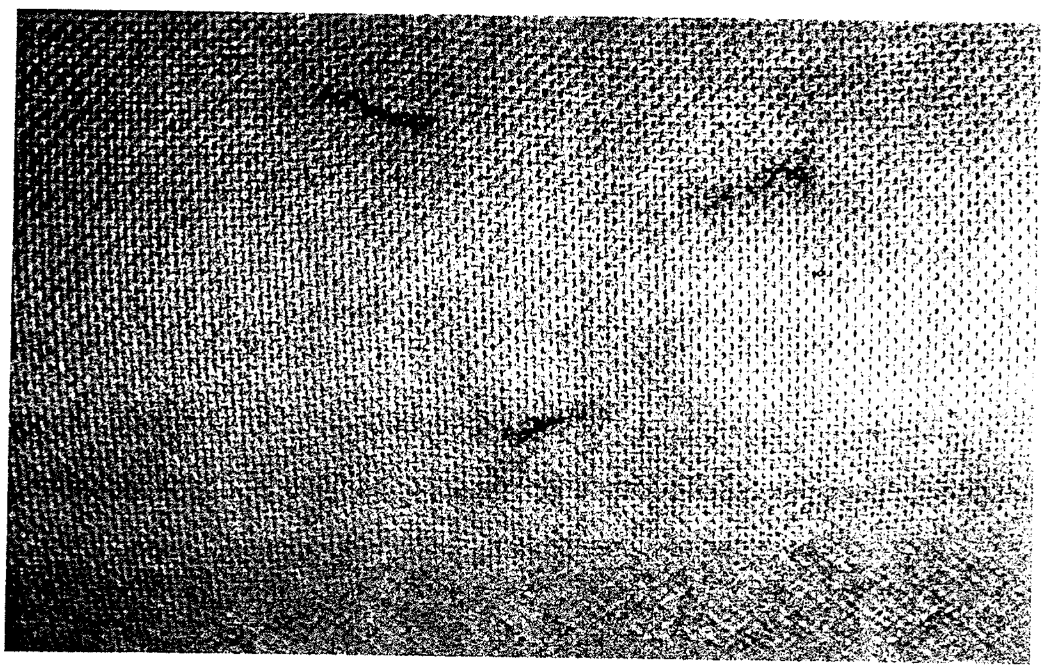

Figure 4.3: Surface track on 10 mm gap produced by +ve dc voltage plus -ve lightning impulse voltages.

In Figs. 4.4 and 4.5, the dependance of total surface breakdown voltage on gap length including the dc and lightning impulse components of the composite voltage with different dc levels have been plotted.

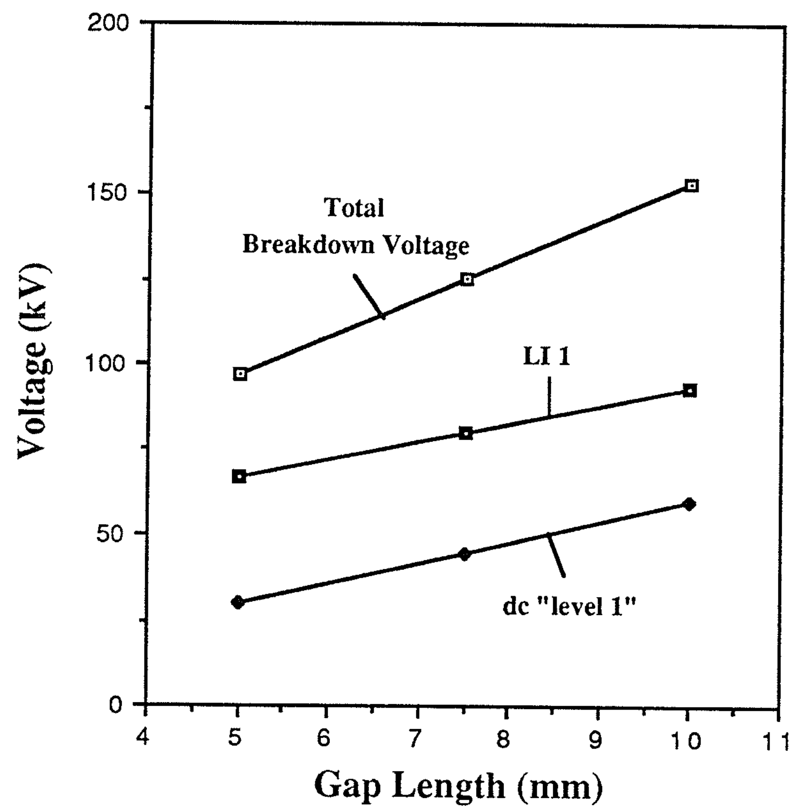

Figure 4.4: Dependance of total surface breakdown voltage on gap length under +ve dc, "level 1", plus corresponding -ve lightning impulse voltages. Both dc and lightning impulse (LI 1) components are shown.

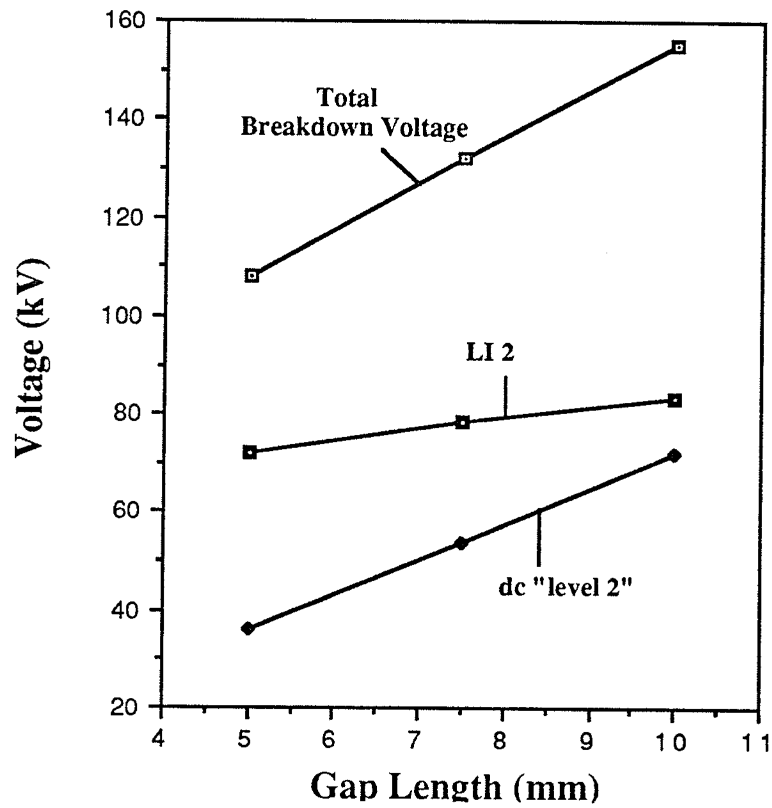

Figure 4.5: Dependance of total surface breakdown voltage on gap length under +ve dc,"level 2", plus corresponding -ve lightning impulse voltages. Both dc and lightning impulse (LI2) components are shown.

In order to have a clear picture of the relationship between dc and lightning impulse voltages, Fig. 4.6 is plotted to show the influence of dc levels on the applied lightning impulse voltages needed to cause breakdown.

It may be seen from Fig. 4.6 that with an increase of 20% in the dc level, the applied lightning impulse voltage does not change much except for gap length of 10 mm.

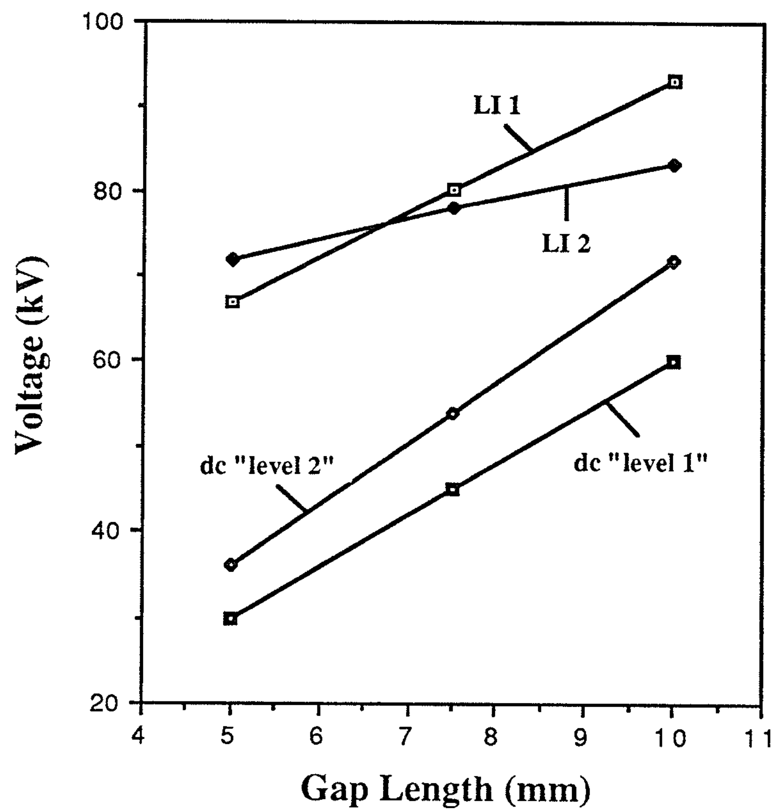

Figure 4.6: Influence of dc levels on the lightning impulse voltages needed to cause surface breakdown.

Similarly, Fig. 4.7 is drawn to show the influence of dc level on the total breakdown voltage of the pressboard-oil insulation under the application of +ve dc voltage superimposed on -ve lightning voltages.

It can easily be seen from the plot that with an increase of 20% in dc voltage, the total breakdown voltage also increased.

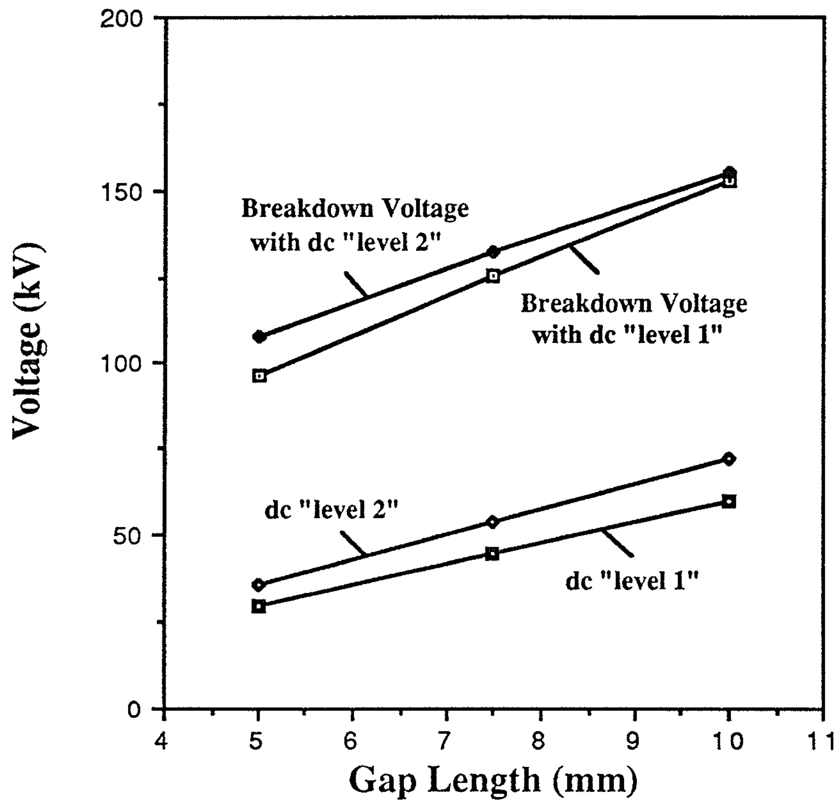

Figure 4.7: Influence of dc levels on the total surface breakdown voltages. +ve dc plus -ve lightning impulse voltages.

Finally, Fig. 4.8 compares the breakdown voltage-gap length relationship under the application of +ve dc voltage (both levels) superimposed on -ve lightning impulse voltages and lightning impulse voltages only.

Figure 4.8 clearly indicates that the surface electric strength of pressboard-oil insulation is higher under pure lightning impulse stresses than under the stresses of +ve dc plus -ve lightning impulse voltages. The only exception is for gap length of 5 mm. In this case, the breakdown voltage is lower under pure lightning impulse than under +ve dc plus -ve lightning impulse voltage.

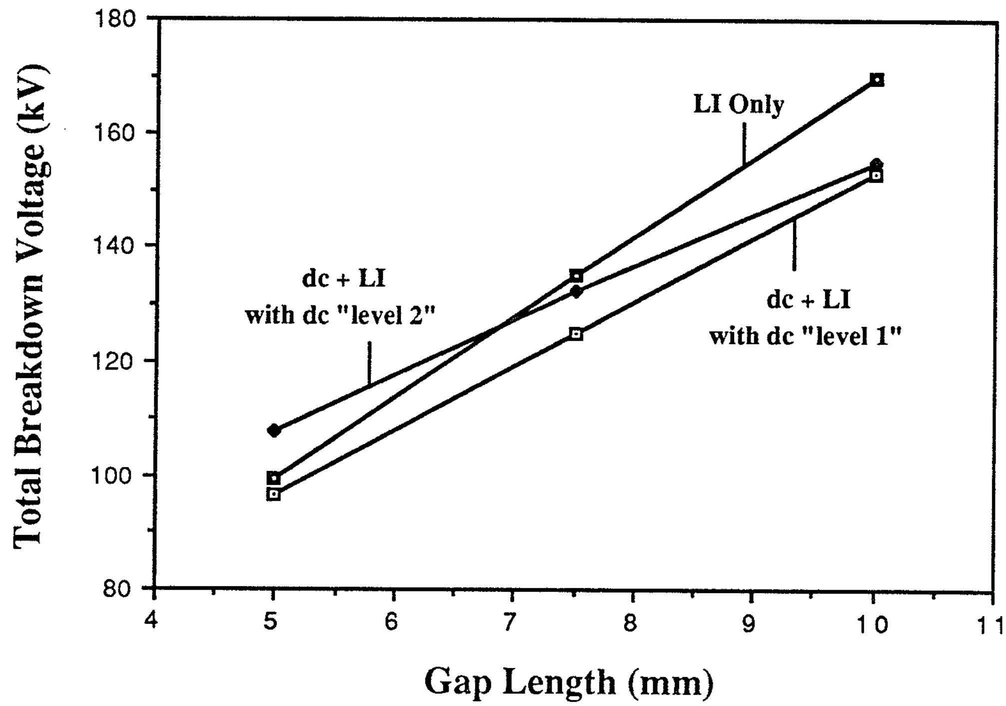

Figure 4.8: Total surface breakdown voltage-gap length relationship under lightning impulse only and +ve dc (both levels) plus -ve lightning impulses (dc+LI).

4.2 Surface Electric Strength of Pressboard-Oil Insulation under dc Voltage Superimposed on Standard Switching Impulse Voltages

The surface strength of mineral oil impregnated pressboard under a composite stress due to application of negative dc voltage plus standard positive switching impulse voltages is shown in Figs. 4.9 and 4.10. In Fig. 4.9, the dc voltage applied to gaps of 5, 7.5 and 10 mm was 30, 45 and 60 kV, respectively while in Fig. 4.10 the dc voltage was 36, 54 and 72 kV for the same gaps respectively. Similarly, the first three dc voltages are referred to as dc "level 1" while the other three dc voltages are referred to as dc "level 2".

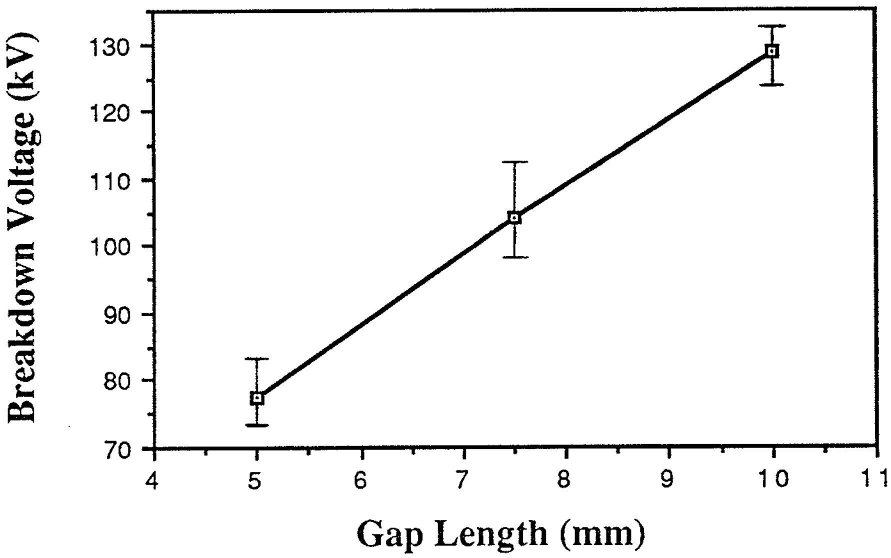

Figure 4.9: Dependance of total surface breakdown voltage on gap length.

-ve dc," level 1", plus corresponding +ve switching impulse (SI 1).

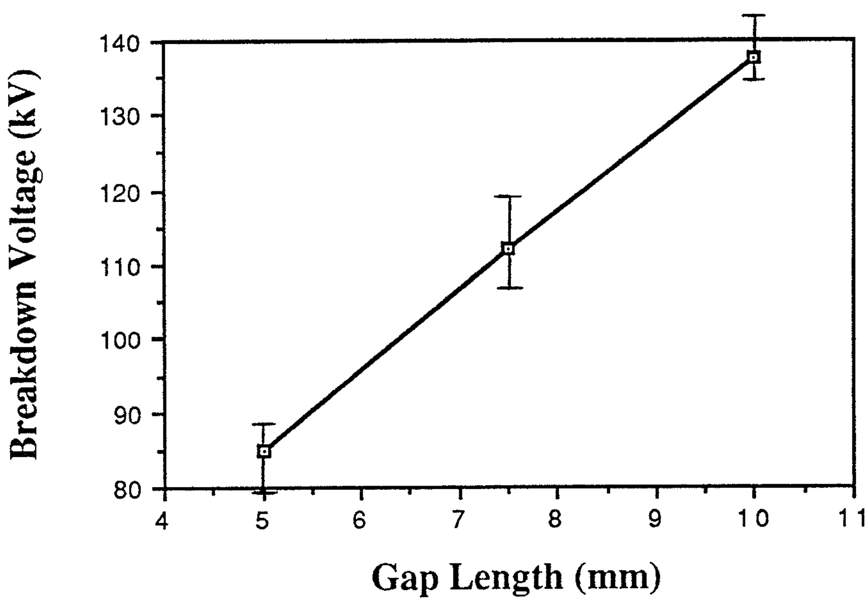

Figure 4.10: Dependance of total surface breakdown voltage on gap length.

-ve dc," level 2", plus corresponding +ve switching impulse (SI 2).

In Figs. 4.9 and 4.10, it may be seen that the surface strength-gap length relationship is almost linear.

In Figs. 4.11 and 4.12, the dependance of surface breakdown voltage on gap length including dc and switching impulse components of the composite stress with different dc levels have been plotted.

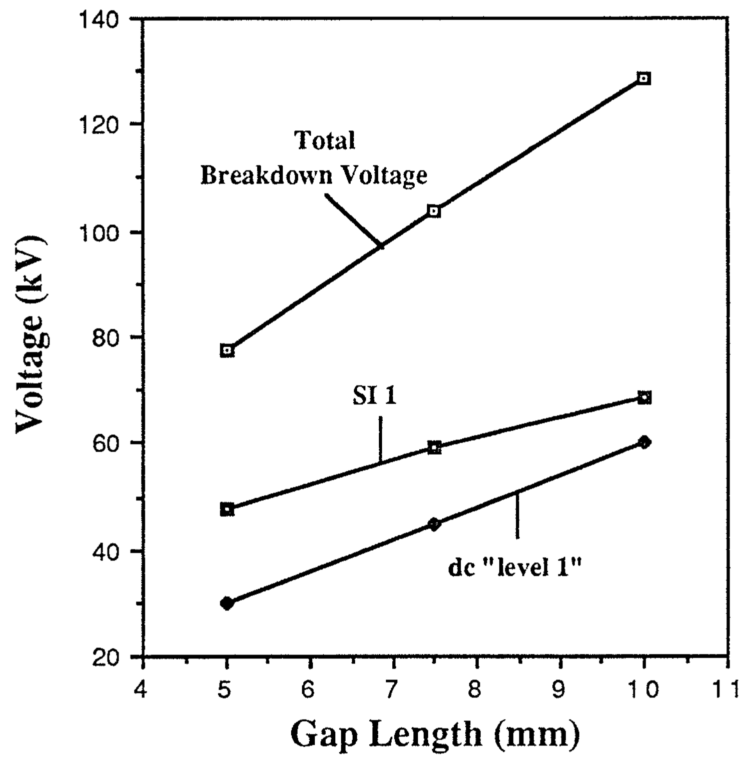

Figure 4.11: Dependance of total surface breakdown voltage on gap length under -ve dc," level 1", plus corresponding +ve switching impulse voltages. Both dc and switching impulse (SI 1) components are shown.

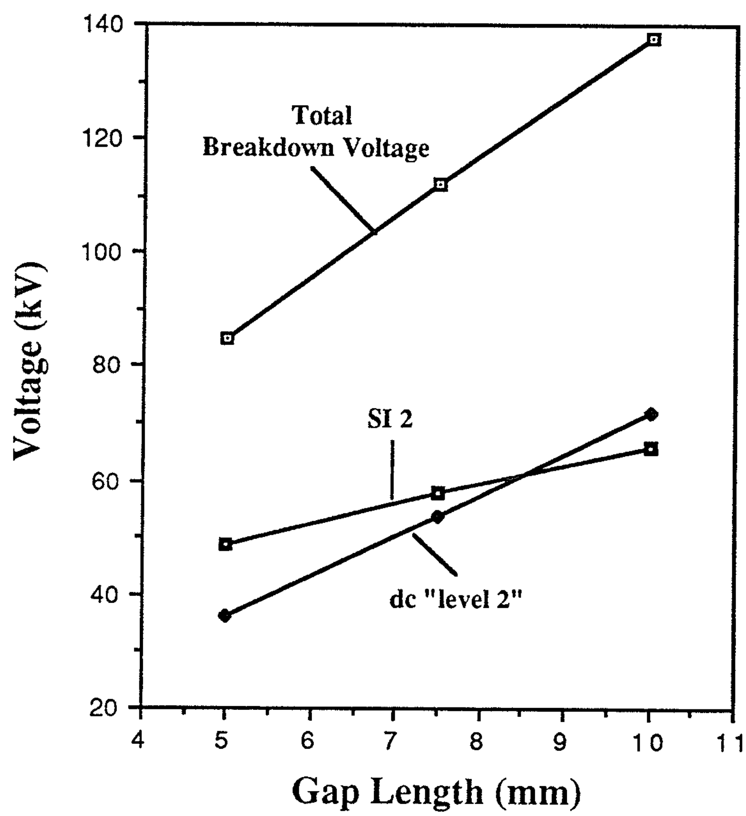

Figure 4.12: Dependance of surface breakdown voltage on gap length under -ve dc,"level 2", plus corresponding +ve switching impulse voltages. Both dc and switching impulse (SI 2) components are shown.

Furthermore, Fig. 4.13 is drawn to show the influence of dc voltages on the applied switching impulse voltages needed to cause surface breakdown.

Figure 4.13 clearly indicates that with an increase of 20% in the dc level, the applied switching impulse voltage which can cause surface breakdown does not change much.

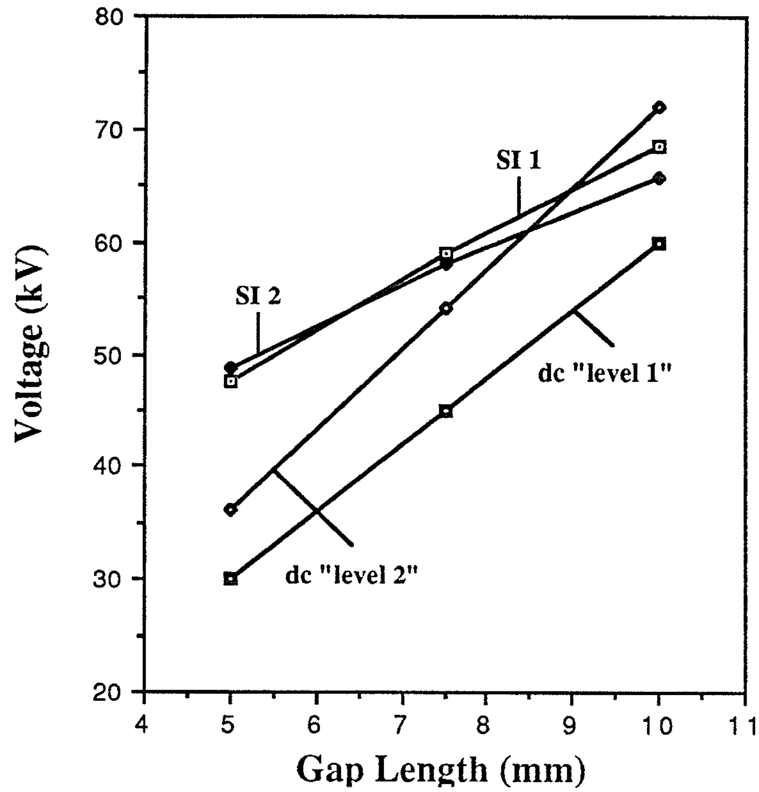

Figure 4.13: Influence of dc voltages on the applied switching impulse voltages needed to cause surface breakdown.

Similarly, Fig. 4.14 is plotted to show the influence of dc level on the total breakdown voltage of the pressboard-oil insulation under the application of -ve dc superimposed on +ve switching impulse voltages.

It is obvious from Fig. 4.14 that with an increase of 20% in the dc voltage, the total breakdown voltage also increased.

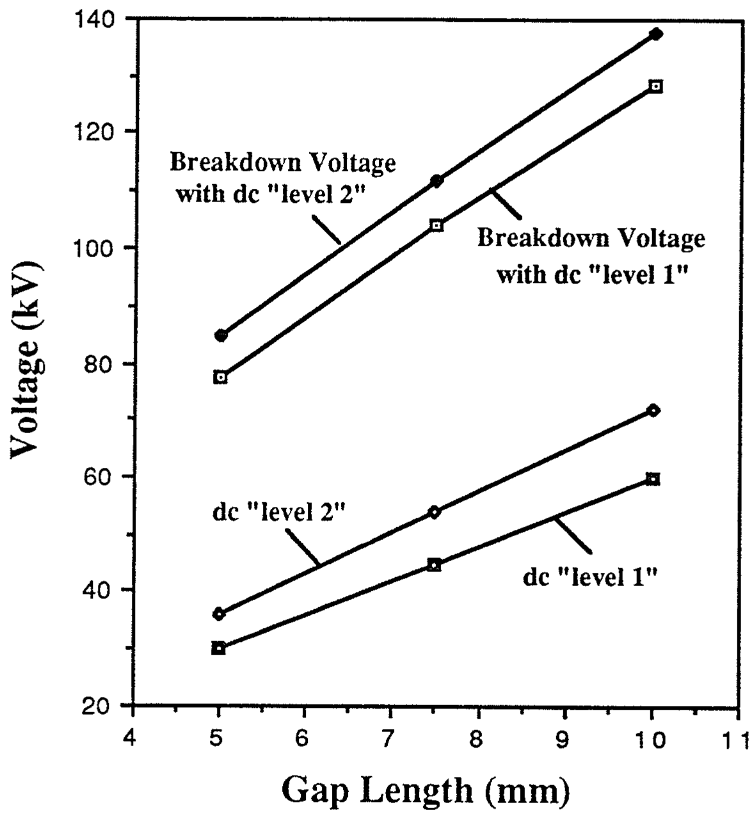

Figure 4.14: Influence of dc voltages on the total surface breakdown voltages.

-ve dc plus +ve switching impulse voltages.

Finally, Fig. 4.15 shows the comparison of the breakdown voltage-gap length relationship under the application of switching impulse voltage only and -ve dc voltage (both levels) plus +ve switching impulse voltages.

The results indicate that the application of pure switching impulse voltage results in the highest breakdown voltage. The breakdown voltage is lower under the composite stresses of -ve dc plus +ve switching impulses.

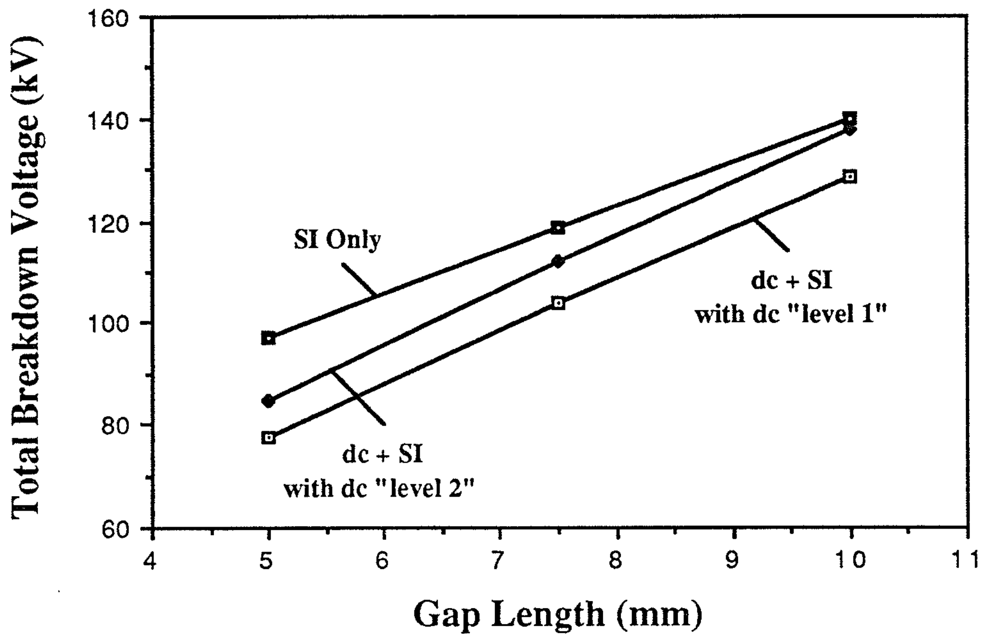

Figure 4.15: Surface electric breakdown voltage-gap length relationship under the stresses of switching impulse only and -ve dc (both levels) plus +ve switching impulse voltages (dc+SI).

Up to now, the test results from dc plus lightning and switching impulse voltages have been presented. To have a better understand of the surface strength under these two kinds of composite stresses, Fig. 4.16 is drawn to compare the breakdown voltage-gap length relationship under the application of +ve dc plus -ve lightning and -ve dc plus +ve switching impulse voltages.

It turns out that the surface electric strength is much higher under +ve dc plus -ve lightning impulse voltages than under -ve dc plus +ve switching impulse voltage just as the case where the surface electric strength is much higher under lightning impulse voltages only than under switching impulse voltages only.

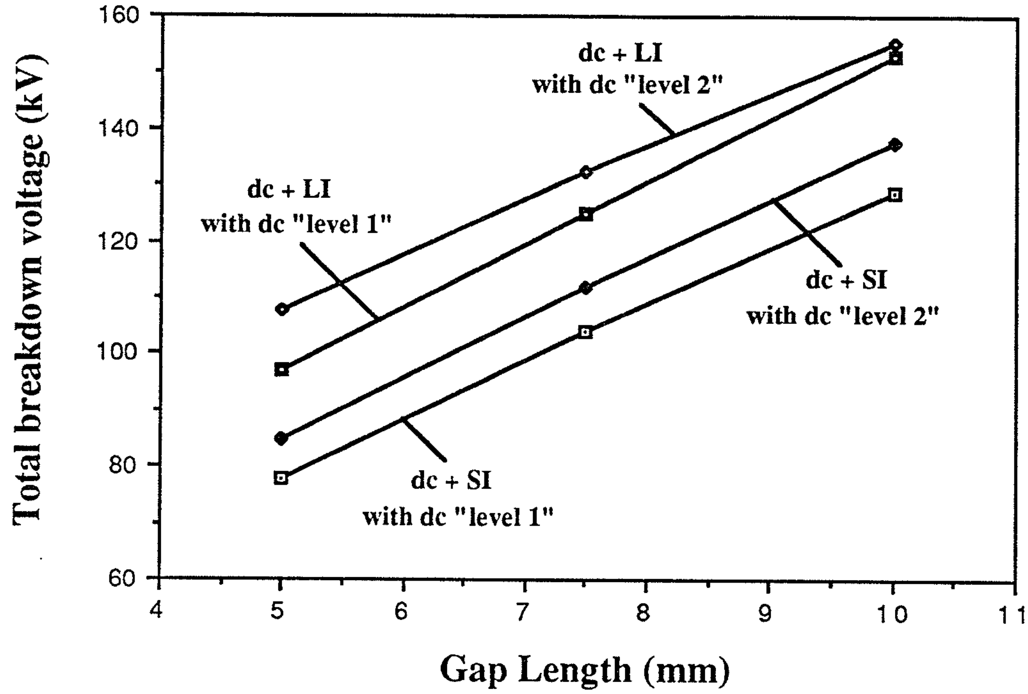

Figure 4.16: Surface breakdown voltage-gap length relationship under +ve dc (both levels) plus -ve lightning (dc+LI) and -ve dc (both levels) plus +ve switching impulse (dc+SI) voltages.

4.3 Surface Electric Strength of Pressboard Impregnated in Aged Mineral Oil under dc Voltage Superimposed on both Standard Lightning and Switching Impulse Voltages

To gain an understanding of the influence of aged oil on the surface electric strength of pressboard-oil insulation, some tests were carried out to determine the surface breakdown voltage of pressboard immersed in aged mineral oil.

The aged mineral oil was Imperial Oil Voltesso 35 and was PCB free. It was procured from Manitoba Hydro's Dorsey T22 converter transformer which has a 230 kV line winding and 300 kV d-c valve winding. The converter transformer has been in service since 1975.

A routine test on this transformer oil showed it to have the following characteristics which are compared with those of unaged oil, as shown in Table 4.1.

Type of Oil	Aged Oil	Unaged Oil
Colour (D1500)	2.0	0.5
Neutralization #	0.02 mg KOH/g	0.05 mg KOH/g
Dielectric Strength	61.0 kV (max.)	N/A
	46.0 kV (min.)	35.0 kV (min.)
Interfacial Tension	31.8 mN/m	45.0 mN/m
Dissipation Factor at 100 °C	0.74 %	0.26 %
Dissolved Water	N/A	< 10 ppm

Table 4.1: Characteristics of aged and unaged transformer oil.

Figure 4.17 shows the surface breakdown voltage of pressboard-oil (aged) insulation under the application of positive dc plus negative lightning impulse voltages for gaps 5, 7.5 and 10 mm. Both dc and lightning impulse components are also shown in the figure.

Similarly, Fig. 4.18 is drawn to show the surface strength under negative dc plus positive switching impulse voltages as well as the dc and switching impulse components. For both +ve dc plus -ve lightning impulse and -ve dc plus +ve switching impulse voltage tests, only one dc level was employed, i.e. a dc voltage of 22.5, 33.8 and 45 kV was applied to 5, 7.5 and 10 mm gaps, respectively. These voltages are referred to as dc "level 3".

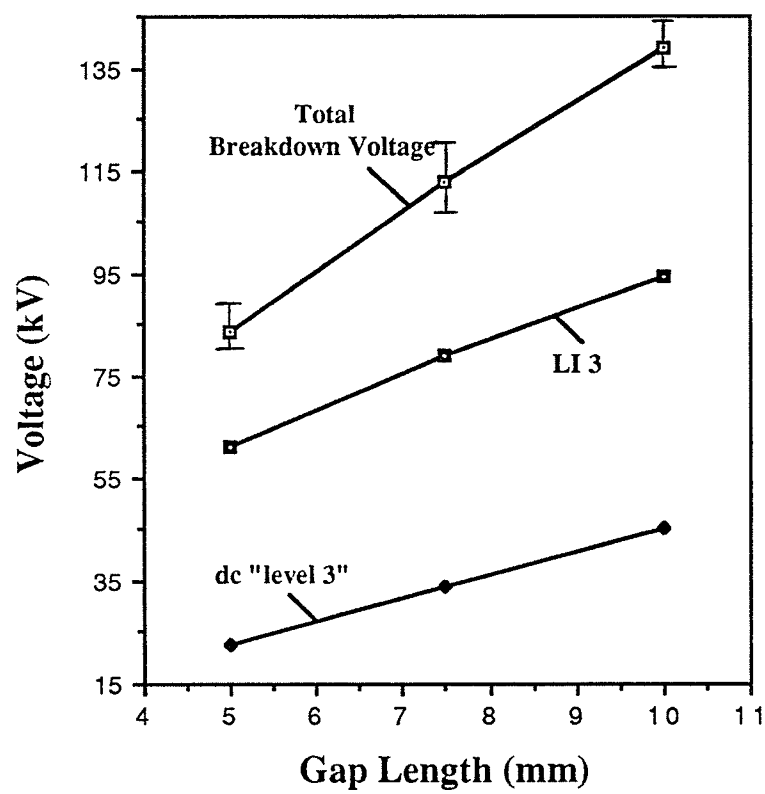

Figure 4.17: Dependance of total surface breakdown voltage on gap length (SPECIMEN PROCESSED WITH AGED OIL) under +ve dc, "level 3", plus corresponding -ve lightning impulse voltages. Both dc and lightning impulse (LI 3) components are also shown.

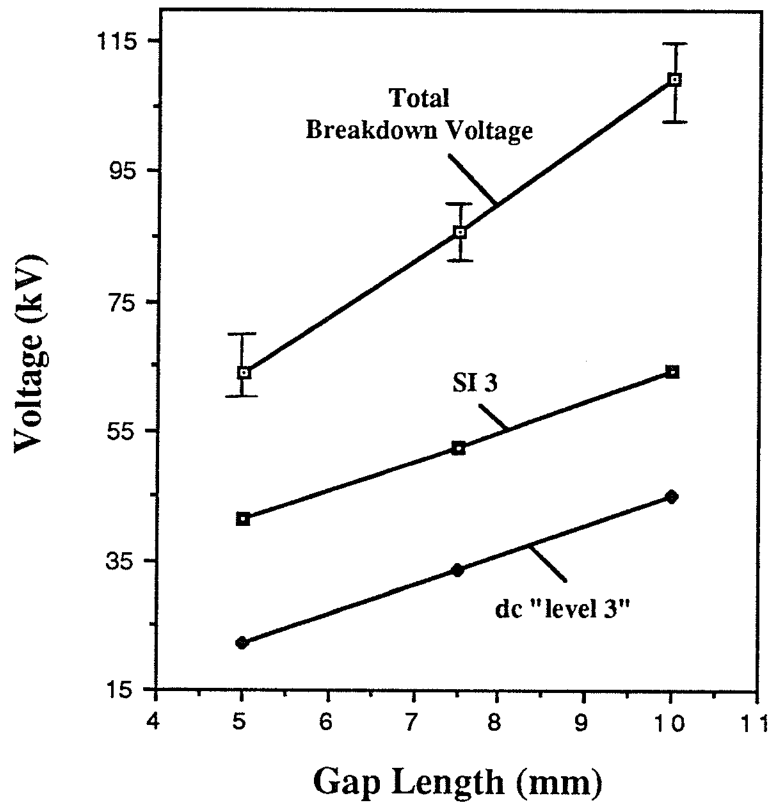

Figure 4.18: Dependance of total surface breakdown voltage on gap length (SPECIMEN PROCESSED WITH AGED OIL) under -ve dc, "level 3", plus corresponding +ve switching impulse voltages. Both dc and switching impulse (SI 3) components are also shown.

To compare the difference in the surface electric strength of pressboard processed with unaged and aged oil, Figs. 4.19 and 4.20 have been plotted.

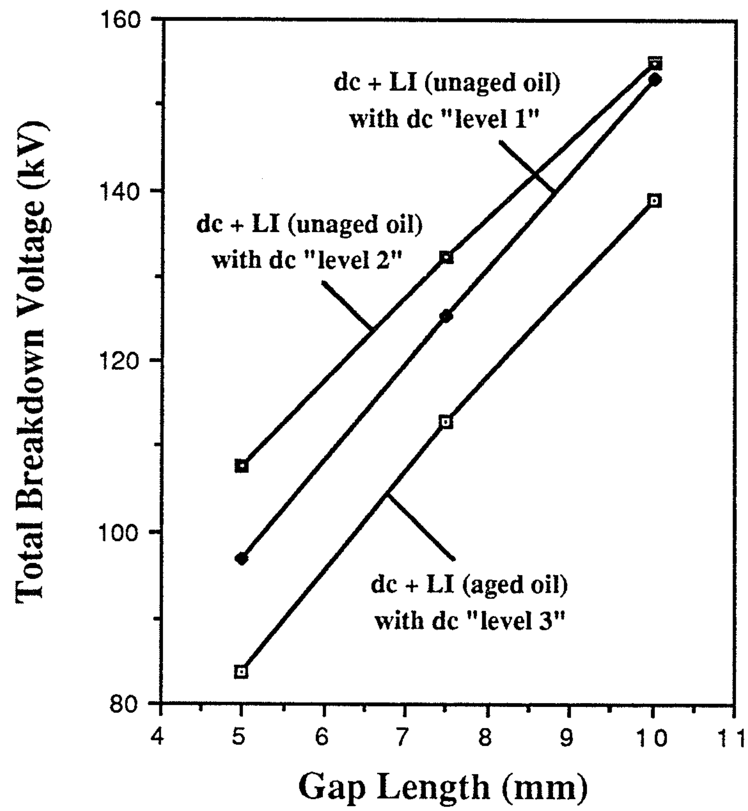

Figure 4.19: Comparison of breakdown voltages of pressboard impregnated in unaged and aged mineral oil under +ve dc plus -ve lightning impulse voltages. Two dc levels are considered for unaged oil test.

The dc level for the aged oil tests, i.e. dc "level 3", was chosen using the same consideration which lead to the choose of dc "level 1" and dc "level 2". When the composite applied voltage consists of dc plus lightning impulse voltage, Fig. 4.19 shows that the dependance of the total breakdown voltage on the dc level is very small. In fact this dependance decreases drastically with gap length and for the 10 mm gap length a 20%

variation of dc level results in a change of about 1.3% in the total breakdown voltage. Therefore, one may compare the effect of processing with aged oil for the 10 mm gap with confidence in spite of the different dc level. For the 10 mm gap, Fig. 4.19 shows that the total breakdown voltage is reduced by 10.1% (compared to the breakdown voltage with dc "level 1") due to the effect of aged oil.

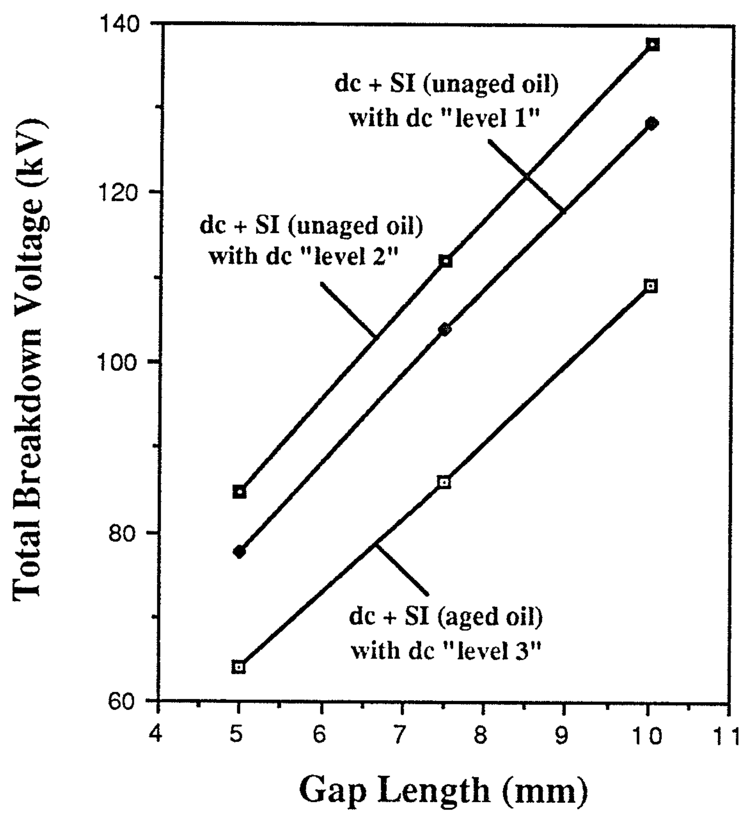

Figure 4.20: Comparison of breakdown voltages of pressboard impregnated in unaged and aged mineral oil under -ve dc plus +ve switching impulse voltages. Two dc levels are considered for unaged oil test.

With switching impulse the total breakdown voltage is not as insensitive to the dc level as was the case with lightning impulse. In spite of the lower dc level used it is clear from Fig. 4.20 that the total breakdown voltage is reduced due to the effect of aged oil.

Finally, the surface electric strength of processed pressboard impregnated in both unaged and aged oil under the application of both pure lightning and switching impulses, and both

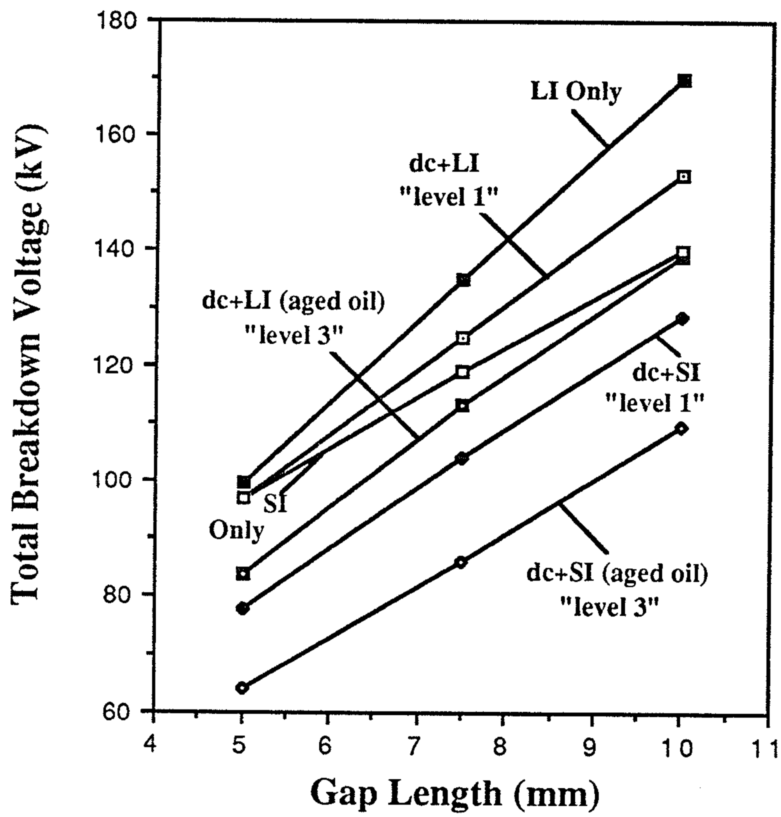

Figure 4.21: Comparison of the surface strength of processed pressboard in both unaged and aged mineral oil under lightning (LI) and switching (SI) impulses only, +ve dc plus -ve lightning (dc+LI) and -ve dc plus +ve switching impulse (dc+SI) voltages.

+ve dc plus -ve lightning impulses and -ve dc plus +ve switching impulse voltages is shown in Fig. 4.21 in order to have a complete view of how pressboard behaves under different stresses and different conditions. For dc voltage plus lightning and switching impulse voltages unaged oil tests, only one dc level (dc "level 1") is used in the plot.

It is obvious that the application of pure lightning impulse voltages results in the highest breakdown voltages; the lowest strengths are obtained under the application of dc voltage superimposed with standard switching impulse voltages with the pressboard impregnated in aged transformer oil. The strength-gap relationship is approximately linear under all the stresses employed in the study.

Chapter 5

Discussion and Explanation of Test Results

Electric breakdown at the interface of a solid-liquid system is quite different from volume breakdown within a solid or liquid alone. Several researchers have indicated that in a composite dielectric system the dielectric strength along or close to a parallel solid-liquid interface is weaker than in the bulk of either of the two materials [8, 13, 30, 34]. A variety of mechanisms may be postulated to explain the lowered strength [2, 9, 12, 13, 30, 31]. Despite this, it has been shown that breakdown does not necessarily take place along an interface, nor is the breakdown voltage of a solid-liquid interface necessarily lower than that of the solid or liquid alone [16] although it is widely assumed that in many situations the interface between the solid and liquid insulation is the point in a complex system at which breakdown would occur. Other researchers have also observed that the breakdown does not necessarily occur along the surface of the interface, and that the breakdown voltage of the composite system is lowered. For example in [8] it is reported that the reduction is 11.9 and 29.2% under lightning and switching impulses respectively which is much larger than that obtained under application of ac voltages. This trend may be explained on the basis of the hypothesis proposed by Devins and Rzad [38] that the presence of a pressboard interface causes the behavior of streamers to be quite different from that observed in oil gaps alone. In the former case the velocities are larger and show a greater voltage dependance thus enabling high velocity streamers to form at lower voltages. This results in a lowering of the breakdown voltage. In [34], the reduction of the dc breakdown voltage at the interface is attributed to the changes in the electrohydrodynamics (EHD) of the gap influenced by the presence of the spacer.

Actually, much of the modern work on interfacial breakdown has been influenced by the results obtained by Wechsler and Riccitiello [30]. They found, under 60 Hz voltages, that the breakdown generally occurred in the liquid at or near the solid-liquid interface. The breakdown strength of the combination was as much as 50% lower than the breakdown strength of the oil alone.

To explain their results, they proposed that the lowered breakdown strength was due to field enhancement in the liquid caused by surface irregularities on the solid. An idealized interfacial surface is shown in Fig. 5.1. They calculated that the ratio of the breakdown strength of the composite system (breakdown at the interface) to breakdown strength of the fluid alone is given by

$$\frac{V_B}{V_{B'}} = (1 + \varepsilon_i) \sum_j Z_{sj} \,/\, d$$

where ε_i is the ratio of the relative permittivity of the liquid to that of the solid along the interface (as shown in Fig. 5.1), and d is the gap spacing.

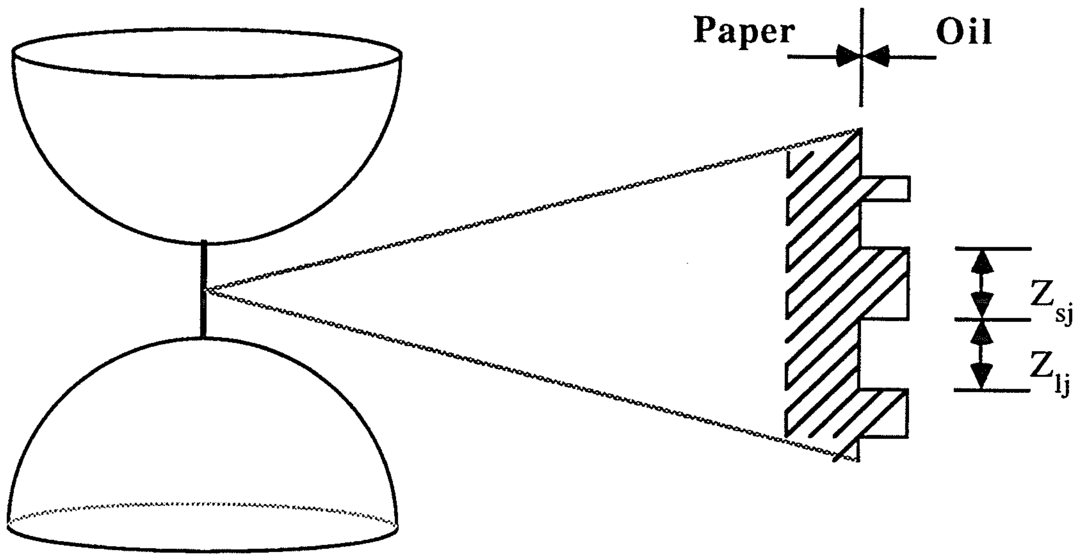

Figure 5.1: Idealized model of paper-oil interface.

Assuming that the electrical strength is related to the field intensity, a surface-charge-induced field enhancement would tend to lower the strength of the interfacial system. The possibility of charge accumulation on the interface is intellectually appealing because such a process has been detected at gas-solid [39] and at vacuum-solid [40] interfaces. So, one might expect such phenomena to carry over to the solid-liquid interfaces. If this process is significant at an oil-paper interface, a model could be used to explain the breakdown phenomenon in a number of insulating systems. Several researchers have investigated the field along an interface using Kerr effect. Some of them employed liquids having relatively large Kerr coefficients [32, 33, 35] while others used transformer oil as the liquid under study [41] because of transformer oil's practical value. The experimental results in [41] indicated that, at room temperature, for the parallel-plate electrode system with and without a pressboard interface bridging the gap between the electrodes, no space- or surface-charge field enhancements are observed even with the interface present. At 125°C space-charge field enhancements are observed in transformer oil, but the field enhancement does not change upon the addition of an interface-the field near the interface was the same as the field away from the interface to within $\pm$ 5% precision of the experiment. Although the breakdown field strength of the interfacial system is substantially lower than one without an interface, macroscopic field enhancements due to surface charging of the interface cannot be invoked to explain the increased failure probability of the interface. These results suggest that microscopic phenomena may play an important role in determining the strength of an interface parallel to the field in a pressboard-oil system.

An alternative explanation of interfacial breakdown under ac or dc applied voltages has also been proposed [32-34]. This model attributes the reduction of breakdown voltage at the interface to electrohydrodynamic phenomena. The experimental results which motivated this explanation were Kerr-effect measurements of the steady-state field distribution in the vicinity of the interface, and liquid-solid interface, current measurements in the vicinity of the interface, and fluid flow measurements. Measurements of the steady-state electric field showed that the field near the interface differed by approximately 10% from the uniform field value. Therefore the authors concluded that these steady-state distributions offer little insight into the interfacial breakdown process. The measured interfacial current density was significantly greater than the current density through the bulk of the fluid. Separate measurements were performed which suggested that the increase in current was due to electrohydrodynamic motion of the fluid. The fluid flow pattern was recorded using conventional flow visualization techniques. These measurements suggested that the fluid cavitation may contribute to a reduction of the breakdown voltage in the vicinity of the interface.

The work reported in [16] indicated, however, that it is a relatively simple matter to force the breakdown to occur at the interface and at the same time reduce the breakdown voltage by ensuring that the pressboard is not completely dried.

In this investigation, the surface electric strength of the pressboard-oil insulation is experimentally determined under the application of dc voltage superimposed on standard lightning and switching impulse voltages. The test results show that for both positive dc plus negative lightning and negative dc plus positive switching impulse voltages, the surface strength is lower than that under pure lightning and switching impulse voltages, respectively. This is quite understandable since the dc breakdown voltage is much lower than both lightning and switching breakdown voltages, as one can see from the test results in [8, 22]. Also, the surface strength under dc plus lightning is higher than that under dc plus switching impulses. This is also reasonable because the lightning surface strength is much higher than the switching surface strength [8, 21, 22]. As far as aged oil is concerned, the surface strength is lower under various stresses as compared with that when unaged oil is used. This phenomenon is caused by the deterioration of the transformer oil.

In addition, as one can see from Figs. 4.6 and 4.13, that for both positive dc plus negative lightning and negative dc plus positive switching impulse voltages, a 20% change in the dc level does not have much effect on the magnitude of the impulse voltages needed to cause surface breakdown except for a gap length of 10 mm under positive dc plus negative lightning impulse voltages. That results in the increase of total breakdown voltage with increase in the dc component of the composite stress, as one can see from Figs. 4.7 and 4.14. This is really an interesting phenomenon because the impulse component needed to cause surface breakdown as well as the total breakdown voltage may be expected to decrease with increase in the dc component. However, the change of dc component seems to have little effect on the impulse component needed to cause surface breakdown. This result may be attributed to electrohydrodynamic (EHD) phenomena [34, 35]. It suggests that EHD motion plays a very dominant role in determining the breakdown of the test gap configuration when the applied voltage is dc or dc plus impulse voltages. Generally speaking, EHD or electroconvection motion occurs when space charge exists in poorly conducting liquids subjected to sufficiently high fields for a voltage-related stability limit to be exceeded. The necessary voltage for the onset of motion ranges from tens of volts to hundreds depending on the physical details of the system. The onset of instability, as pointed out by Cross [35], is not instantaneous when a high stress is applied to the liquid, delays of the order of milliseconds are typical, therefore electroconvection can play no role in the impulse breakdown of liquids except perhaps with very long switching surges. That means, for dc plus impulse voltages, that the influence of impulse component on EHD motion is negligible. It is therefore assumed that under different dc voltages over onset but not in a very wide range the characteristics of EHD motion do not change much if the test gap length is not changed. So, with 20% increase in dc component of the composite stress, the EHD motion does not change much which results in the little change in impulse component needed to cause surface breakdown. That is why the breakdown voltage increases with the increase of dc component of the composite stress, just as the test results illustrate.

Chapter 6

Conclusions and Suggestions for Future Work

In this investigation the surface electric strength of processed pressboard samples immersed in both unaged and aged mineral oil at room temperature has been determined experimentally for three gap lengths in the range of 5 to 10 mm under the application of dc voltage superimposed on standard lightning and switching impulse voltages. This composite test voltage was positive dc plus negative lightning impulses (i.e. +ve dc plus -ve LI) or negative dc plus positive switching impulses (i.e. -ve dc plus +ve SI). These were obtained by superimposing dc and impulse voltages on opposite ends of the test gap. The pressboard was tested in a cylindrical configuration with ring shaped electrodes fitted snugly around it. In the tests conducted with unaged oil two levels of the dc component of the composite stress were considered for both +ve dc plus -ve lightning and -ve dc plus +ve switching impulse voltages in order to determine the influence of dc component on the total breakdown strength of the pressboard-oil insulation. For aged oil tests, only one dc level was employed.

Based on the test results obtained from the experiments and previous discussions, the following conclusions can be drawn:

For +ve dc voltage plus -ve lightning unaged oil tests, the breakdown voltage-gap length relationship is almost linear in all the cases and the breakdown strength is higher when the dc component of the composite voltage is higher. As far as the influence of dc component on the impulse component needed to cause surface breakdown is concerned, a change in the dc level does not have much of an effect on the lightning impulse component needed to cause surface breakdown except for a gap length of 10 mm. Also, the breakdown voltage under the composite stress is lower than that under the application of lightning impulse voltage only.

Similarly, for -ve dc plus +ve switching impulse voltage tests in unaged oil, the breakdown voltage-gap length relationship is almost linear in all cases, and the breakdown strength is higher when the dc component of the composite voltage is higher. As far as the influence of dc component on the switching impulse component needed to cause breakdown is concerned, a change in the dc level does not have much of an effect on the switching impulse component needed to cause surface breakdown. Also, the breakdown voltage under the composite stresses is lower than that under the application of switching impulse voltage only.

The surface breakdown voltage is higher under the application of +ve dc plus -ve lightning impulse than that obtained under the application of -ve dc plus +ve switching impulse voltages.

For aged oil tests, the breakdown voltage is lower than that when unaged oil was employed for both +ve dc plus -ve lightning and -ve dc plus +ve switching impulse voltages, respectively. Also, the breakdown strength is lower under the application of -ve dc plus +ve switching impulse voltages than that under +ve dc plus -ve lightning impulse voltages.

Finally, as it may be seen from Fig. 4.21, that under the stresses of pure lightning, pure switching, +ve dc plus -ve lightning and -ve dc plus +ve switching impulses in both unaged and aged oil, the application of pure lightning impulse voltage results in the highest breakdown voltage in unaged oil; the lowest surface strength is obtained under the application of -ve dc voltage superimposed on +ve switching impulses with pressboard impregnated in aged oil.

From the test results for both +ve dc plus -ve lightning and -ve dc plus +ve switching impulse voltages, it is found that the total breakdown voltage increases with an increase in the dc component of the composite stress, this is because the dc component has little effect on the impulse component needed to cause surface breakdown. As mentioned in Chapter 5, it is an interesting phenomenon since the total breakdown voltage is supposed to decrease with increase of dc component because dc voltage is more powerful compared to lightning or switching impulse voltages. However, the results do not support the assumption. Therefore, it is suggested that further tests be carried out using more dc levels to check the effect of dc component on the impulse component needed to cause surface breakdown.

In addition, in this study, an interface was always introduced during the investigation by using a pressboard cylinder impregnated in transformer oil. Because practical evidence suggests that the interface between different dielectrics may be a preferred site for electrical failure, as reported by a number of researchers [8, 9, 21, 22, 30-34]. On the contrary, it has been shown that breakdown does not necessarily take place along an interface, nor is the breakdown voltage of a solid-liquid interface necessarily lower than that of the liquid or solid alone [16]. Therefore, to further confirm the influence of the pressboard-oil interface on the surface electric strength of the electrode system, some experiments are necessary using oil gaps of similar geometry by exclusion of the presence of pressboard cylinder from the test set up, as was done in [8] for lightning and switching impulse voltages.

References

1. H.C. Hall and D.J. Skipper, " The Impulse Strength of Lapped Impregnated Paper Dielectric." Proc. IEE, Vol. 103A, pt. A, pp. 571-582, 1956.

2. P.N. Nikolopoulos, G.C. Sakkas and D.N. Diamantopoulos, " The Practical Aspects of the Behavior of the Pressboard Oil Insulation of Large electric Equipment under Impulse and Alternating Voltages." CIGRE, Paper No. 15-03, 1982.

3. P.D. Burkas and I.A. Stathopulos, " Partial Discharges in the Pressboard-Oil Insulation under Switching Impulse Voltages." Proc. of the Fifth International Symposium on High Voltage Engineering, Paper No. 23.16, Braunschweig, West Germany, Aug. 1987.

4. E. Takahashi, Y. Tsutsumi, K. Okuyama and F. Ogata, " Partial Discharge Characteristics of Oil-Immersed Insulation Systems under DC, Combined AC-DC and DC Reversed Polarity Voltage." IEEE Trans. Power Apparatus and Systems , Vol. PAS-95, No. 1, Jan./Feb. 1976.

5. H. Nowaczyk, S. Grzybowski and E. Kuffel, " Electrical Breakdown Strength of Paper Oil Insulation under Pulsating Voltages." IEEE Trans. Elec. Insul., Vol. EI-22, No.3, pp.249-253, June 1987.

6. Y. Kamata, K. Endoh, S. Furukawa, F. Endoh, K. Nonomura, Y. Iwata, S. Horiuchi and N. Takasu, " Dielectric Strength of Oil-Immersed Transformer Insulation under Superimposed Voltage Condition between Lightning Impulse and AC Voltage." *Proc. of the Sixth International Symposium on High Voltage Engineering*, Paper No. 11.06, New Orleans, U.S.A., Sept. 1989.

7. S.R. Naidu, J.B. Neilson and K.D. Srivastava, " The Volt-time Characteristics of Oil-impregnated Paper Insulation in the Submicrosecond and Microsecond Regime." *IEEE Trans. Elec. Insul.*, Vol. EI-24, pp. 39-46, Feb. 1989.

8. M.R. Raghuveer, " Experimental Determination of the Electrical Surface Strength of Processed Pressboard in Mineral Oil under dc Voltage with Ripple." *Report to Manitoba HVDC Research Center* in fulfillment of contract # HVDC E.4.62, 1989.

9. L. Lundgaard and H. Daielson, " the Influence of Pressboard Parallel to the Field on AC-Breakdown in Oil Gaps." *Proc. of the Fourth International Symposium on High Voltage Engineering*, Athens, Greece, Sept. 1983.

10. E.F. Kelley, R.E. Hebner, W.E. Anderson, J.A. Lechner and J.L. Blue, " The Effect of an Oil-Paper Interface Parallel to an Electric Field on the Breakdown Voltage at Elevated Temperatures." *IEEE Trans. Elec. Insul.*, Vol. EI-23, No.2, pp.249-259, April 1988.

11. T.C. Cheng, C.Y. Wu and H. Nour, " DC Interfacial Breakdown on Contaminated Electrolytic Surfaces." *IEEE Trans. Elec. Insul.*, Vol. EI-19, No. 6, pp. 536-542, Dec. 1984.

12. J.G. Anderson and T.W. Liao, " The Propagation Mechanism of Impulse Creepage Discharge over Oil-Immersed Surface." *Trans. AIEE*, Vol. 74, pp. 218-226, May 1955.

13. W.G. Standring and R.C. Hughes, " Breakdown under Impulse Voltages of Solid and Liquid Dielectrics in Combination." *Proc. IEE*, Vol. 103A, pp. 583-597, 1956.

14. W.G. Standring and R.C. Hughes, " Impulse Breakdown Characteristics of Solid and Liquid Dielectrics in Combination." *Proc. IEE*, Vol. 109A, pp.473-488, Oct. 1962.

15. R.J. Taylor, " Effect of Permittivity Matching on the Flashover of Solid/Liquid Interfaces." *Proc. IEE*, Vol. 124, pp. 899-904, Oct. 1977.

16. E.F. Kelley and R.E. Hebner, Jr., " Electrical Breakdown in Composite Insulating Systems: Liquid-Solid Interface Parallel to the Field." *IEEE Trans. Elec. Insul.*, Vol. EI-16, pp. 297-303, Aug. 1981.

17. P.N. Nikolopoulos and G.C. Sakkas, " Discharge Propagation on the Surface and in the Volume of a Pressboard-Mineral Oil Combination under Impulse Voltages." *Proc. of the Fourth International Symposium on High Voltage Engineering*, Paper No. 24.11, Athens, Greece, Sept. 1983.

18. H. Okubo, M. Ikeda, M. Honda and S. Yanabu, " Creepage Discharge Propagation in Transformer Oil with Impulse Voltages." *Proc. of the Fourth International Symposium on High Voltage Engineering*, Paper No. 24.04, Athens, Greece, Sept. 1983.

19. M.U. Anker, " Effect of Test Geometry, Permittivity Matching and Metal Particles on the Flashover Voltage of Oil/Solid Interfaces." _IEEE Trans. Power Apparatus and Systems_, Vol. 102, pp. 3796-3802, Dec. 1983.

20. H. Okubo, K. Okamura, M. Ikeda and S. Yanabu, " Creepage Flashover Characteristics of Oil/Pressboard Interfaces and their Scale Effects." _IEEE Paper No. WM 148-1_, present at the IEEE Winter Power Meeting, New York, U.S.A. 1986.

21. Z. Kolaczkowski, M.R. Raghuveer, S. Grzybowski and E. Kuffel, " Lightning and Switching Impulse Surface Strength of Processed Pressboard." _Proc. of the Sixth International Symposium on High Voltage Engineering_, New Orleans, U.S.A., Aug. 1989.

22. M.R. Raghuveer, Z. Kolaczkowski, W. Jin and E. Kuffel, " Surface Electric Strength of Processed Pressboard under Composite ac and dc and Conventional Stresses." _IEEE Trans. Elec. Insul._, Vol. EI-25, No.2, pp. 341-350, April 1990.

23. S. Grzybowski, M.R. Raghuveer and E. Kuffel, " Dependance of Surface Electric Strength of Impregnated Pressboard on Ripple Content of DC Applied Voltage." _Proc. of the Fifth International Symposium on High Voltage Engineering_, Braunschweig, west Germany, Aug. 1987.

24. G. Maier and H.J. Vorwerk, " Dielectric Strength of Oil-Impregnated Insulation under H.V.D.C. Stresses." _Brown Boveri Review,_ No. 5, pp. 246-255, 1969.

25. R.E. Harrison, " Special Problems in the Design and Testing of HVDC Transformers." _CEA Meeting_, Vancouver, Mar. 1971.

26. P. Hessen and W. Lampe, " Insulating Problems in HVDC-converter transformers." _Direct Current,_ Vol. 2, No. 1, Feb. 1971.

27. Z. M. Beletsky, V.G. Butkevitch, A.K. Lokhanin, E.L. Topoliansky and I.D. Voevodin, " Insulation Problems in Power Transformers for HVDC Transmissions." _CIGRE_, Paper No. 12-04, 1976.

28. W.G. Lawson, F.K. Padgham and P. Metra, " The Effect of Polarity Reversals on the Dielectric Strength of Oil-Impregnated Paper Insulation for H.V.d.c. Cables." _IEEE Trans. Power Apparatus and Systems_, Vol. PAS-97, pp. 884-890, May/June 1978.

29. A.K. Lokhanin, V.M. Sukhanov, E.L. Topoliansky, I.D. Voevodin and V.I. Zaitsev, " Converter Transformers for ±750 kV DC Systems." _CIGRE_, Paper No. 12-13, 1986.

30. K. Wechsler and M. Riccitiello, " Electric Breakdown of a Parallel Solid and Liquid Dielectric System. " _Trans. AIEE,_ Vol. 80, pp.365-369, 1961.

31. H. Sueda and K.C. Kao, " Determination of Electric Field Distributions along Fluid-Solid Interfaces Using a Schlieren Techniques." _IEEE Trans. Elec. Insul._, Vol. EI-17, No.5, pp. 405-413, Oct. 1982.

32. J.D. Cross and R. Tobazeon, " Electric Field Distortions Produced by Solid Dielectric Spacers Separating Uniform Field Electrodes in Nitrobenzene." _IEEE Trans. Elec. Insul._, Vol. EI-8, No. 1, pp.25-29, Mar. 1973.

33. E.A. Cherney and J.D. Cross, " Electric-Field Distortions at Solid-Liquid Dielectric Interfaces." _IEEE Trans. Elec. Insul._, Vol. EI-9, No. 2, pp. 37-42, June 1974.

34. E.A. Cherney and J.D. Cross, " Electrical Breakdown at Solid-Liquid Interfaces." _IEEE Trans. Elec. Insul._, Vol. EI-12, No. 3, pp. 214-218, June 1977.

35. J.D. Cross, " Breakdown across a Dielectric Spacer in Insulating Oil and the Role of Electrohydrodynamics in Liquid Breakdown." _IEEE Trans Elec. Insul._, Vol. EI-17, No. 6, pp. 493-498, Dec., 1982.

36. E. Kuffel and W.S. Zaengl, _High-Voltage Engineering_, Pergamon Press, 1984, pp.474.

37. J. Gzylewski and Z. Makowski, " Suszenie Prozniowe Kondensatorow Energetycznych." _Przeg Elektrot._ R XLVIII 2 10, pp. 447, 1972 (in Polish).

38. J.C. Devins and S.J. Rzad, " Streamer Propagation in Liquids and over Liquid-Solid Interfaces." _IEEE Trans. Elec. Insul._, Vol. EI-17, No. 6, pp. 512-516, Dec. 1982.

39. J. Lewis, T.S. Sudarshan, J.E. Tompson, D. Lee and R.A. Dougal, " Pre-breakdown and Breakdown Phenomena along PMMA Surface in Vacuum and Nitrogen Gas Stressed

by 60 Hz Voltages." *IEEE Trans. Elec. Insul.*, Vol. EI-19, No. 6, pp.512-518, Dec. 1984.

40. A.S. Pillai and R. Hackam, " Electric Field Distribution at a Solid Insulator-Vacuum Interface of Different Electrode-Insulator Geometries." *IEEE Trans. Elec. Insul.*, Vol. EI-19, No. 6, pp. 502-511, Dec. 1984.

41. E.F. Kelley and R.E. Hebner, " Measurement of the Electric Field in the Vicinity of an Oil-Pressboard Interface Parallel to the Field." *IEEE Trans. Elec. Insul.*, Vol. EI-19, No. 6, pp. 519-523, Dec. 1984.

Appendix A

Breakdown Voltages Obtained in the Investigation

Figure 4.1: +ve dc Plus -ve Lightning Impulses (dc level 1)

Gap Length (cm)	Total Breakdown Voltage (kV)	Standard Deviation	+ Max. Deviation (kV)	- Max. Deviation (kV)
0.5	96.8	16.47 %	8.3	4.7
0.75	125.1	22.74 %	10.5	7.6
1.0	153.2	19.07 %	5.1	5.2

Figure 4.2: +ve dc Plus -ve Lightning Impulses (dc level 2)

Gap Length (cm)	Total Breakdown Voltage (kV)	Standard Deviation	+ Max. Deviation (kV)	- Max. Deviation (kV)
0.5	107.8	5.89 %	3.3	1.9
0.75	132.2	16.19 %	7.2	5.7
1.0	155.2	14.15 %	6.1	8.2

Figure 4.9: -ve dc Plus +ve Switching Impulses (dc level 1)

Gap Length (cm)	Total Breakdown Voltage (kV)	Standard Deviation	+ Max. Deviation (kV)	- Max. Deviation (kV)
0.5	77.6	11.26 %	5.5	4.9
0.75	104.0	18.29 %	8.3	6.0
1.0	128.6	10.27 %	3.9	5.2

Figure 4.10: -ve dc Plus +ve Switching Impulses (dc level 2)

Gap Length (cm)	Total Breakdown Voltage (kV)	Standard Deviation	+ Max. Deviation (kV)	- Max. Deviation (kV)
0.5	84.8	12.16 %	3.0	6.1
0.75	112.1	15.44 %	6.6	5.1
1.0	137.7	10.49 %	5.5	3.6

Figure 4.17: +ve dc Plus -ve Lightning Impulses (aged oil, dc level 3)

Gap Length (cm)	Total Breakdown Voltage (kV)	Standard Deviation	+ Max. Deviation (kV)	- Max. Deviation (kV)
0.5	83.8	7.15 %	4.7	3.1
0.75	113.0	9.66 %	6.2	5.4
1.0	139.1	8.25 %	4.9	2.9

Figure 4.18: -ve dc Plus +ve Switching Impulses (aged oil, dc level 3)

Gap Length (cm)	Total Breakdown Voltage (kV)	Standard Deviation	+ Max. Deviation (kV)	- Max. Deviation (kV)
0.5	64.0	5.87 %	5.1	2.7
0.75	86.0	7.62 %	4.1	3.7
1.0	109.4	11.97 %	5.5	6.2

Appendix B

Data Obtained in the Investigation

Data of Figure 4.1: +ve dc Plus -ve Lightning Impulses (dc level 1)

Vacuum:2-5x10^{-2} Torr, Temp.:22-24°C, Ratio of Divider:2588

1.0 cm GAP

DC (kV)	LT (mV)	BD VOLT (10V/div)	TIME (2μs/div)	NOTE
60	76	3.8	1.8	OIL
60	70	3.7	2.35	OIL
60	78	3.8	2.2	DAM
60	70	3.3	1.65	OIL
60	80	3.8	1.3	OIL
60	75	3.7	6.8	OIL
60	80	3.8	1.2	OIL
60	76	3.4	1.5	OIL
60	70	3.4	1.7	OIL
60	75	3.6	1.8	OIL
60	75	3.5	1.0	DAM
60	70	3.4	2.7	OIL

AVE. BD VOLTAGE: 93.2 kV TOTAL: 153.2 kV

0.75 cm GAP

DC (kV)	LT (mV)	BD VOLT (10V/div)	TIME (2μs/div)	NOTE
45	65	3.1	2.0	OIL
45	67	2.8	2.8	OIL
45	68	3.25	2.0	DAM
45	66	3.05	5.5	OIL
45	66	3.2	2.8	OIL
45	70	3.5	1.45	OIL
45	65	3.3	2.6	OIL
45	63	2.9	1.2	OIL
45	60	2.8	1.85	OIL
45	65	3.25	1.5	OIL
45	70	2.9	2.7	OIL

AVE. BD VOLTAGE: 80.1 kV TOTAL: 125.1 kV

0.5 cm GAP

DC (kV)	LT (mV)	BD VOLT (10V/div)	TIME (2μs/div)	NOTE
30	60	2.9	1.2	OIL
30	60	2.8	1.5	OIL
30	55	2.65	1.4	OIL
30	55	2.6	1.5	OIL
30	53	2.5	1.6	OIL
30	53	2.45	1.5	OIL
30	55	2.7	1.2	OIL
30	56	2.5	1.6	OIL
30	55	2.4	2.0	OIL
30	52	2.4	1.5	OIL
30	55	2.5	1.4	OIL

AVE. BD VOLTAGE: 66.8 kV TOTAL: 96.8 kV

Data of Figure 4.2: +ve dc Plus -ve Lightning Impulses (dc level 2)

Vacuum: 2-5x10^{-2} Torr, Temp.: 22-24°C, Ratio of Divider: 2588

1.0 cm GAP

DC (kV)	LT (mV)	BD VOLT(10V/div)	TIME (2μs/div)	NOTE
72	63	3.2	2.95	OIL
72	61	3.15	1.85	OIL
72	60	2.9	2.05	OIL
72	63	3.25	2.1	OIL
72	61.5	3.15	1.8	OIL
72	63.5	3.3	2.4	OIL
72	66	3.25	1.35	OIL
72	64	3.3	2.2	OIL
72	69	3.45	2.15	OIL
72	65	3.2	4.7	OIL

AVE. BD VOLTAGE: 83.2 kV TOTAL: 155.2 kV

0.75 cm GAP

DC (kV)	LT (mV)	BD VOLT(10V/div)	TIME (2μs/div)	NOTE
54	58	3.0	1.45	OIL
54	60	2.8	1.45	OIL
54	59	2.9	1.65	OIL
54	63	3.0	2.5	OIL
54	64	3.3	4.7	OIL
54	61	3.1	1.5	OIL
54	66	3.2	1.7	OIL
54	62	3.1	2.15	OIL
54	60	2.8	1.4	OIL
54	61	3.0	1.6	OIL

AVE. BD VOLTAGE: 78.2 kV TOTAL: 132.2 kV

0.5 cm GAP

DC (kV)	LT (mV)	BD VOLT(10V/div)	TIME (2μs/div)	NOTE
36	60	2.8	3.75	OIL
36	55	2.8	0.8	OIL
36	57	2.75	2.5	OIL
36	59.5	2.9	3.2	OIL
36	60	2.8	2.6	OIL
36	58	2.8	2.05	OIL
36	55	2.75	6.5	OIL
36	58	2.75	0.9	OIL
36	58	2.7	1.0	OIL
36	57	2.7	2.6	OIL

AVE. BD VOLTAGE: 71.8 kV TOTAL: 107.8 kV

Data of Figure 4.9: -ve dc Plus +ve Switching Impulses (dc level 1)

Vacuum: 2-5x10^{-2} Torr, Temp.: 22-24°C, Ratio of Divider: 2588

1.0 cm GAP

DC (kV)	LT (mV)	BD VOLT (10V/div)	TIME (0.2ms/div)	NOTE
60	75	2.6	1.3	OIL
60	75	2.45	0.85	OIL
60	80	2.8	2.55	DAM
60	75	2.6	1.7	OIL
60	75	2.8	2.5	OIL
60	75	2.65	1.75	DAM
60	75	2.65	1.7	OIL
60	83	2.7	1.4	OIL
60	80	2.65	1.0	OIL
60	75	2.6	1.65	OIL

AVE. BD VOLTAGE: 68.6 kV TOTAL: 128.6 kV

0.75 cm GAP

DC (kV)	LT (mV)	BD VOLT (10V/div)	TIME (0.2ms/div)	NOTE
45	63	2.6	3.6	OIL
45	65	2.2	1.0	DAM
45	60	2.1	1.2	OIL
45	68	2.4	1.5	OIL
45	80	2.55	1.0	OIL
45	65	2.2	1.8	OIL
45	65	2.05	1.0	OIL
45	65	2.2	0.8	OIL
45	65	2.2	0.9	OIL
45	65	2.3	1.4	OIL

AVE. BD VOLTAGE: 59.0 kV TOTAL: 104.0 kV

0.5 cm GAP

DC (kV)	LT (mV)	BD VOLT (10V/div)	TIME (0.2ms/div)	NOTE
30	50	1.65	1.4	OIL
30	53	1.8	1.7	DAM
30	55	1.8	1.1	DAM
30	55	1.95	2.65	DAM
30	57	1.9	0.75	OIL
30	60	2.05	1.6	OIL
30	57	1.8	1.05	DAM
30	54	1.75	1.5	OIL
30	55	1.8	1.5	OIL
30	55	1.9	1.7	OIL

AVE. BD VOLTAGE: 47.6 kV TOATL: 77.6 kV

Data of Figure 4.10: -ve dc Plus +ve Switching Impulses (dc level 2)

Vacuum: 2-5x10^{-2} Torr, Temp.: 22-24°C, Ratio of Divider: 2588

1.0 cm GAP

DC (kV)	LT (mV)	BD VOLT (10V/div)	TIME (0.2ms/div)	NOTE
72	85	2.6	0.8	DAM
72	85	2.55	0.95	OIL
72	85	2.75	0.6	OIL
72	85	2.4	1.05	OIL
72	80	2.5	1.2	OIL
72	75	2.5	0.8	OIL
72	75	2.6	1.2	OIL
72	80	2.4	1.2	OIL
72	80	2.6	0.95	OIL
72	80	2.5	1.0	OIL

AVE. BD VOLTAGE: 65.7 kV TOTAL: 137.7 kV

0.75 cm GAP

DC (kV)	LT (mV)	BD VOLT (10V/div)	TIME (0.2ms/div)	NOTE
54	80	2.15	1.3	OIL
54	80	2.3	1.5	OIL
54	65	2.05	1.5	OIL
54	80	2.3	0.7	OIL
54	85	2.5	1.2	OIL
54	80	2.4	0.5	OIL
54	70	2.1	1.4	OIL
54	75	2.15	1.4	OIL
54	80	2.5	3.8	OIL
54	75	2.2	1.5	OIL
54	75	2.1	1.5	OIL
54	80	2.2	1.4	OIL

AVE. BD VOLTAGE: 58.1 kV TOTAL: 112.1 kV

0.5 cm GAP

DC (kV)	LT (mV)	BD VOLT (10V/div)	TIME (0.2ms/div)	NOTE
36	55	1.85	0.6	OIL
36	55	1.65	1.0	OIL
36	50	1.9	0.5	OIL
36	60	1.9	2.3	OIL
36	65	2.0	2.8	OIL
36	65	2.0	1.2	DAM
36	60	2.0	1.9	DAM
36	65	2.0	1.2	OIL
36	65	1.75	1.4	OIL
36	58	1.8	1.5	OIL

AVE. BD VOLTAGE: 48.8 kV TOATL: 84.8 kV

Data of Figure 4.17: +ve dc Plus -ve Lightning Impulses (dc level 3) (aged mineral oil)

Vacuum: 2-5x10^{-2} Torr, Temp.: 22-24°C, Ratio of Divider: 2588

1.0 cm GAP

DC (kV)	LT (mV)	BD VOLT (15V/div)	TIME (5μs/div)	NOTE
45	85	2.55	1.2	OIL
45	85	2.45	1.3	DAM
45	90	2.5	1.4	OIL
45	90	2.55	1.2	OIL
45	78	2.4	1.2	OIL
45	85	2.35	1.3	OIL
45	85	2.35	1.25	DAM
45	80	2.35	1.1	OIL
45	75	2.4	1.0	OIL
45	80	2.35	1.2	OIL

AVE. BD VOLTAGE: 94.1 kV TOTAL: 139.1 kV

0.75 cm GAP

DC (kV)	LT (mV)	BD VOLT (15V/div)	TIME (5μs/div)	NOTE
33.8	63	2.1	1.2	OIL
33.8	70	2.2	1.0	DAM
33.8	65	2.05	1.1	OIL
33.8	65	2.1	1.05	OIL
33.8	60	1.9	1.1	OIL
33.8	60	1.95	1.15	OIL
33.8	65	2.15	1.05	OIL
33.8	65	2.0	1.0	OIL
33.8	60	2.0	1.2	OIL
33.8	58	1.95	1.2	OIL

AVE. BD VOLTAGE: 79.2 kV. TOTAL: 113.0 kV

0.5 cm GAP

DC (kV)	LT (mV)	BD VOLT (15V/div)	TIME (5μs/div)	NOTE
22.5	55	1.7	0.8	DAM
22.5	55	1.65	1.1	OIL
22.5	50	1.65	1.0	OIL
22.5	48	1.6	1.2	OIL
22.5	48	1.55	0.8	OIL
22.5	50	1.6	0.85	OIL
22.5	45	1.55	1.1	OIL
22.5	45	1.5	1.05	OIL
22.5	47	1.5	1.2	OIL
22.5	45	1.5	1.0	OIL

AVE. BD VOLTAGE: 61.3 kV. TOTAL: 83.8 kV

Data of Figure 4.18: -ve dc Plus +ve Switching Impulses (dc level 3) (aged mineral oil)

Vacuum: 2-5x10^{-2} Torr, Temp.: 22-24°C, Ratio of Divider: 2588

1.0 cm GAP

DC (kV)	LT (mV)	BD VOLT (15V/div)	TIME (0.2ms/div)	NOTE
45	100	1.8	3.5	OIL
45	100	1.8	0.5	OIL
45	95	1.6	2.2	OIL
45	90	1.7	0.3	DAM
45	100	1.7	1.5	OIL
45	100	1.5	2.2	OIL
45	105	1.8	1.2	OIL
45	95	1.65	1.8	OIL
45	95	1.5	2.0	OIL
45	95	1.55	2.0	OIL

AVE. BD VOLTAGE: 64.4 kV TOTAL: 109.4 kV

0.75 cm GAP

DC (kV)	LT (mV)	BD VOLT (15V/div)	TIME (0.2ms/div)	NOTE
33.8	80	1.4	1.4	OIL
33.8	78	1.3	1.5	OIL
33.8	85	1.45	1.2	OIL
33.8	70	1.25	2.0	OIL
33.8	75	1.3	2.5	OIL
33.8	75	1.3	1.6	OIL
33.8	75	1.25	1.6	OIL
33.8	85	1.45	0.8	DAM
33.8	80	1.35	1.0	OIL
33.8	80	1.4	1.0	OIL

AVE. BD VOLTAGE: 52.2 kV TOTAL: 86.0 kV

0.5 cm GAP

DC (kV)	LT (mV)	BD VOLT (15V/div)	TIME (0.2ms/div)	NOTE
22.5	60	1.05	1.5	OIL
22.5	60	1.1	1.2	OIL
22.5	60	1.05	1.5	OIL
22.5	60	1.0	1.3	OIL
22.5	58	1.05	1.2	OIL
22.5	60	1.1	1.0	DAM
22.5	60	1.2	1.0	DAM
22.5	59	1.0	1.25	OIL
22.5	60	1.1	1.2	OIL
22.5	60	1.05	1.25	OIL

AVE. BD VOLTAGE: 41.5 kV. TOTAL: 64.0 kV