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DETERMINATION OF THRESHOLD AND MAXIMUM
OPERATING ELECTRIC STRESSES FOR SELECTED
HIGH VOLTAGE INSULATIONS

By
M. Sosnowski
G. S. Eager, Jr.

March 1984

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Cable Technology Laboratories, Inc.
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DETERMINATION OF THRESHOLD AND MAXIMUM
OPERATING ELECTRIC STRESSES FOR
SELECTED HIGH VOLTAGE INSULATIONS

(Task III - Investigation of High Voltage Capacitor Insulation)

DOE CONTRACT DE-AC02-80RA5056

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Prepared by: M. Sosnowski
G. S. Eager, Jr.

Approved by: C. Katz

March 1984

MASTER

CABLE TECHNOLOGY LABORATORIES, INC.

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1. SUMMARY

This report covers the investigation of threshold voltage of capacitor insulation. The experimental work was performed on samples prepared from commercial polypropylene insulated, liquid-filled capacitors. The samples were vacuum-impregnated with the original capacitor insulating liquid obtained from the manufacturer. A limited number of full-size capacitor elements also were tested.

Impulse voltage breakdown tests with dc voltage prestressing were performed at room temperature and 75°C. From the results of these tests, the threshold voltage of the samples of the capacitor insulation was determined at both temperatures and that of the whole capacitor elements at room temperature.

The threshold voltage of the capacitor insulation was found to be approximately equal to the impulse breakdown voltage. No difference was found between the threshold voltage at room temperature and at 75°C. The threshold voltage of the whole capacitor elements at room temperature was found to be equal to approximately 80% of the threshold voltage of the capacitor insulation samples.

2. INTRODUCTION

The threshold voltage stress is a very important parameter which characterizes electrical insulation. It defines the lowest voltage at which internal discharges appear in the insulation system.¹ These discharges cause degradation of the insulation which leads to breakdown. The difference between operating stress and threshold voltage stress determines the rate of aging and service life of the insulation system. The first study of threshold voltage in crosslinked polyethylene (XLPE) and ethylene propylene rubber (EPR) insulated cables² was performed at Cable Technology Laboratories (CTL) under the sponsorship of the Department of Energy (DOE). Since the first publications describing application of the concept of threshold voltage to high voltage cables,^{1,2} this approach has gained increasing acceptance.^{3,4}

The objective of the current DOE project being conducted at CTL is the verification of the existence of threshold voltage in selected high voltage insulation systems. A detailed investigation of threshold voltage levels and their relation to ac breakdown stress was conducted in Task I of the project on XLPE insulated cables having different dielectric strengths. The dielectric strength of the cables was varied by introducing artificial contaminants in the insulation. The technique, which was devised at CTL¹ permits the measurement of threshold voltage in relatively short time without necessity of performing long ac breakdown or endurance tests. This dual polarity test method utilizes impulse breakdown with opposite polarity dc prestressing. Threshold voltage determined with this

method was demonstrated to be equal to the threshold voltage level observed in voltage versus life time plot for XLPE insulated cable.²

Despite the growing use of polymeric insulations in power cables, paper-oil insulation is still widely used, particularly in cable systems of highest voltage rating. Investigation of this type of insulation was carried out in Task II of the project. The dual polarity measurements showed that the threshold voltage stress of pressurized paper-oil insulated model cables is approximately 2.5 times higher than the threshold voltage of XLPE cables.⁵ This fact can be understood in the light of the absence of gas voids in paper-oil insulated cable under normal operating conditions. Gas voids in polymeric insulation are the sites of discharges which appear at the threshold voltage stress. The discharges may appear also in paper-oil insulation at very high stress levels when formation of small gas bubbles and disintegration of oil can occur in the butt gaps. A characteristic feature of the paper-oil insulation is a small difference between the threshold voltage stress, as measured in the dual polarity method, and the impulse breakdown voltage stress.

Recently performed measurements of the ac breakdown voltage on pressurized oil-paper insulated model cables show that the ratio of 1 minute ac breakdown voltage to the ac threshold voltage is approximately 1.3. The same ratio for XLPE insulated cable at room temperature was found to be 2.8.²

Another type of laminar insulation in high voltage power systems is found in capacitors used for power factor correction in distribution lines. The most common capacitors installed today utilize polypropylene insulation impregnated with dielectric fluid. Investigation of the threshold voltage in such insulation, which is the subject of Task III of the project, is summarized in this report. Description of the capacitors used for testing is given in the following section. Preparation of samples, description of the test apparatus and the test procedure are given in Section 4. Impulse voltage test, impulse voltage with dc prestressing and ac breakdown tests were performed on the capacitor insulation samples. The results of these tests are given in Section 5. Discussion of the results and determination of threshold voltage is given in Section 6. Section 7 summarizes conclusions of this phase of the study.

3. SELECTION OF CAPACITORS

In selecting the capacitor insulation for this study, consideration was given to the fact that insulation studied should be currently available and widely used by the power industry. After consultation with several capacitor manufacturers and utilities, capacitors with polypropylene insulation were selected. Older type paper-insulated capacitors with dielectric liquid containing polychlorinated biphenyls (PCB) are no longer manufactured and their use is restricted due to the environmental hazard. The selected capacitor had rated voltage of 2400 V at 60 Hz and its nominal Basic Impulse Level (BIL) was 75 kV. The capacitor is made of a number of elements (books) consisting of long sheets of polypropylene sandwiched between two layers of aluminum foil and rolled into a compact packet. There are two sheets of polypropylene between the two aluminum foils which form electrodes of the element. The electrodes of different elements are connected in a mixed parallel and series circuit to obtain the rated voltage and capacitance of the assembly. All elements are tightly packed in a steel can which is connected to the ground electrode of the assembly. The other electrode is connected to the high voltage lead in a ceramic bushing. The steel container and the bushing are filled with the insulating liquid.

The dielectric liquid has a lower viscosity at room temperature and a higher vapor pressure than oils used for impregnating paper insulated

cables and transformers. More detailed information concerning the insulation and composition of the dielectric liquid was not available as the manufacturer considered it proprietary. The thickness of the polypropylene layer measured with a micrometer was approximately 0.03 mm (1 mil). The thickness of the aluminum foil was determined by a weighting method at 0.015 mm (0.5 mil). The aluminum foil was embossed.

4. TEST PROCEDURE

4.1 Preparation of Samples

Two types of test samples were prepared from the capacitor elements. Sample type A was prepared from a part of the capacitor section. It had a small electrode area and its capacitance was approximately 5nF. Samples type A were used in most measurements of threshold voltage and in ac breakdown tests. Sample type B utilized a whole section of the capacitor. Its capacitance was approximately 2 μ F. These samples were used for verification of the threshold voltage level obtained with samples type A.

The procedure of preparation of samples for testing consisted of the following steps:

1. The steel can of a new capacitor was cut open and capacitor elements disconnected and removed.

Sample Type A - The insulating material, together with aluminum electrode foils, was unfolded and cut into strips. Two aluminum strips 36 cm long and 3 cm wide and four polypropylene strips 37 cm long and 5 cm wide were used to prepare one sample. The cut material was wound on a solid nylon cylinder 4.5 cm in diameter. The two aluminum foils were insulated from each other by two layers of polypropylene. Nominal thickness of the insulation was 2 mils. Greater width of the insulating strips assured good separation of the aluminum foil edges. The cylinder was mounted in the test vessel equipped with a high voltage electrode supported by a ceramic bushing. One of the aluminum foils was connected to the high voltage electrode and the other to the metal body of the test chamber. The test chamber with the high voltage bushing (See Fig. 1) was vacuum tight.

Sample Type B - A whole element (book) removed from the capacitor can was placed in a steel cylinder equipped with a high voltage bushing. One of the leads of the capacitor electrode was connected to the body of the cylinder; the other lead to the bushing electrode. The

Figure 1

Chamber for Testing Capacitor Insulation

aluminum electrodes of this sample had dimensions 34.3 cm by 12 m. The sheets of the polypropylene between the electrodes measured 38.1 cm by 12 m. The nominal thickness of the insulation was 2 mils, the same as in Sample Type A.

2. The test chamber was evacuated through a valve at its top, connected by a hose to a mechanical vacuum pump. The chamber was heated to 90°C to facilitate outgassing and drying of the sample. The elevated temperature and the vacuum were maintained for a minimum of 5 hours.
3. After drying and degassing, the impregnating liquid was transferred under vacuum to the test chamber. The impregnating liquid, obtained from the capacitor manufacturer, was the same as used originally in the capacitor. Upon completion of the transfer of the liquid, the pressure in the test vessel was equalized with the ambient atmosphere.

4.2 Threshold Voltage Test

The threshold voltage test of capacitor insulation was conducted according to the procedure established for cable threshold voltage measurements.^{1,2} This procedure consisted of impulse breakdown and impulse breakdown with opposite polarity dc prestressing. The main difference between the test set-up for cables and for capacitor insulation was in the termination of the samples. While resistive termination was used for the cable impulse test, a ceramic oil-filled bushing provided both impulse and dc terminations for capacitor insulation samples. This arrangement was possible due to a relatively low breakdown voltage of the capacitor samples. A schematic of the test circuit is shown in Figure 2.

Standard impulses (1.2/50 μ s) were obtained from a specially arranged one-stage 150 kV impulse generator. The impulse wave shape was monitored with an oscilloscope while the impulse amplitude was measured with a peak memory voltmeter connected to the sample through a 1:10000 resistive voltage divider. Initially an impulse voltage equal to one-half of the expected breakdown voltage value was applied to the sample. This was followed by one impulse at each voltage level which was increased in 10% steps until breakdown. In impulse tests with dc prestressing, the dc voltage (opposite in polarity to the impulse) was applied for approximately one minute before the first impulse. Most of the tests were performed on samples type A at room temperature and at 75°C. The results were verified on a number of samples type B at room temperature.

Figure 2
Test Circuit for Threshold Voltage Measurement
of Capacitor Insulation

C - Capacitor; M.V. - Memory Voltmeter; O - Oscilloscope;
 R_f - Front Resistor; R_1 , R_2 - Voltage Divider; S - Sample Under Test

4.3 AC Breakdown Test

AC breakdown tests were performed on samples type A only since the very large capacitance of samples type B caused excessive current drain from the test power supply. The 60 Hz voltage was increased in 10% steps starting from one-half of the expected breakdown voltage level. Two sets of tests were performed, one with one minute and one with thirty minutes voltage application at each level. The measurements were performed at room temperature.

5. RESULTS OF BREAKDOWN TESTS

5.1 Impulse Breakdown Voltage with DC Voltage Prestressing (Sample A)

The results of impulse breakdown tests, with various dc prestressing voltage levels, performed at room temperature and at 75°C are given in Table 1 and Table 2, respectively. The sample number gives its order in a sequence of preparation from the capacitor and testing which is not related to the sequence of increasing dc prestressing voltage levels. The procedure minimizes the influence of a possible change of the insulation with time (after opening of the capacitor) on the measured dependence of the impulse breakdown voltage (V_{imp}) on the dc prestressing voltage (V_{dc}). The relation between the impulse breakdown voltage and the dc prestressing voltage is illustrated in Figure 3.

Table 1

DUAL POLARITY IMPULSE BREAKDOWN TEST
FOR CAPACITOR INSULATION AT ROOM TEMPERATURE

(Samples Type A)

Sample Number	V _{dc} DC Prestressing Voltage kV	V _{dp} Dual Polarity Impulse Voltage kV	V _{imp} Impulse Breakdown
C1	0.0	17.2	17.2
C3	0.0	17.2	17.2
C6	0.0	15.7	15.7
C7	0.0	17.2	17.2
C15	0.0	17.2	17.2
C28	0.0	15.7	15.7
C10	6.3	24.7	18.4
C25	6.3	24.7	18.4
C2	10.5	32.2	21.7
C14	10.5	27.7	17.2
C24	10.5	32.2	21.7
C27	10.5	23.2	12.7
C32	10.5	29.2	18.2
C12	12.6	27.7	15.1
C13	12.6	24.7	12.1
C34	12.6	32.2	19.6
C35	12.6	33.7	21.1
C4	16.8	30.7	13.9
C19	16.8	29.2	12.4
C22	18.9	30.7	11.8
C23	18.9	21.7	2.8
C30	18.9	24.7	5.8
C5	21.0	17.2	-3.7
C9	21.0	14.2	-6.7

Table 2

DUAL POLARITY IMPULSE BREAKDOWN TEST
FOR CAPACITOR INSULATION AT 75°C

(Samples Type A)

Sample Number	V _{dc} DC Prestressing Voltage kV	V _{dp} Dual Polarity Impulse Voltage kV	V _{imp} Impulse Breakdown Voltage kV
C36	0	17.2	17.2
C42	0	15.7	15.7
C51	0	15.7	15.7
C41	6.3	26.2	19.9
C37	10.5	30.7	20.2
C40	12.6	32.2	19.6
C44	14.7	30.7	16.0
C48	14.7	33.7	19.0
C45	16.8	30.7	13.9
C49	16.8	35.2	18.4
C52	16.8	32.2	15.4
C55	16.8	29.2	12.4
C50	18.9	12.7	-6.2
C53	18.9	11.2	-7.7
C54	18.9	0*	----
C56	18.9	11.2	-7.7

*Breakdown occurred under dc voltage, without impulse.

Figure 3

Voltage Waveform in Threshold Voltage Test

V_{dc} - dc prestressing voltage; V_{imp} - impulse voltage

V_{dp} - dual polarity impulse voltage

The numbers of samples tested at different dc voltage levels were not the same. They were selected to maximize the relevant information from the limited number of tests. More samples were tested for dc voltage levels relevant to establishing the threshold voltage.

The data obtained with a given dc prestressing voltage were averaged and are shown in Table 3 and 4 for the two temperatures. The results presented in these tables are given also in terms of the average voltage stresses E_{dc} and E_{imp} , calculated for the nominal insulation thickness of 2 mils. The graphs presented in Figures 4 and 5, for room temperature and 75°C, respectively, show the relation between the impulse breakdown voltage stress and the dc voltage stress. The dashed lines in these figures show the impulse breakdown voltage stress level (for $E_{dc} = 0$), while the dotted lines represent the trend of the decreasing impulse breakdown stress above the threshold level. These graphs were used for establishing the threshold voltage stress of the capacitor insulation.

Table 3

DETERMINATION OF THRESHOLD VOLTAGE
FOR CAPACITOR INSULATION AT ROOM TEMPERATURE

V_{dc} DC Voltage Prestressing kV	E_{dc} DC Voltage Stress V/mil	V_{dp} Dual Polarity Impulse Voltage kV	V_{imp} Impulse Breakdown Voltage kV	E_{imp} Impulse Breakdown Voltage Stress V/mil
0	0	16.7	16.7	8350
6.3	3150	24.7	18.4	9200
10.5	5250	28.9	18.4	9200
12.6	6300	29.6	17.0	8500
16.8	8400	30.0	13.2	6600
18.9	9450	25.7	6.8	3400
21.0	10500	15.7	-5.3	-2650

Table 4

DETERMINATION OF THRESHOLD VOLTAGE
FOR CAPACITOR INSULATION AT 75°C

V_{dc} DC Voltage Prestressing kV	E_{dc} DC Voltage Stress V/mil	V_{dp} Dual Polarity Impulse Voltage kV	V_{imp} Impulse Breakdown Voltage kV	E_{imp} Impulse Breakdown Voltage Stress V/mil
0	0	16.2	16.2	8100
6.3	3150	26.2	19.9	9950
10.5	5250	30.7	20.2	10100
12.6	6300	32.2	19.6	9800
14.7	7350	32.2	17.5	8750
16.8	8400	31.9	15.1	7550
18.9	9450	11.7	-7.2	-3600

Figure 4
Determination of Threshold Voltage Stress
For Capacitor Insulation at Room Temperature

Figure 5
Determination of Threshold Voltage Stress
For Capacitor Insulation at 75°C

5.2 Testing of Capacitor Elements (Sample B)

Capacitor elements (books) are the building blocks of a capacitor. While Sample A contained a modified section of the capacitor element, Sample B contained a whole element as prepared in the factory.

Electrical testing of the capacitor elements (Sample B) was complicated by their large capacitance. The measured capacitance of Sample B was approximately $2\mu\text{F}$, a value which is poorly matched to the impedance of a high voltage impulse generator providing standard $1.2/50\mu\text{s}$ wave shape. Therefore, the dual polarity breakdown test on samples type B was performed using impulse wave shape with short rise time and duration. A test circuit, as in Figure 2, but without resistor R_f , was used. The resulting impulse had a very short rise time ($< 1\mu\text{s}$) and the amplitude and the wave form of the voltage on the sample was defined by the distributed impedance of the test circuit elements and the sample. The amplitude of the voltage on the sample was proportional to the generator voltage measured with the resistive voltage divider (R_1, R_2 in Fig. 2). The data obtained in the test are given in terms of the impulse generator nominal voltage in Table 5.

Since the impulse voltage on the sample is proportional to the generator voltage, approximate calibration of the data can be made by

Table 5

DUAL POLARITY IMPULSE BREAKDOWN TEST
ON CAPACITOR ELEMENTS AT ROOM TEMPERATURE

Sample Number	V _{dc} DC Prestressing Voltage kV	Impulse Generator Nominal Voltage kV
CB2	16.8	*
CB3	14.7	*
CB5	12.6	240
CB6	10.5	240
CB7	8.4	144
CB8	0.0	120
CB9	8.4	240
CB10	0.0	144
CB11	10.5	216
CB12	12.6	216

*Breakdown occurred after applying dc voltage for less than 10 seconds.

assuming that the impulse breakdown voltage of the capacitor insulation is proportional to its threshold voltage. Such proportionality has been found for XLPE insulation.² The impulse breakdown voltage of Samples A can then be related to be the impulse breakdown voltage of Samples B through equation:

$$V_{ib}^B = \frac{V_{ib}^A}{V_t^A} V_t^B \quad (1)$$

where V_{ib}^A and V_{ib}^B are the impulse breakdown voltages (for $V_{dc} = 0$) while V_t^A and V_t^B are the threshold voltages of Samples A and B, respectively. The value V_t^A determined from Figure 4 is 16.5 kV and is nearly equal to the value of V_{ib}^A (16.7 kV) given in Table 3. The difference between these quantities is within the experimental error. Since the threshold voltage is equal to the impulse breakdown voltage of Samples A, the same is true from eq. (1) for Samples B. The threshold voltage of Samples B can be estimated from the data of Table 5. It has to be smaller than the dc breakdown voltage (14.7 kV for Sample CB3) but should be greater than 12.6 kV, the dc prestress voltage of Sample CB5 which breaks down at relatively high generator voltage of 240 kV.

The average value of these two dc voltage levels, equal to 13.6 kV, was chosen as the estimated threshold voltage. Further verification of this choice is made by plotting the data of Table 5 on a graph similar

to that of Figure 4 to establish if they follow the dependence of E_{imp} on E_{dc} characterized by the estimated threshold level.

From eq. (1) and the above estimate of the threshold voltage, V_{ib}^V also equals to 13.6 kV while other values of dual polarity impulse breakdown V_{ip} may be obtained from the relation:

$$V_{dp} = V_{ib}^B \frac{V_G}{V_G^0} \quad (2)$$

where V_G is the impulse generator nominal voltage for a given V_{dc} prestressing while V_G^0 is the generator nominal voltage at breakdown for $V_{dc} = 0$. From Table 5, by averaging the impulse generator voltages at breakdown of Sample CB8 and CB10, one obtains $V_G^0 = 132$ kV. Eq. (2) expresses the fact that the amplitude of the voltage on the sample is proportional to the generator nominal voltage.

Data of Table 5 averaged for each prestressing voltage V_{dc} and normalized according to eq. (2) with $V_{ib}^B = 13.5$ kV are presented in Table 6. The average voltage stress was calculated for the nominal insulation thickness of 2 mils. These data are plotted in Figure 6. The shaded area in this figure shows the region of uncertainty where the impulse voltage decreases as the prestressing voltage exceeds the threshold level. Figure 6 shows that within the uncertainties originating from the scatter of the data points, the value of threshold voltage stress of 6.8 kV/mil is consistent with the results of the dual polarity measurements.

Table 6

DETERMINATION OF THRESHOLD VOLTAGE FOR CAPACITOR ELEMENTS

V_{dc} DC Voltage Prestressing kV	E_{dc} DC Voltage Stress V/mil	V_c Impulse Generator Nominal Voltage kV	V_{dp} Dual Polarity Impulse Voltage kV	V_{imp} Impulse Breakdown Voltage kV	E_{imp} Impulse Breakdown Voltage Stress V/mil
0	0	132	13.6	13.6	6800
8.4	4200	192	19.8	11.4	5700
10.5	5250	228	23.5	13.0	6500
12.6	6300	228	23.5	10.9	5450
14.7	7350	0	0	*	----
16.8	8400	0	0	*	----

*Breakdown under dc voltage

Figure 6

Determination of Threshold Voltage Stress
For Capacitor Elements at Room Temperature

5.3 AC Breakdown Voltage Test

Two ac breakdown voltage tests were performed on samples of capacitor insulation. In one test the voltage was increased in 1 kV steps and maintained at each level for one minute. In the second test, the voltage was increased in 0.5 kV steps and maintained at each level for 30 minutes. In both tests, the voltage frequency was 60 Hz. Results of the ac breakdown voltage tests with one minute and 30 minute voltage duration are presented in Table 7 and 8, respectively. The Weibull plots of the data are given in Figures 7 and 8. The breakdown voltage values corresponding to the 50% probability derived from these plots are 7.2 kV for 1 minute voltage duration test and 4.7 kV for the 30 minute duration test. The average breakdown voltage stress values are 3600 V/mil and 2350 V/mil for 1 minute and 30 minutes test, respectively.

Table 7

AC BREAKDOWN VOLTAGE TEST
FOR CAPACITOR INSULATIONS AT ROOM TEMPERATURE
(1 Minute Schedule)

Sample Number	Breakdown Voltage kV	Breakdown Voltage Stress V/Mil	Time at Breakdown Voltage Seconds
A1	11.0	5500	1
A2	7.0	3500	1
A3	8.0	4000	10
A4	5.0	2500	15
A5	7.0	3500	20
A6	6.0	3000	24

Table 8

AC BREAKDOWN VOLTAGE TEST
FOR CAPACITOR INSULATION AT ROOM TEMPERATURE
(30 Minute Schedule)

Sample Number	Breakdown Voltage kV	Breakdown Voltage Stress V/mil	Time at Breakdown Voltage Minutes .
A7	4.0	2000	1
A8	4.5	2250	15
A9	5.0	2500	12
A10	4.5	2250	24
A11	5.0	2500	18
A12	5.0	2500	14
A13	6.0	3000	4
A14	5.5	2750	5
A15	4.5	2250	6
A16	3.0	1500	0.1

Figure 7
Weibull Probability Distribution for AC (1 Minute)
Breakdown Voltage of Capacitor Insulation

Figure 8
Weibull Probability Distribution for AC (30 Minutes)
Breakdown Voltage Test of Capacitor Insulation

5.4 Results of the Examination of Capacitor Insulation Samples After Breakdown Test

After every breakdown test, the insulation sample was removed from the test chamber and examined. A failure point was easily recognizable. The breakdown punctured all layers of insulations as well as the aluminum foil electrodes. Most failures were located on the edge of the electrodes. This was expected as the electric field lines are concentrated at the conductor discontinuity. Some failures, however, occurred in the middle of the foils. Examination of the surface of the aluminum electrodes revealed numerous small wrinkles. Intensification of the electric field on the uneven electrode surface must be responsible for some of the failure points located away from the foil edges. A photograph of three capacitor insulation samples, after unrolling of the foils, is shown in Figure 9. Different locations of the failure points can be seen.

In samples Type B, most of the failure points were located not on the foil edges but in the middle of the foils. This is not suprising since the ratio of the electrode area to the length of the edge is much larger in Samples B and the foils in the capacitor elements were not as smooth as were the foils wound on a cylindrical mandrel in Samples A.

Figure 9

Three Samples of Capacitor Insulation after Breakdown Test

6. DISCUSSION

The data presented in 5.1 show that the tested capacitor insulation exhibits the familiar dependence of impulse breakdown voltage on the dc voltage prestressing found in other insulation systems. The impulse breakdown voltage is almost constant with the increasing dc voltage up to a certain threshold level above which the impulse breakdown voltage decreases with the dc voltage. There is particularly strong resemblance between Figure 4 and a similar plot for oil-filled paper-insulated cables.⁵ High value of the dc voltage at which the impulse breakdown voltage begins to fall appears to be the characteristic feature of laminar insulation systems impregnated with liquid dielectric. For pressurized oil-filled paper-insulated cables, the ratio between the threshold voltage determined by the dual polarity method and the impulse breakdown voltage was found to be 0.8. From the data given in Tables 3 and 4 and plotted in Figures 4 and 5, this ratio for the capacitor insulation is approximately 1. By contrast, the measurements of Task 1 of this project demonstrated that for crosslinked polyethylene insulated cables the same ratio is only 0.3.

This large difference between the ratios of threshold voltage determined by dual polarity method to impulse breakdown voltage reflects the physical difference between the laminar and solid insulation systems. The so called solid insulation contains not only the solid dielectric but also gas in numerous voids found in extruded polymeric material. The presence of the gas voids plays an essential role in the breakdown process of the solid insulation. According to the model

of electrical breakdown and aging developed in the earlier DOE study,¹ the gas discharge inside the voids initiates the process of electrical degradation of the insulation which leads to a failure. The threshold voltage is the inception voltage of the gas discharge. The electric charge transferred in the discharges in the microscopic voids is very small, below the sensitivity of the existing partial discharge detectors. The dual polarity impulse breakdown method was designed to overcome this problem. It consists of application of the prestressing voltage, usually in the form of dc voltage followed by an impulse voltage of opposite polarity. If the prestressing voltage is below the threshold level, it does not have an effect on the impulse voltage at which the insulation breaks down (V_{imp} in Fig. 3). If, however, the prestressing voltage exceeds the threshold voltage, it generates discharge inside the insulation voids and the generated charge lowers the voltage level at which the subsequent impulse of opposite polarity breaks down the insulation. On the V_{imp} versus V_{dc} graph (Figs. 3 and 4), the threshold voltage is found as the abscissa of the point of the intersection of two lines approximating the trend of the data.

In laminar insulation systems properly impregnated with dielectric liquid, there should be no gas voids prior to the voltage application. They may appear, however, at very high electric stress (eg in the butt gaps of the paper-insulated cable) when the breakdown of dielectric liquid occurs. Electrical, thermal and chemical breakdown of the dielectric liquid, followed by breakdown of the laminate, leads to the failure of

the whole insulation system. From the data on paper-insulated cable⁵ and particularly the data of Section 5 of this report on the capacitor insulation, it appears that the dc prestressing does not affect the laminar insulation until a high dc voltage level, equal to the impulse breakdown voltage (without dc prestressing), is approached. At such a high dc voltage level, the insulation is in a pre-breakdown state, in which forming of gas bubbles in the insulating liquid may be initiated. A further increase of the voltage above this level leads to a failure. By contrast, extruded polymeric insulation can withstand dc or impulse voltage exceeding more than twice its threshold voltage level.

While the tested capacitor insulation and pressurized paper-oil cable insulation belong to the laminar type of insulations, the differences between them are significant. The components of the two insulation systems have different chemical composition. Also, the tested paper-oil impregnated cable was pressurized while the capacitor insulation was subjected only to atmospheric pressure. These differences lead to different electrical properties of the two insulation systems. While comparing the dielectric strengths of the two insulations based on the obtained data, one should bear in mind the difference in thickness of the tested materials. The insulation wall thickness of the tested paper cable⁵ was 1.4 mm (56 mils) while the capacitor

insulation had only two layers of 1 mil thick film. The impulse breakdown voltage of the paper cable at room temperature was 168 kV which corresponds to a stress of 3000 V/mil. The impulse breakdown voltage of the capacitor insulation (Table 3) is 16.7 kV which corresponds to 8000 V/mil. The apparent great difference in the impulse breakdown stress of the two materials can be explained by the well-known increase in breakdown voltage stress for thin insulation layers.

There is also a significant difference in the construction of the paper-insulated cable and of the capacitor samples. Critical areas of high electric stress in the cable are the butt gaps. There are no butt gaps in the capacitors but the electric field is intensified at the edges of the aluminum foil electrodes. Also, numerous wrinkles in the middle of the aluminum electrode area were observed, particularly in the case of Samples B.

A characteristic feature of the plots in Figures 4 and 5 is the existence of data points corresponding to negative V_{imp} values. It can be seen from Figure 3 that:

$$V_{imp} = V_{dp} - V_{dc} \quad (3)$$

The V_{imp} becomes negative when the dc voltage V_{dc} exceeds the V_{dp} . In these cases the insulation is able to withstand certain dc voltage, but breaks down under the impulse voltage of opposite polarity which is below the dc voltage level. This occurs when the dc voltage is above the threshold voltage and just below the dc breakdown voltage.

It is apparent that in this range of the prestressing voltage, the gas bubbles form and persist in the low pressure dielectric liquid. There may not be many new discharges in the bubbles under the dc voltage alone but a voltage impulse, even lower in amplitude than the dc voltage, generates more discharges and precipitates the system failure. It is probable that at the dc voltage levels at which the impulse breakdown voltage V_{imp} is negative, the insulation would fail if the dc voltage was maintained for a long time.

Another feature of the capacitor insulation data is the small difference in the impulse breakdown voltage at room temperature and at 75°C. The difference in the values for $E_{dc} = 0$, given in Tables 3 and 4, is not larger than the experimental errors. The levels of impulse breakdown voltage stress for zero dc prestressing are represented by the dashed lines in Figures 4 and 5 for ambient temperature and 75°C, respectively. Some data points, particularly at $E_{dc} = 3150$ V/mil and $E_{dc} = 5250$ V/mil at 75°C, are above these levels. Statistical scatter may be responsible for this anomaly.

There is, however, a significant difference between the data obtained at the two temperatures at high prestressing voltage. The impulse breakdown voltage stress at 75°C drops sharply for $E_{dc} > 8500$ V/mil and the value of the impulse breakdown voltage is negative at $E_{dc} = 9450$ V/mil. This voltage stress is very close to the dc breakdown voltage stress as seen from the result of testing sample C54 (Table 2). By comparison

at room temperature, the impulse breakdown voltage stress becomes negative at 1000 V/mil higher dc voltage stress and no dc breakdown occurs up to the voltage stress of 10500 v/mil. It is clear from the comparison of Figures 4 and 5 that the slope of the falling part of the E_{imp} versus E_{dc} graph is steeper at the elevated temperature. Once the threshold voltage is exceeded, further increase in the dc voltage has greater effect at higher temperature. This is consistent with formation of gas bubbles in the dielectric liquid preceeding the failure. Despite the difference of the slopes in the plots of Figures 4 and 5, and the lower dc breakdown voltage at 75°C, no difference in the threshold voltage level at the two temperatures can be discerned. It may well be that the representation of the trend in the data points in Figures 4 and 5 by two straight dotted lines is an oversimplification and that the dependence of the impulse voltage on the dc prestressing voltage should be described by a more complex function. Still, the sharp drop in the impulse breakdown voltage stress, after the prestressing voltage exceeds the threshold level, remains the main feature of this relation. The threshold voltage level for Samples A was established at 16.5 kV, corresponding to a voltage stress of 8250 V/mil.

For full-size capacitor elements (Samples B), only an approximate determination of threshold voltage was possible. The shaded area in Figure 6 covers the region where the E_{imp} versus E_{dc} function drops from a high level equal to the impulse voltage (for $E_{dc} = 0$) to zero.

The threshold voltage stress value lies in the interval defined by the intersection of the shaded area with the E_{dc} axis and was estimated at 6800 ± 500 V/mil. Both the impulse breakdown voltage stress and threshold voltage stress are lower for Samples B and equal to approximately 80% of the values for Samples A. This can be explained by the fact that Samples A were prepared by careful winding of the insulation and electrode layers on a smooth cylindrical mandrel while Samples B had wrinkles and creases in the electrodes and insulating foils. Also, the area of the electrodes was much larger in the case of Samples B.

The results of ac breakdown tests performed at room temperature are shown in the form of Weibull distributions in Figures 7 and 8. The breakdown voltage stresses corresponding to the 50% breakdown probability obtained in 1 minute and 30 minutes ac tests are 3600 V/mil and 2350 V/mil, respectively. These are surprisingly low values in comparison with the dc threshold voltage stress measured with dual polarity impulse breakdown method. If $V_t^{(dc)}$ is the dc threshold voltage as measured in the dual polarity impulse breakdown method while $V_t^{(ac)}$ is the ac threshold voltage expressed as r.m.s. value, then:

$$V_t^{(ac)} = \frac{V_t^{(dc)}}{2\sqrt{2}} \quad (4)$$

From the dc threshold voltage stress of the capacitor insulation measured with dual polarity impulse method at 8250 V/mil, the value of $V_t^{(ac)} = 2920$ V/mil, is obtained from equation (4). The ratio of the one minute ac breakdown voltage stress to this threshold level is only 1.2, while for XLPE insulation this ratio was approximately 3. More importantly, the 30 minute ac breakdown voltage stress which equals 2350 V/mil is below this threshold level. There is a contradiction in this relation since, by definition, no electrical aging or breakdown should occur below the threshold level.

An explanation of the observed ac breakdown voltage stress in relation to the dc threshold voltage stress may involve the difference in the mechanism of impulse breakdown and the ac voltage aging. This difference is most probably related to the physical phenomena occurring in the liquid component of the laminar insulation during voltage application. If the breakdown progresses through the phase of gas bubble development, the time of the voltage application may have great influence on the breakdown voltage. Even at relatively low voltage stresses, the growth of gas bubbles may progress at a slow rate, particularly in low pressure systems such as a capacitor. This may lead to a breakdown after application of large number of cycles of ac voltage at relatively low level. By contrast, during application of pulsed voltage of short duration, there is not enough time for development of gas bubbles and, consequently, the breakdown voltage is high.

The relation between ac breakdown voltage and the threshold voltage determined with the dual polarity impulse method should be studied further.

7. CONCLUSIONS

- The dependence of impulse breakdown voltage on the dc prestressing voltage for capacitor insulation is similar to the same relation found for paper-oil impregnated cables.
- The threshold voltage of the tested capacitor insulation is approximately equal to its impulse breakdown voltage.
- No change of impulse breakdown voltage and threshold voltage was observed for the tested capacitor insulation when its temperature was increased from room temperature to 75°C.
- Threshold voltage of whole capacitor elements was found to be equal to approximately 80% of the threshold voltage of small samples prepared from smooth insulation and electrode material of the capacitors.
- AC breakdown tests indicate that phenomena, other than those associated with the dc threshold voltage, are important in the ac breakdown mechanism of liquid impregnated laminar insulation system under low pressure.

8. REFERENCES

1. G. Bahder, T. Garrity, M. Sosnowski, R. Eaton, C. Katz, "Physical Model of Electric Aging and Breakdown of Extruded Polymeric Insulated Power Cables". IEEE Transaction of Power Apparatus and Systems PAS 101, June 1982, pp 1379-1390.
2. G. Bahder, M. Sosnowski, C. Katz, R. Eaton, K. Klein, "Electrical Breakdown Characteristics and Testing of High Voltage XLPE and EPR Insulated Cables". IEEE Transaction on Power Apparatus and Systems, Vol. PAS 102, No. 7, July 1983, pp 2173-2185.
3. T. W. Dakin, "Theory of Voltage Endurance". Paper S-1 presented at the Conference on Electrical Insulation and Dielectric Phenomena, Poconos, October 1983.
4. Simoni et al., "Voltage Endurance of XLPE Insulated Cable Models", paper B2, presented at the 1984 IEEE International Symposium on Electrical Insulation, Montreal, June 1984.
5. "Determination of Threshold and Maximum Operating Electrical Stress for Selected High Voltage Insulations", Progress Report No. 3, June 1983.

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