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PARTIAL DISCHARGE INCEPTION AND BREAKDOWN STUDIES ON MODEL SHEET-WOUND, COMPRESSED SF_6 GAS-IMPREGNATED, POLYMER FILM-INSULATED WINDINGS

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ABSTRACT

As part of a program funded by the United States Department of Energy and New York State ERDA covering an investigation of advanced concepts for gas-insulated power transformers, experimental studies have been made on model turn-to-turn insulation structures comprised of sheet aluminum conductors insulated with two sheets of polymer film and impregnated with compressed SF_6 gas. Precautions were taken to eliminate particles using electrostatic techniques during winding of the models. Partial discharge inception and breakdown measurements have been made at 60 Hz applied voltages and room temperature; the effect of polymer film thickness has been investigated.

INTRODUCTION

A program funded by the United States Department of Energy and New York State ERDA has been addressing the following concepts for a gas-insulated power transformer (1):

- Sheet aluminum conductors for the windings.
- Polymer film* turn-to-turn insulation.
- A system of sealed, self-contained, annular cooling ducts containing circulating fluid to cool the windings.
- Compressed gas insulation (which fills the space in the film-insulated windings and also insulates all the major gaps).

*The polymer film used throughout these investigations has been the polyethylene terephthallate (polyester) film, Mylar[R] ([R] Registered trademark of the E.I. du Pont de Nemours and Co.). Whether Mylar or some other polymer film will provide optimum performance under the combined electrical, mechanical and thermal requirements of this application will be determined in future studies of these technologies.

As part of this program, a study of the dielectric strength performance of the proposed turn-to-turn insulation system -- polymer film impregnated with SF_6 gas-- was made using a test coil built on a new winding apparatus incorporating features to minimize the air space within the winding and to eliminate the presence of foreign particles. Comparisons were made of the partial discharge inception and breakdown voltage at 60 Hz applied voltages of model samples wound concentrically on the test coil using two sheets of 0.0125 mm thick polymer film as the "turn-to-turn" insulation and samples wound with two sheets of 0.0233 mm polymer film.

EXPERIMENTAL

Coil Construction

The test coil consisted of two sets of "capacitor type" samples wound concentrically onto a fiberglass-reinforced epoxy cylinder, approximately 50.8 cm O.D. and 1.9 cm wall thickness. Each of the samples was constructed by winding a six layer sandwich (Fig. 1): aluminum sheet (the high voltage electrode), two layers of polymer film, aluminum sheet (the ground electrode), then finally two more layers of polymer film.

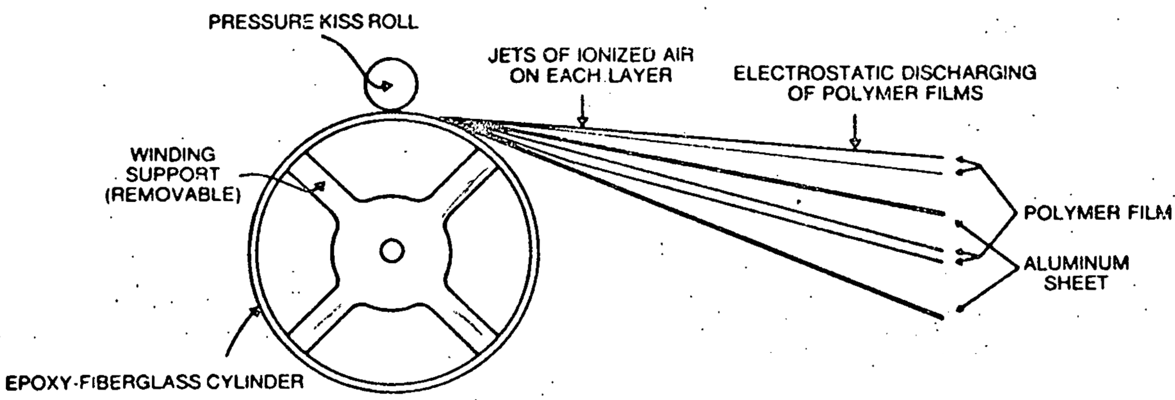

Fig. 1. Schematic drawing of the winding of a "capacitor type" test sample

Winding of the coil was performed on the apparatus shown in Fig. 2. In order to minimize the air space within the winding, the coil was wound under tension using a combination of electromagnetic brakes, to apply tension to the sheet aluminum conductor, and a 12.7 cm-diameter pressure kiss roll, which exerted several hundred pounds force at the point of contact between the webs of aluminum sheet and polymer film and the epoxy-fiberglass cylinder. Stringent precautions were taken during the winding to eliminate particles from being introduced into the capacitor samples: As each sheet of film was unwound from its supply roll it was discharged using either a polonium γ-source or a corona charge generator; then, jets of ionized air were directed over both the aluminum sheet and polymer film webs to blow off any particles. Twelve test samples were constructed as follows:

- Six samples (#s 1-6) constructed with 5 turns of 0.076 mm thick, 61 cm wide aluminum sheet + 2 layers of 0.0125 mm thick, 62.5 cm wide polymer film.
- Six samples (#s 7-12) constructed with 5 turns of 0.076 mm thick, 61 cm wide aluminum sheet + 2 layers of 0.0233 mm thick, 62.5 cm wide polymer film.

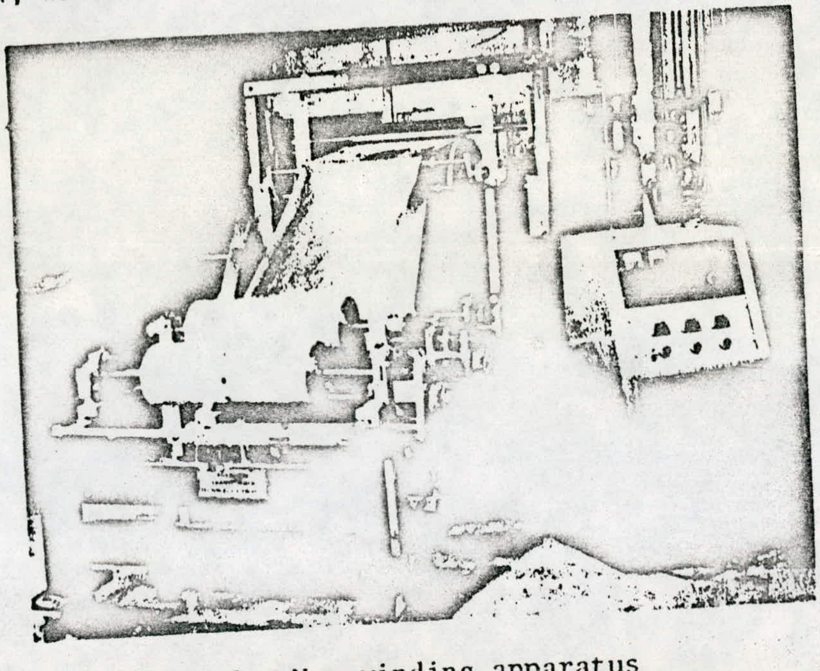

Fig. 2. New winding apparatus

The leads were 5.1 cm wide, 0.076 mm thick aluminum, attached at the start of each conductor. Additional layers of 0.05 mm polymer film were employed over the leads at the start of the test coil and between conductors at the finish. To prevent breakdown damage in a given sample from affecting its neighbors, protective pads of "buffer" insulation, each comprised of eight layers of 0.127 mm polymer film, were wound between successive capacitor samples.

In both sets of six samples, 5 turns were wound for each sample: the approximate capacitance of samples #1-6 was 12 μF, that of samples #7-12 was 6 μF. The area of dielectric material under electric stress was ~16 m^2. A schematic drawing of the finished coil is shown in Fig. 3.

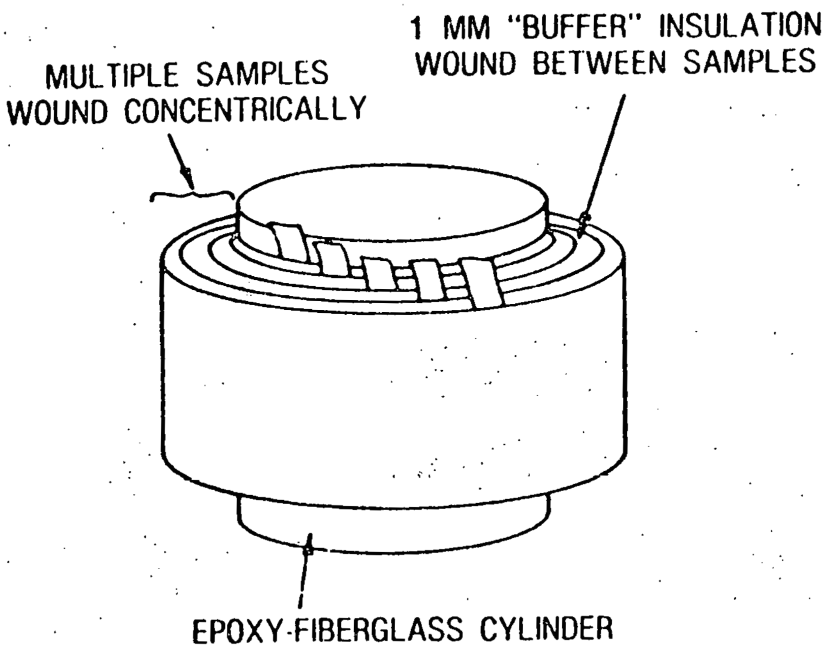

Fig. 3. Schematic drawing of dielectric test coil

Test Procedure

After assembly (Fig. 4), the test coil was installed in a pressure vessel. Specially-shaped connectors, seen in Fig. 3, were constructed in order to provide corona-free connections between the sheet aluminum taps from the capacitor samples and the 3.2 mm O.D. tubing leads used to make contact with the pressure vessel bushings. Connections to six capacitor samples were made simultaneously through these bushings so that the pressure vessel needed to be opened only three times in testing all twelve samples.

After the test coil was mounted in the test vessel and the six bushing connections were made, the vessel was sealed and evacuated to a pressure of less than 100 μm for at least 24 hours. The time required to reach this pressure level varied considerably in subsequent test vessel evacuations, and seemed to depend on both the initial state of the test coil and the pumping apparatus and procedure. The 24-hour period under vacuum was necessary to insure that impurities and moisture has been removed from the capacitor samples before back-filling with SF_6.

After the period of evacuation, the vessel was filled with SF_6 to a pressure of 6 atm abs and the samples were allowed to impregnate in this condition for at least 48 hours prior to testing. The test circuit shown in Fig. 5 was developed for making partial discharge and breakdown measurements. The elements of the circuit included a large kVA transformer which was required because of the high capacitance of the samples. The tuning reactor was placed on the low voltage side of the transformer to act as a resonant element in order to limit the current-carrying duty of the control circuitry. The test circuit contained two parallel arms, one with the dielectric test sample and the other with a balancing capacitor. A differential measurement of partial discharges was used in order to obtain as high a sensitivity as possible for determining the corona inception level. Additional elements of the circuitry included protective resistors and detecting impedances. The final oscilloscope display sensitivity that was achieved - 50 pC/cm - appears rather low compared to partial discharge measurements made on typical electrical equipment. However, this sensitivity is considered to be quite good, considering the high capacitance of the samples, and was deemed to be adequate for a reasonable interpretation of the discharge phenomena. The minimum detectable discharge was about 30 pC.

RESULTS

Three test series were performed on the capacitor samples:

Test Series #1. Corona inception measurements were made on the outer six (6 μF; #s 7-12) capacitor samples up to and slightly beyond inception but not to breakdown.

Test Series #2. Corona inception measurements were made on the inner six (12 μF; #s 1-6) capacitor samples, followed by breakdown tests on these samples.

Test Series #3. Discharge inception measurements were remade on the outer six samples, followed by breakdown measurements on these samples.

The results for both discharge inception and breakdown measurements are given in Table 1. In Table 1, only final values for discharge inception are presented, since it was generally found that discharge inception voltages increased when the measurements were repeated. For example, on sample #12, partial discharges were observed at 1650 V during test series #1, but later, in series #3, were not detected until 3000 V. This type of "conditioning" may result from additional SF_6 impregnation or from a "burning out" of discharge sites. These effects require additional study. It should be noted that the voltage was increased in 100 V steps, and was held at each level for at least one minute. Discharge extinction levels ranged as low as 80% of the inception levels.

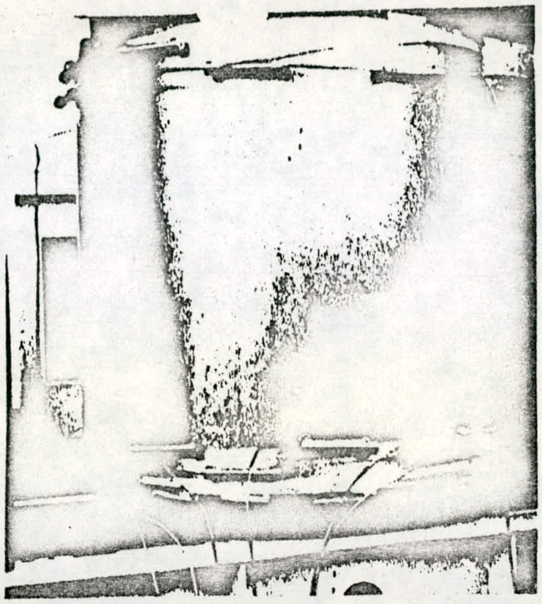

Fig. 4. Dielectric test coil mounted in the pressure vessel

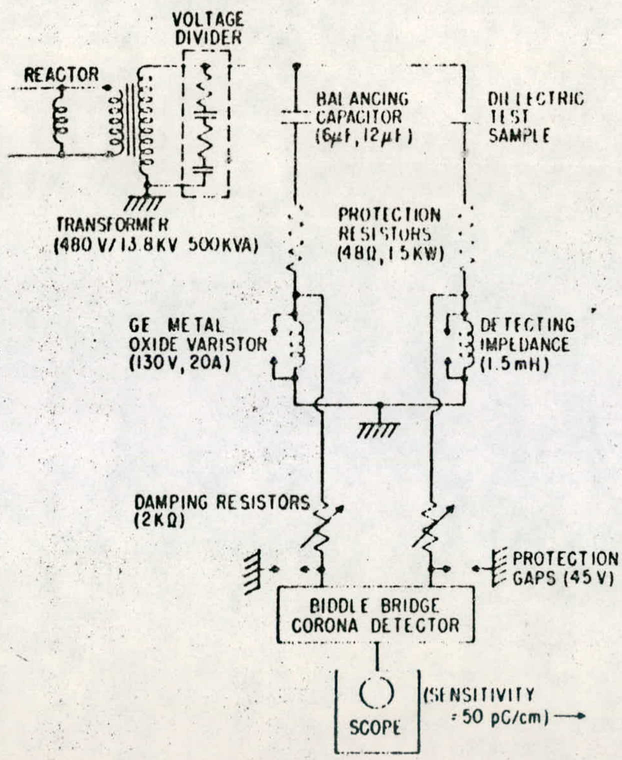

Fig. 5. Test circuit used for partial discharge and breakdown measurements on dielectric test coil

TABLE 1

PARTIAL DISCHARGE INCEPTION AND BREAKDOWN MEASUREMENTS* ON DIELECTRIC TEST COIL

Sample #	Partial Discharge Inception Voltage volts peak (volts rms)	Partial Discharge Inception Stress kV peak/mm (kV rms/mm)	Breakdown Voltage volts peak (volts rms)	Breakdown Stress kV peak/mm (kV rms/mm)
		2 x 0.0125 mm thick polymer film		
1	--	--	1410 (1000)	55.7 (39.4)
2	2120 (1500)	83.4 (59.0)	2260 (1600)	89.0 (63.0)
3	--	--	1555 (1100)	61.2 (43.3)
4	--	--	<212 (<150)	<8.3 (<5.9)
5	--	--	566 (400)	22.2 (15.7)
6	2120 (1500)	83.4 (59.0)	2260 (1600)	89.1 (63.0)
		2 x 0.0233 mm thick polymer film		
7	3960 (2800)	84.6 (59.8)	5020 (3550)	107.0 (76.0)
8	3820 (2700)	82.0 (57.9)	5510 (3900)	118.0 (83.5)
9	3960 (2800)	84.6 (59.8)	4380 (3100)	93.7 (66.3)
10	4525 (3200)	97.1 (68.5)	2260 (1600)	48.5 (34.3)
11	4240 (3000)	90.8 (64.2)	5660 (4000)	121.0 (85.6)
12	4240 (3000)	90.8 (64.2)	4670 (3300)	100.0 (70.7)

*Since it is the peak voltage that initiates discharges, particularly in a gas dielectric, the partial discharge inception and breakdown stresses are given in peak values. However, it is normal design practice for the transformer industry to refer to rms values, hence the equivalent rms values are given in brackets.

DISCUSSION

Two observations can be made from Table 1. First, the thin (2 x 0.0125 mm) samples show a relatively wide dispersion in breakdown stress and a lower mean stress than the thicker (2 x 0.0233 mm) samples. Second, with the exception of one test, all the thicker samples have a breakdown stress in excess of 93 kV peak/mm. In Fig. 6, the discharge inception and breakdown stresses are shown for all the 2 x 0.0233 mm samples together with the data for two of the 2 x 0.0125 mm samples with highest discharge inception and breakdown. It is significant that one sample (#10) with a low breakdown stress had an initial corona inception level which was far higher: we suggest that in this case breakdown may have been influenced by the breakdown of an adjacent sample.

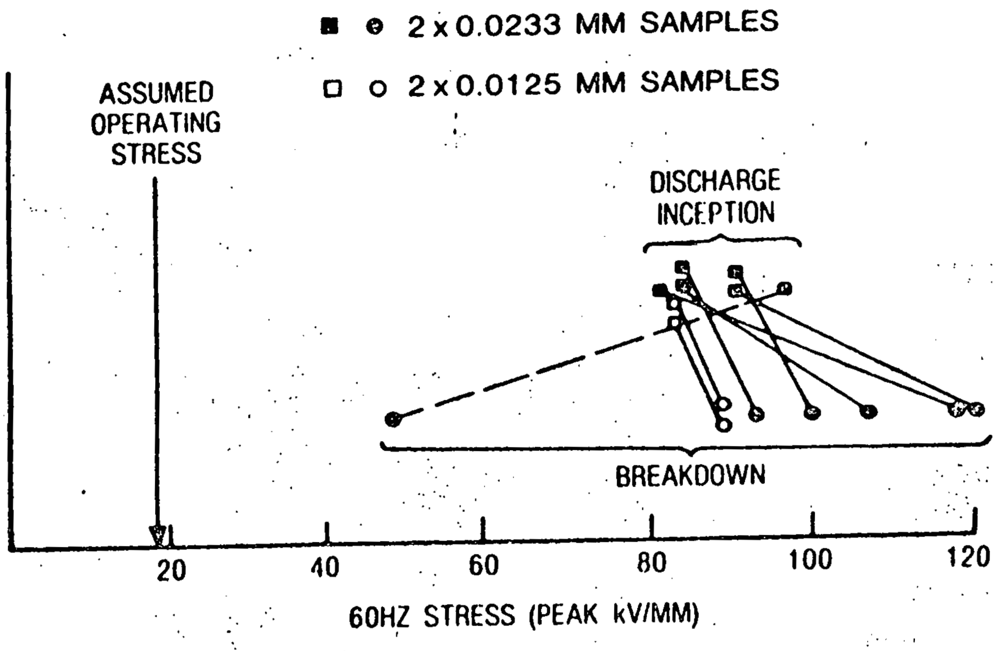

Fig. 6. Plot of the 60 Hz partial discharge inception and breakdown stresses for selected samples from dielectric test coil. Discharge inception and breakdown values on given samples are connected.

After the coil was removed from the pressure vessel, post mortem analyses were performed on the individual test samples. These revealed that failure sites were removed from the conductor edge and were randomly distributed. This suggests that the breakdowns were generally caused by particles randomly introduced during winding. The breakdown site for sample #10 was located directly opposite that of the adjacent sample, #9. This supports the view that the breakdown voltage of sample #10, which was lower than the discharge inception voltage, was probably lowered by breakdown in the adjacent sample.

The results shown in Fig. 6 are considered to be encouraging for the proposed application of this (SF_6-impregnated polymer film) insulation system to a sheet-wound transformer. Two reasons for this optimism follow. First, the 60 Hz breakdown stress is at least 5 times higher than the assumed operating stress of 18.4 kV/mm, used as the basis of a preliminary design of a 500 kV, 500 MVA generator step-up transformer (2). Second, even if the impulse ratio is as low as 1.0, the results in Fig. 6 indicate that the minimum impulse breakdown stress of the 2 x 0.0233 mm insulation system would be on the order of 93 peak kV/mm. This is to be compared with a BIL of approximately 67 kV/mm which has been assumed in the preliminary design estimates for a conceptual 500 MVA, 500 kV generator step-up transformer (2).

Although the number of samples tested above is insufficient to suggest a statistically acceptable design stress, the data lead to considerable optimism about the maximum stresses which can be achieved in the proposed turn-to-turn insulation system. However, it is acknowledged that other factors, such as the area under test and the conductor edge length, could reduce the attainable stress levels in SF_6-impregnated polymer film insulation significantly from those reported in Fig. 6. In other insulation structures, such as the oil-paper structure of large power transformers, it is known that in going from tests on small models to large coil studies the dielectric strength is decreased considerably. The influence of such factors requires considerable future study in order to obtain appropriate design information.

ACKNOWLEDGEMENTS

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