

Weibull Statistics in Dielectric Strength of Oil-impregnated Pressboard under Ramped AC and DC Voltages

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Abstract: AC and DC breakdown tests were performed on large populations of oil-impregnated pressboard samples. The effect of voltage ramp rate on dielectric strength has been investigated. A statistical analysis of breakdown data was carried out using the Weibull distribution. The 90% confidence intervals of Weibull graphs were calculated. The study shows that dielectric strength and shape parameter change versus ramp rate. The variations are attributed to the size and number of defects. Discharges occur from the oil to the oil-pressboard interface and lead to breakdown. DC dielectric strength is larger than that corresponding to AC voltage. This is ascribed to the dissipated energy difference under the two types of field and the fatigue produced by the alternating voltage. This phenomenon is related to space charge. Under DC stress, dielectric strength is higher under negative polarity. It is assigned to the different quantities of space charge accumulated under the two polarities.

Key words: Oil-impregnated pressboard, dielectric strength, Weibull statistics.

1. Introduction

Cellulosic materials, as pressboard and kraft paper, have been used in high voltage transformers because of their good electrical, chemical and mechanical properties together with their low cost. Cellulose is the most abundant natural polymer on the earth, consisting of glucose-glucose linkages arranged in linear chains, where every other glucose residue is rotated in opposite direction. It has a high degree of crystallinity which is a consequence of the extensive hydrogen bonding which occurs between adjacent units along the chain. High crystallinity and large density are responsible for the good mechanical strength of the insulation.

It is well known that cellulose is hygroscopic, i.e., it can absorb water vapor from the environment. At room

temperature, it can hold from 4% to 8% moisture in the relative range of 30% to 70% typical in factory floors in winter and summer conditions [1]. The moisture level in insulation in a newly built transformer should be about 0.5% [1]. One percent moisture can increase the aging rate with more than a factor of three [2]. Therefore, it is necessary to dry scrupulously the equipment insulation.

Cellulose is composed by wood fibers and between them remains some air spaces: capillaries. Although these pores are tiny individually, they still occupy a considerable amount of volume in the solid insulating material. For the reliable operation of high voltage power transformers, it is essential that the cellulose insulation structures used in their construction are completely impregnated. This procedure is important to ensure that no cavities are left inside the cellulose and thereby dangerous partial discharges are avoided [3].

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For the manufacture of pressboard, layers of cellulose are pressed together with a typical quantity of 35 layers per mm. Thin channels remain between the layers. For the impregnation, oil fills the capillaries and channels [4]. During the functioning of transformers, oil operates as a heat transfer fluid as well as a dielectric material.

Mathes et al. [5] have indicated that the dielectric properties of oil-paper insulation system are good when the oil is dried and essentially free of contaminating particles. Oommen et al. [6] and Miners [7] have mentioned that the breakdown voltage of oil depends on the water presence or particles of different concentrations. Van Top et al. [8] have reported the presence of 2,000 particles in 100 mL of filtered oil ranging between 2 μm and 10 μm .

One of the important properties of solid insulating material is dielectric strength which is the ability of the insulator to withstand high voltages and maintain its resistance to current flow. If the dielectric strength is exceeded, the material may breakdown, meaning that the insulation has lost its high resistance to current flow and has become conductive. Several investigations [9-11] have pointed out that the dielectric strength can be significantly reduced by the water content in the paper. Krause et al. [11] have assumed that the fiber orientation has an impact: the dielectric strength of impregnated pressboard is higher when the majority of the cellulose fibers are perpendicular to the electric field.

The purpose of this paper is to study the effect of voltage ramp rate on dielectric strength of oil-impregnated pressboard under AC and DC electric fields. Large AC and DC dielectric strength are required on the insulation of high voltage transformer. It is a well known fact that electrical breakdown of a matter, an insulating fluid or any dielectric material, is a statistical process [12-14]. Therefore, a statistical analysis is highly useful. Among the statistical models, the Weibull distribution is preferred and widely applied to analyse dielectric breakdown data [15-17].

Consequently, in this work, the obtained values of dielectric strength will be analyzed using the two-parameter Weibull model.

2. Experimental Techniques

2.1 Preparation of Samples

Pressboard studied was supplied by ISOVOLTA, Spanish manufacturer, in sheet form of 2,000 mm long, 1,000 mm large and 0.5 mm thickness. Circular samples of 7.5 cm in diameter were cut from the sheets. The specimens were first dried in an air circulation oven for 48 h at 105 °C. Also, an insulating mineral oil (“BORAK 22”), intended for impregnation of the pressboard, was dried under the same conditions. Then, the samples were put into an impregnation chamber at a vacuum level of 1 mbar for 72 h at 80 °C and maintained until the tests were performed.

2.2 Breakdown Tests

The dielectric breakdown was carried out with a high voltage transformer delivering an AC/DC voltage. The samples were subjected to a voltage ramp of different rates: 0.5, 1, 2, 2.5, 3, 4 and 4.5 kV/s. The tests were performed under AC and DC (positive and negative polarities) electric fields. The voltage was uniformly increased with a chosen constant speed until the breakdown of the composite material occurred. The experiments were realized, at room temperature, under a quasi-uniform electric field obtained with plane electrodes of brass, the axis of which being horizontal. The test cell containing the arrangement of electrodes was filled with mineral oil (“BORAK 22”). After rupture, the breakdown voltage was recorded and the thickness of the insulation, at the point of failure, was measured. The oil was stirred during all the tests. The dielectric strength is derived as the quotient of the breakdown voltage and the thickness of the specimen. For a chosen form of applied voltage and a given rate, the tests were executed on a large population of 90 samples.

3. Statistical Analysis of Dielectric Strength Data

The two-parameter Weibull distribution is expressed by Ref. [18]:

$$P(E) = 1 - \exp \left[- \left(\frac{E}{E_0} \right)^\beta \right] \quad (1)$$

where, $P(E)$ is the cumulative probability, E is the dielectric strength, E_0 is the scale parameter representing the value of E corresponding to a cumulative probability of 63.2% (nominal value) and β is the shape parameter which is the slope of straight line of Weibull plot.

The experimental data plot must be a straight line whose slope is β in the coordinate system:

$$X = \log E \quad (2)$$

and

$$Y = \log \left(\ln \frac{1}{1-P} \right) \quad (3)$$

where, P is the cumulative breakdown probability.

The different steps of the statistical analysis are as follows:

The dielectric strength data were classified by ascending order;

The cumulative breakdown probability P_i was calculated for each E_i value using the following relationship [19]:

$$P_i = \frac{i}{N+1} 100\% \quad (4)$$

where, N is the total number of tested samples and i is the value rank of E_i .

The curves of $\log \left(\ln \frac{1}{1-P_i} \right)$ versus $\log E_i$ were represented;

The best linear fit of Weibull plot was determined from the graph by an estimation based on the method of the maximum likelihood. Then both values of the scale parameter and the shape parameter were derived;

The 90% confidence intervals were calculated using the method described by Lawless [20, 21] for a Weibull distribution.

The Weibull model was validated by the χ^2 test

which consists in testing the adjustment of an observed distribution with a theoretical distribution. The procedure is given below:

The distribution form of the dielectric strength values was represented by a series of N values by plotting the histogram corresponding: distribution of the N values in k classes. Each class i is characterized by the number of values N_i and the theoretical rupture probability in the centre of the interval P_i . χ^2_{cal} was calculated as follows:

$$\chi^2_{\text{cal}} = \sum_{i=1}^{i=k} \frac{(N_i - NP_i)^2}{NP_i} \quad (5)$$

Then, this value is compared with $\chi^2_{v,a}$ given in tables on the χ^2 law in function of degree of freedom $v = k - 1$ and the limit probability a (risk).

One chooses a limit of the risk equal to 5% that one runs to refuse the hypothesis whereas it is true. In the field of reliability, the risk is normally included between 1% and 5%. The decision criterion is such as:

If $\chi^2_{\text{cal}} > \chi^2_{v,a}$, the hypothesis on the model is infirmed;

If $\chi^2_{\text{cal}} < \chi^2_{v,a}$, the hypothesis on the model is not infirmed.

The different steps (i.e., from the data classification by ascending order up the χ^2 test) were executed using a computer program. For more convenience, only the Weibull diagrams corresponding to a ramp rate of 4 kV/s will be presented.

4. Results and Discussion

4.1 Statistical Analysis

Figs. 1-3 represent the Weibull plots of dielectric strength under AC and DC electrical fields.

Tables 1-3 were exposed the confidence intervals results of E_0 and β , and the equations of Weibull graphs. The findings of χ^2 tests were given in Tables 4-6. As one can see, for all the cases, the test is favorable.

4.2 Variation of Dielectric Strength versus Ramp Rate

The evolution of nominal dielectric strength (63.2%) or scale parameter in function of ramp rate is shown in Fig. 4.

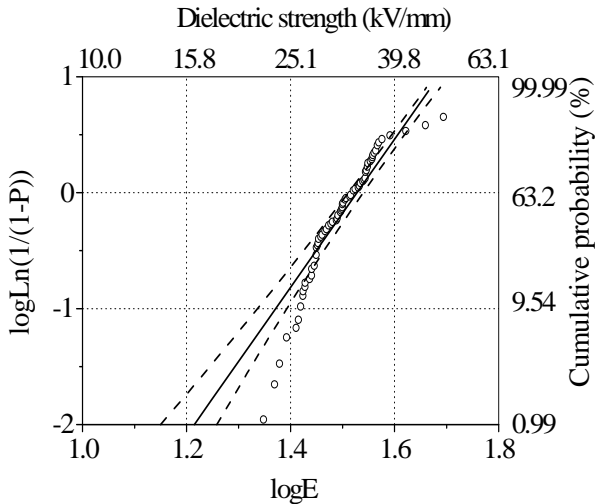


Fig. 1 Weibull plot of dielectric strength data under AC electric field.

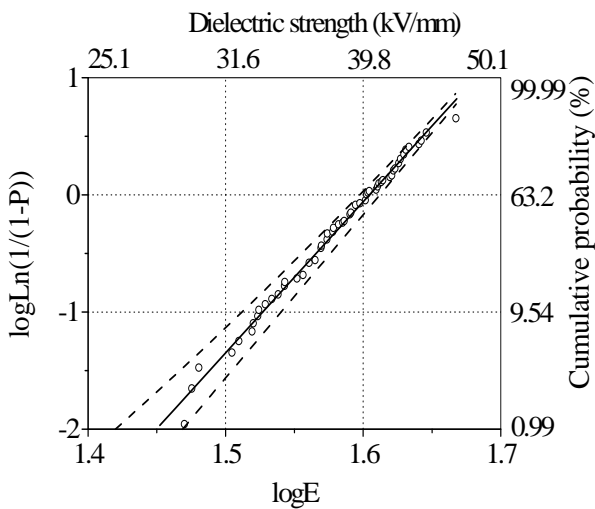


Fig. 2 Weibull plot of dielectric strength data under positive polarity DC electric field.

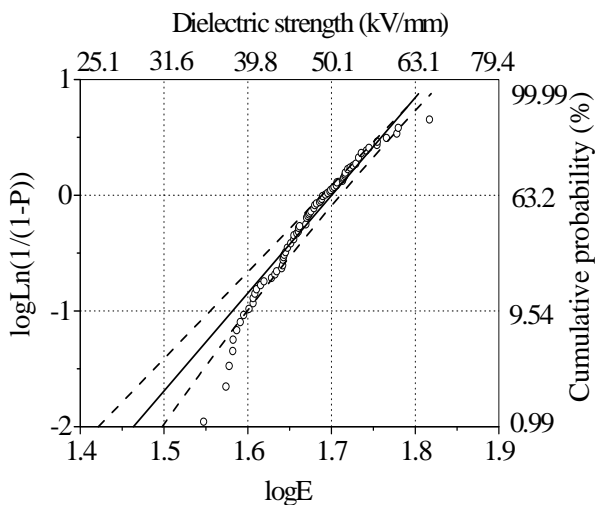


Fig. 3 Weibull plot of dielectric strength data under negative polarity DC electric field.

The variations can be summarised as follows:

Under AC electric field, E_0 decreases lightly from 33.8 kV/mm to 32.2 kV/mm and raises slowly to 33.4 kV/mm. Then it falls abruptly until 26.5 kV/mm for a ramp rate of 3.1 kV/s. After the minimum, E_0 grows rapidly to 33.7 kV/mm and weakens until 31.5 kV/mm for 4.5 kV/s. The maximum variation is of 21.3%. The values are in the same magnitude order than those reported by Darveniza et al. [22] and Martin et al. [23] in the study of dielectric strength of 3 mm mineral oil impregnated pressboard.

Under positive DC electric field, E_0 decreases from 44.4 kV/mm to 37.3 kV/mm then grows until 44.1 kV/mm corresponding to a ramp rate of 2.4 kV/s. Afterwards, it shortens to 39.2 kV/mm, raises slightly to 40.2 kV/mm for 4 kV/s and remains somewhat constant. The maximum variation is 16.3%.

Under negative DC electric field, E_0 heightens from 44.4 kV/mm up to 49.7 kV/mm for a ramp rate of 2.6 kV/s. Between 2.6 kV/s and 4 kV/s, E_0 is practically unvarying. Then, it decreases to 48.2 kV/mm corresponding to 4.5 kV/s. The maximum variation is equal to 12.8%.

The maximum quotient of the negative DC dielectric strength to the positive DC dielectric strength is of 1.3. Also, the maximum quotient between DC dielectric strength and the AC dielectric strength reaches 1.9.

4.3 Variation of the Shape Parameter versus Ramp Rate

The variation of the shape parameter against the ramp rate is presented in Fig. 5.

The evolutions can be described as follows:

Under AC electric field, β decreases from 8.4 to 5.7 and grows until 8.3 for a ramp rate of 2.1 kV/s. Then it lowers to 6.2 and rises slowly to 7.3 corresponding to 4.5 kV/s. The maximum variation is of 32.3%.

Under positive DC electric field, β decreases firstly from 11.0 to 7.8, raises up to 8.7 and shortens to 7.7 for 2.9 kV/s. Beyond this ramp speed, β grows rapidly to 13.1 for 4 kV/s then weakens to 11.5 corresponding to 4.5 kV/s. The maximum variation is of 67.0%.

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Table 1 Values of confidence intervals of scale parameter and shape parameter, and equations of Weibull graphs under AC electric field.

Ramp rate (kV/s)	Scale parameter (kV/mm)	Shape parameter	Equation of Weibull graph
0.5	$32.9 < E_0 = 33.7 < 34.4$	$7.2 < \beta = 8.4 < 9.6$	$Y = 8.4 X - 12.9$
1	$32.6 < E_0 = 33.6 < 34.7$	$5.0 < \beta = 5.8 < 6.6$	$Y = 5.8 X - 8.9$
2	$31.9 < E_0 = 32.6 < 33.4$	$7.0 < \beta = 8.2 < 9.4$	$Y = 8.2 X - 12.5$
2.5	$31.9 < E_0 = 2.7 < 33.4$	$6.8 < \beta = 8.0 < 9.1$	$Y = 8.0 X - 12.1$
3	$26.2 < E_0 = 26.8 < 27.5$	$6.1 < \beta = 7.1 < 8.1$	$Y = 7.1 X - 8.3$
4	$32.6 < E_0 = 33.6 < 34.5$	$5.5 < \beta = 6.4 < 7.3$	$Y = 6.4 X - 9.8$
4.5	$30.7 < E_0 = 31.5 < 32.3$	$6.2 < \beta = 7.3 < 8.3$	$Y = 7.3 X - 10.9$

Table 2 Values of confidence intervals of scale parameter and shape parameter, and equations of Weibull graphs under positive polarity DC electric field.

Ramp rate (kV/s)	Scale parameter (kV/mm)	Shape parameter	Equation of Weibull graph
0.5	$43.7 < E_0 = 44.5 < 45.2$	$9.4 < \beta = 11.0 < 12.5$	$Y = 11.0 X - 18.1$
1	$37.4 < E_0 = 38.2 < 39.0$	$7.4 < \beta = 8.7 < 9.9$	$Y = 8.7 X - 13.8$
2	$40.8 < E_0 = 41.7 < 42.7$	$7.0 < \beta = 8.2 < 9.4$	$Y = 8.2 X - 13.3$
2.5	$43.1 < E_0 = 44.0 < 44.9$	$7.3 < \beta = 8.6 < 9.8$	$Y = 8.6 X - 14.1$
3	$39.5 < E_0 = 40.4 < 41.4$	$6.7 < \beta = 7.8 < 8.9$	$Y = 7.8 X - 12.6$
4	$39.7 < E_0 = 40.2 < 40.8$	$11.2 < \beta = 13.1 < 14.9$	$Y = 13.1 X - 21.0$
4.5	$39.4 < E_0 = 40.0 < 40.7$	$9.8 < \beta = 11.5 < 13.1$	$Y = 11.5 X - 18.4$

Table 3 Values of confidence intervals of scale parameter and shape parameter, and equations of Weibull graphs under negative polarity DC electric field.

Ramp rate (kV/s)	Scale parameter (kV/mm)	Shape parameter	Equation of Weibull graph
0.5	$43.8 < E_0 = 44.6 < 45.4$	$9.1 < \beta = 10.6 < 12.1$	$Y = 10.6 X - 17.5$
1	$44.9 < E_0 = 45.7 < 46.6$	$8.4 < \beta = 9.8 < 11.2$	$Y = 9.8 X - 16.3$
2	$45.8 < E_0 = 46.8 < 47.9$	$6.8 < \beta = 8.0 < 9.1$	$Y = 8.0 X - 13.3$
2.5	$48.3 < E_0 = 49.5 < 50.8$	$6.1 < \beta = 7.2 < 8.2$	$Y = 7.2 X - 12.2$
3	$48.3 < E_0 = 49.6 < 50.9$	$5.9 < \beta = 6.9 < 7.9$	$Y = 6.9 X - 11.8$
4	$49.1 < E_0 = 50.2 < 51.2$	$7.2 < \beta = 8.5 < 9.6$	$Y = 8.5 X - 14.4$
4.5	$47.4 < E_0 = 48.3 < 49.3$	$8.0 < \beta = 9.4 < 10.7$	$Y = 9.4 X - 15.8$

Table 4 Results of χ^2 test under AC electric field.

Ramp rate (kV/s)	χ^2_{cal}	$\chi^2_{v.a}$	Results
0.5	5.3	14.1	Favorable
1	13.7	14.1	Favorable
2	11.2	15.5	Favorable
2.5	14.0	15.5	Favorable
3	9.5	15.5	Favorable
4	9.9	15.5	Favorable
4.5	10.6	15.5	Favorable

Table 5 Results of χ^2 test under positive polarity DC electric field.

Ramp rate (kV/s)	χ^2_{cal}	$\chi^2_{v.a}$	Results
0.5	9.8	15.5	Favorable
1	10.0	15.5	Favorable
2	14.8	15.5	Favorable
2.5	9.5	15.5	Favorable
3	13.7	15.5	Favorable
4	2.9	14.1	Favorable
4.5	9.1	15.5	Favorable

Table 6 Results of χ^2 test under negative polarity DC electric field.

Ramp rate (kV/s)	χ^2_{cal}	$\chi^2_{v.a}$	Results
0.5	8.1	14.1	Favorable
1	11.8	14.1	Favorable
2	11.1	15.5	Favorable
2.5	14.9	15.5	Favorable
3	12.9	15.5	Favorable
4	9.3	15.5	Favorable
4.5	7.9	15.5	Favorable

Under negative DC electric field, β falls abruptly from 10.6 to 6.8 corresponding to 2.9 kV/s. Then it increases rapidly until 9.4 for 4.5 kV/s. The maximum variation is equal to 35.1%.

The values of β are similar to those given by Basappa et al. [10] in the investigation on breakdown voltage of cellophane (cellulose).

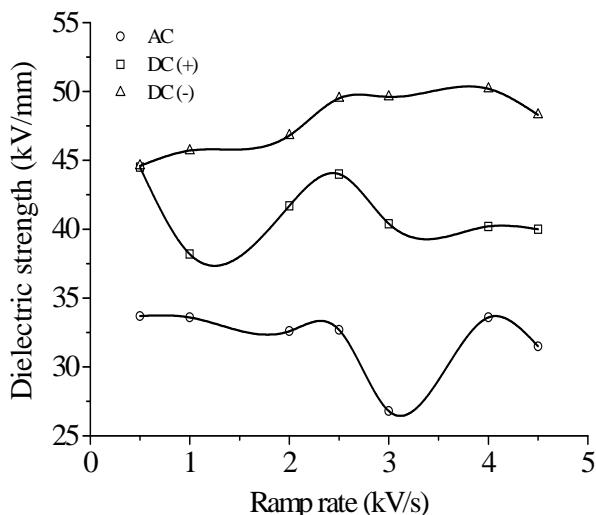


Fig. 4 Variation of dielectric strength versus ramp rate.

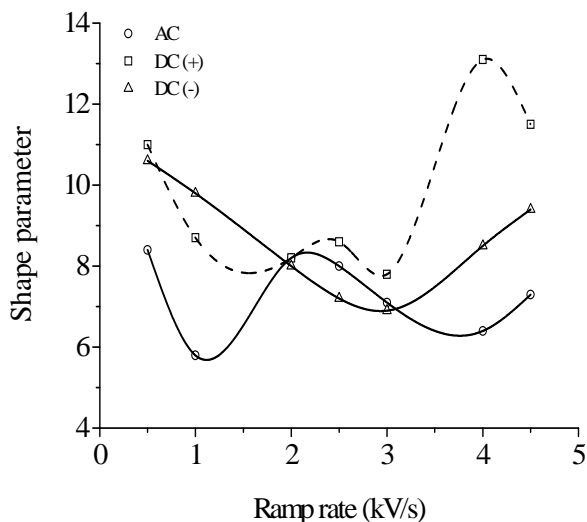


Fig. 5 Variation of shape parameter in function of ramp rate.

4.4 Discussion

The statistical analysis shows that the dielectric strength data can be partly or totally inside the confidence intervals indicated by discontinuous straight lines. The width of the tolerance intervals is larger for the lower probabilities.

Shape parameter is distribution dependent. Its variation is attributed to the size distribution and the type of defects presents in the composite dielectric or created when the voltage is applied to the insulation system. Defects may be moisture in oil, particles as cellulose fibers and dust. The higher values of shape parameter correspond to narrower size and smaller

number of defects leading to a delayed failure. On the contrary, its lower values are ascribed to the amount of defects with large size producing catastrophic or sudden failure. Also, the decrease of β is assigned to the reduction in the critical defect density required to form a breakdown path.

When an AC voltage is applied to the composite insulator, the electric stress is shared between the oil and the impregnated pressboard as a function of the dielectric constants of the two materials. The relative dielectric constants are 4.4 and 2.2 for the impregnated pressboard and the oil, respectively. If the insulation system is subjected to DC voltage, the electric field is shared between the two materials versus the ratio of the volume resistivities. The quotient of volume resistivities of the impregnated pressboard and the oil may vary in the range of 10 to 500, depending on several factors like oil quality, moisture content, etc.. Due to the ratio of the relative dielectric constants/the quotient of the volume resistivities, the electric field is higher across the oil than through the impregnated pressboard. When the magnitude of electric stress across the liquid reaches a critical threshold value, discharges occur from the oil to the oil/pressboard interface. This phenomenon has been reported by Idea et al. [24]. Han et al. [25] observed surface discharges in composite oil-pressboard insulation system. The discharges induce a conductive track (carbonized area) in the composite material leading to breakdown. This process was highlighted by Krause et al. [11] and Dai et al. [26].

At a constant ramp rate, the DC dielectric strength is larger than that under AC field. It is attributed in part to the different dissipated energy under the two types of field and in the second place due to the fatigue induced by the alternating voltage. Space charge content in samples under AC fields, which is always significantly smaller than under DC electric field, is behind this behaviour as well. Basappa et al. [10] noted that DC breakdown values are higher than those corresponding to AC case.

DC dielectric strength depends on the polarity of the electric field. At a fixed ramp speed, the negative value is greater than that obtained under positive polarity. This phenomenon is assigned to the different quantities of the space charge accumulated under the two polarities.

Dielectric strength depends on the voltage ramp rate. The increase of E_0 versus ramp speed can be explained by the required time for the accumulation of defects and charges leading to breakdown. It expresses a condition to attain more elevated electric field to get enough density of injected charge carriers. In fact, the insulator is subjected to the cumulative action of the electric field and the time. On the other hand, the decrease of E_0 is attributed to the rise of the defects amount and their size.

5. Conclusions

This investigation shows that shape parameter of Weibull graphs changes with ramped voltage. The maximum variation is of 67.0%. The higher values correspond to shorter size and smaller number of defects leading to a delayed failure. On the other hand, its lower values are ascribed in part to the high number of defects with wide sizes leading to a sudden failure, and in the second place to the lessening in the critical defect density required to form a breakdown path. Dielectric strength of the composite material varies with respect to ramp speed. The variation reaches 21.3%. When the electric field reaches a critical threshold value, discharges occur from the oil to the oil/pressboard interface and produce a conductive path leading to the breakdown of the insulation system. For a given speed, DC dielectric strength is greater than that corresponding to AC electric stress. It is attributed firstly to the different dissipated energy under the two forms of field and the fatigue induced by AC voltage. Secondly, it is assigned to the quantity of space charge which is smaller under AC voltage. The negative DC dielectric strength is larger than that under positive polarity. This phenomenon is due to the difference

between the space charge amounts formed under both polarities.

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