Electrical Breakdown Strength of Insulation under Combined DC-AC Voltages

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ABSTRACT

Electrical breakdown strength of paper-oil and polypropylene/film-oil insulation samples was measured under dc, ac and pulsating voltages. The latter was obtained by superimposing ac upon dc voltage and provides an attractive method for a simultaneous testing and assessment of the state of insulation of the various parts of HV apparatus in service. The measurements were carried out over a wide range of the pulsation ratio defined as $p = Eac / Edc$. The results obtained under pulsating voltages follow closely an expression which relates the breakdown strength to the sum of arc tangent and arc cotangent function of the parameter *p*. The study was carried out using dry paper as well as paper containing various degrees of moisture. The presence of moisture showed a pronounced effect upon the breakdown strength which varied with the pulsation parameter *p*.

INTRODUCTION

The possibility of a simultaneous assessment of the insulation state of the various electrical apparatus in service, in order to eliminate weakened spots prior to failure, has been of great interest to the electrical utilities for a long time. Of particular interest are methods which require relatively low power during testing. In principle, the tests can be carried out under dc or power-frequency ac. Under dc, the necessary testing apparatus is simple, but the testing conditions do not correspond to the conditions experienced by the insulation operating under ac. This is particularly true in the case of multi-layer paper-oil insulation or polymer-oil insulation, where the voltage distribution in the two cases may be widely different. In addition, the absence of partial discharges during tests under dc may provide different results than tests carried out with ac. On the other hand, testing insulation of e.g. cables or capacitors with ac requires large testing transformers, which is a disadvantage and sometimes difficult to realize, Hence, there has been a growing interest in employing pulsating test voltages (dc with superimposed ac voltage).

There is a lack of published data which would provide the basis of predicting the behavior of insulation under pulsating voltages, and hence for establishing rational values of testing voltages. On the basis of the available data for the electrical strength of insulation under ac and dc voltages, specifically those published earlier [1-5], it may be assumed that the electrical strength under pulsating volt-ages falls between that measured under dc and ac voltage. Furthermore, there is no published mathematical relation which could be used to estimate the insulation strength under any arbitrarily chosen pulsating test voltage.

This paper presents experimental data for breakdown strength of paper-oil insulation and polypropylenefilm-oil insulation under pulsating voltages with different ratios of ac to dc voltages. Mathematical expressions are developed which relate the breakdown strength under pulsating voltage to the ratio of the parameter $p = Eac/Edc$

APPARATUS AND TEST PROCEDURE

A block diagram of the testing circuit adopted is shown in Figure 1. It consists of a 100 kV dc source connected in series with a 40 kV testing transformer, with the test specimen placed between the HV leads of the sources. The dc voltage was varied by means of a regulating transformer driven by a motor, while the ac voltage was changed manually by means of an auto-transformer. The regulating transformer and manual control could be interchanged. During the tests, the ac voltage was set at a predetermined value, and the dc voltage was increased at a constant rate until breakdown occurred. The ac voltage was then increased by 1.6 kV max, and the direct voltage was increased from 0 up to breakdown. Alternatively, the dc voltage was changed in steps of 3.5 kV and the ac voltage was increased smoothly by means of the regulating transformer. This procedure ensured that breakdown was always caused by a voltage increasing at a constant rate.

A cross-section of electrode arrangement is shown in Figure 2. The upper electrode was of plane shape of 25mm diameter with a uniform field profile termination. The lower electrode was plane-shaped of 75 mm diameter. Both electrodes were made of brass. To maintain reproducibility of constant pressure, the upper electrode was additionally loaded with a 1kg weight.

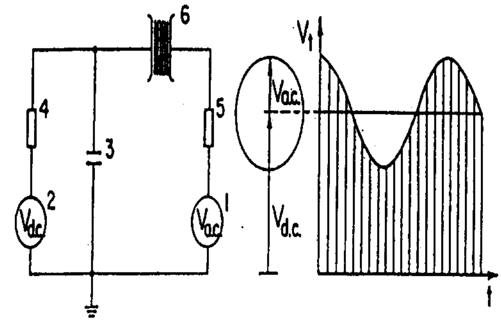


Fig. 1. (a) Schematic diagram of the test circuit. 1. ac source; 2. dc source; 3. smoothing capacitor; 4,5. limiting resistors; 6. test sample; (b) Wive shape of pulsating voltage

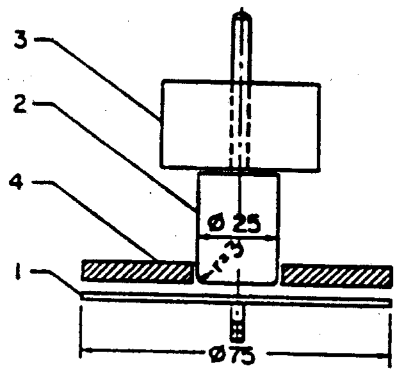


Fig. 2. Cross-section of electrode arrangement. 1. lower plane electrode: 2. upper plane electrode 3. additional weight; 4. semiconducting rubber guard ring

IMPREGNATION OF PAPER-OIL INSULATION

The test cell housed 16 sets of electrodes. The samples were introduced between the sets of electrodes at the same time. During anyone test, only one set of electrodes was connected to the HV sources: The system was insulated for the full voltage.

The individual paper sheets were of an average thickness of 0.0566 mm and a weight of 44.18 g/m^2. Each test sample consisted of 7 layers of paper sheets for a total thickness of 0.396 mm.

The samples were dried in a chamber at a pressure reduced from 13 *kPa* to 130 *Pa* and a tempera-ture which increased from 90 to 110 °C over a period of 144 h. The paper samples were then impregnated with degassed mineral oil at a temperature of 20±2 °C.

The drying procedure adopted reduced the water content in the paper down to 0.04% by weight, which was considered acceptable for the proposed test program. Samples with larger water content were obtained by suitably shortening the drying period. To obtain samples with water content in excess of that corresponding to ambient humidity, the samples were placed in a fog chamber at a temperature of about 80°C. In this way, the water content could be increased up to 12.36%.

ELECTRICAL STRENGTH OF PAPER-OIL INSULATION

Prior to applying the pulsating voltages, the breakdown strength of the test samples was measured separately under dc(*Ebdc*) and ac(*Ebac*) voltages. Subsequent measurements were carried out under pulsating voltages by varying the ratio of ac to dc voltage. The measured breakdown strength *Ebt* data obtained under pulsating voltages are plotted in Figure 3 as a function of *Edc* (electrical field intensity value of dc voltage component) (Figure 3a) and *Eac* (electrical field intensity value of ac voltage compo-nent) (Figure 3b). The same data are replotted in Figure 3c, showing the relationship of the *Edc and eac* component to the total field strength *Ebt* at which breakdown occurred. However, the curves in Figure 3 give no information on the interrelation between the dc and ac components of the applied voltage and the breakdown strength of the samples.

A more informative relationship is obtained when the measured breakdown strength under pulsating voltages *Ebt* is plotted as a function of the ratio of ac to dc component of the electric field intensity, as shown in Figure 4. The ordinate represents the measured *Ebc* while the abscissae gives the pulsation, defined as the ratio $p = b/a$, where a is the dc component of the applied field intensity and b is the corresponding ac component.

To establish the relationship between the breakdown strength *Ebt* and the parameter p (Figure 4), the insulation strength of the samples was determined for various values of p, The ac volt-age component was preset at a given value, and the dc voltage was then raised smoothly at a rate of 1 kV/s until breakdown occurred. The ac voltage was then increased in steps of 1.6 kV max and in each case, the dc voltage was increased smoothly until breakdown as described above. The experiment was then repeated in reverse sequence, i.e., the dc voltage was increased in steps of 3.5 kV, and the ac voltage was raised smoothly at a rate of I kV/s until

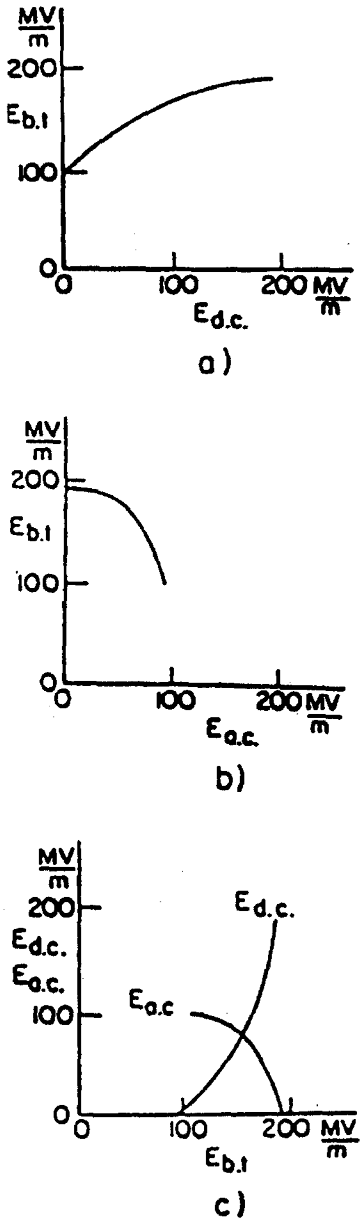


Fig. 3. Breakdown strength of paper-oil insulation under pulsating voltage.
(a) *Ebt=f(Edc);* (b) *Ebt=f(Eac);* (c)*Edc, Eac=f(Ebt).*

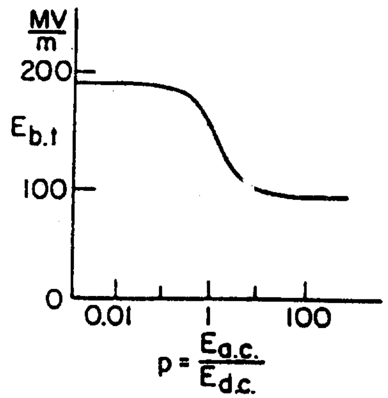


Fig. 4. Blectrical breakdown strength - pulsation ratio p relationship

breakdown occurred. The measured breakdown data *Ebt* were found to be the same irrespective of which component of the voltage was varied insteps.

The results are plotted in Figure 5, which shows the relationships of *Edc* and *Eac* to the parameter p at breakdown as well as the relationship of the resultant breakdown strength *Ebt* to the parameter p. Each point represents the average value of 16 measurements. The scatter of results was very small in the case of $p< 1$, but it increased for higher ac voltage component ($p> 1$) and for samples with high water contents.

Upon analyzing the characteristic of the electrical field intensity components a = *Edc* and b = *Eac* as function of the pulsation parameter $p=b/a$, it becomes apparent that these relations follow the arc-cotangent and arc tangent functions, respectively.

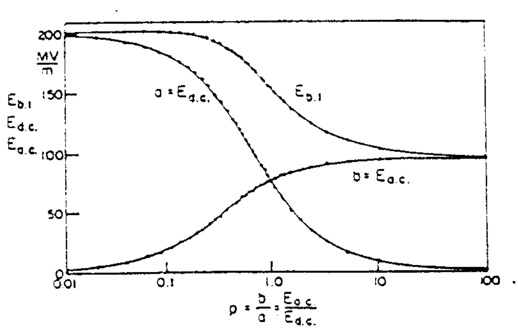


Fig. 5. Electrical breakdown strengthand its components *Edc and Eac* - pulsationratio p relationship

To formulate these regulations mathematically, the following notation (sketched in Figure 6) has been adopted.

Let:

A = *Ebdc* - breakdown strength value at dc voltage (ac voltage $=0$, $p=0$)

B = *Ebac* - breakdown strength value at ac voltage (dc voltage = 0, $p=$)

a = *Edc* - electrical field intensity value of dc voltage component

b = *Eac* - electrical field intensity value of ac voltage component

$c = a + b$ = *Ebt* - the resultant applied electric field intensity at breakdown

a = value of dc characteristic pulsation (p = when a = 0.5A)

p = value of ac characteristic pulsation (p = when b =0.5B)

$p = b/a$ (pulsation of the testing voltage).

Hence, the equations for the respective voltage components a=*Edc* and b=*Eac* become

a = 2/ A *arccotan (p/ a)* = *2/ A arctan (a/p)* (1)

b=2/B *arctan* (p/β) (2)

The resultant field intensity at which breakdown of the sample occurs is given by

Ebt = *2/ A arctan (a/p)* + $2/\pi$ *B arctan* (p/β) (3)

The calculation of the characteristic pulsation parameters a and p are presented in the appendix. It follows from Equation (3) and the conclusion derived from the appendix that the electrical strength of paper-oil insulation for given conditions could be calculated and plotted as a function of p, based only on the measured values of electrical strength under dc (*Ebdc*) and under ac (*Ebac*) volt-ages. In this case, lengthy measurements for different values p could be avoided. To compare the calculated values of *Ebt* (for different p) with measured results, it is necessary to carry out the measurements of *Ebt* for few selected values of p only,

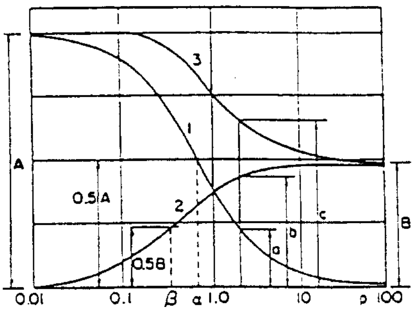


Fig. 6. Function diagram defining parameters.
(1) $a = (2/\pi) A \text{ arc cotan } (p/\alpha)$
(2) $b = (2/\pi; B \text{ arc tan } (p/\beta)$
(3) $c = a + b$

DETERMINATION OF THE MAXIMAL VALUEOF THE RESULTANT FUNCTION

During the course of experiments, it was found that for some test samples the breakdown strength under pulsating voltages exceeded that obtained under dc or ac voltages. The phenomenon was later attributed to moisture present in the insulation and will be further discussed in the next section.

The mathematical expression for the resultant pulsating voltage at which maximum breakdown strength occurs can be obtained by differentiating (3) and equating the derivative to zero, i.e.,

$$\frac{dc}{dp} = \frac{2}{\pi} A \frac{1}{1+(a/p)^2}(\frac{a}{p^2}) + \frac{\pi}{2} B \frac{1}{1+(p/\beta)^2}\frac{1}{\beta} \tag{4}$$

Thus, when $dc/dp=0$,

$$p_m = \pm\sqrt{\alpha\beta\frac{A\beta - B\alpha}{B\beta - A\alpha}} \tag{5}$$

The parameters in Equation (5) are true only for positive values of p. It should be noted that the parameters A, B, a, and are characteristic of a given insulation material as well as the degree of moisture.

The maximal resultant electric field intensity thus becomes

$$C_m = \frac{2}{\pi} A \arctan(a/p_m) + \frac{2}{\pi} B \arctan(p_m/\beta) \tag{6}$$

EFFECT OF MOISTURE ON ELECTRICAL STRENGTH OF PAPER-OIL INSULATION UNDER PULSATING VOLTAGE

To check the effect of moisture on the breakdown strength, 22 sets of samples with different mois-ture content were studied. The data obtained for five selected pulsating voltages are presented in Figure 7, which shows the breakdown strength Ebt as a function of moisture content in %. Curve (1) gives the dc strength $p = 0$, curve (2) was obtained under pulsating voltage for $p = 0.5$, curve (3) for $P = 1.0$, curve (4) for $p=2.0$ and curve (5) under ac voltage $p = \infty$).

Note the value shown as $Ebt100\%$ corresponds to dried paper under dc ($p = 0$) with moisture content of 0.049%.

The results show that the effect of moisture is largest under dc voltages (curve 1), notably when the moisture content m exceeds 1%. It decreases with increasing the ac voltage component or increasing p and becomes smallest for ac voltage. The breakdown data from Figure 7 are replotted as function of pulsation parameter p in Figure 8,

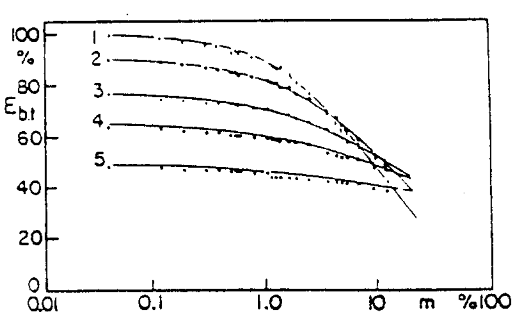
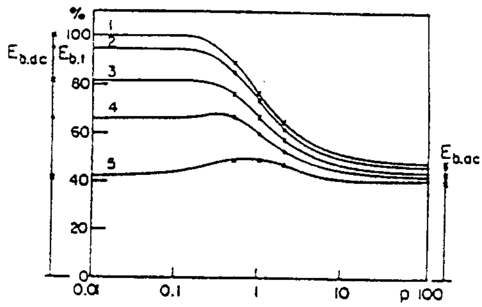


Fig. 7. Relative electric breakdown strength Ebt as function of moisture m in % for different pulsation values p.
1) $p=0$ (dc); 2) $p = 0.5$; 3) $p = 1$; $p = 2$; 5) $p =$ (ac)



Ebt = 100 % for dry paper, *m* = 0.04 % at dc.

Fig. 8. Relative electric breakdown strength as function of pulsation for selected moisture contents, data calculated using 1) m = 0.04%; 2) m = 0.51%; 3) m = 1.98%; 4) m = 4.47%; 5) m= 12.36%

which shows the breakdown strength (*Ebt-p*) relationship for five selected samples of paper-oil insulation with different moisture contents varying from 0.04% to 12,36%. These data show that the ac voltage component begins to influence the breakdown strength when it exceeds about 20% of the total applied voltage (p > 0.2). The relative effect is largest for the dried paper (curve 1) and de-creases with increasing moisture content. For wet paper, curves (4) and (5) display distinct maximum values in the range between 0.1 and 1.0 of pulsation value and it happens when the ac breakdown strength is exceeding 50% of the dc breakdown.

Reference to the existence of maximum values was made in the previous section, and the phenomenon was attributed to the fact that the parameters *A*, *B*, a, and B are characteristic of a given material and also depend upon the moisture content.

Analysis of the data presented in Figure 7 readily shows that for a given pulsation parameter *p*, the lowering of the breakdown strength *Ebt* = *100 Ebt* with the increasing of the moisture content follows the relation:

$$\Delta E_{bt} = C_m^D \qquad (7)$$

where the constant C and the exponent D depend upon the pulsation *p* value. The values of *C* and D corresponding to the selected pulsation values (Figure 7) were obtained by plotting the experimental results on a log-log scale. The coefficients C and D were then inserted into (7) leading to the curves of Figure 7. With the exception of the ac values (curve 5), the experimental data fit well the curves predicted by the simple expression of Equation (7).

This expression enables also the estimation of the breakdown strength for given pulsations out-side the range of water content presented in this paper. The results in Figure 7 also show that the breakdown strength of the paper insulation under ac voltage (curve 5) is affected relatively little by the moisture over the range of moisture investigated.

ELECTRICAL STRENGTH OF POLYPROPYLENEFILM OIL-IMMERSED INSULATION

A block diagram of the circuit used for generating the combined ac-dc voltage is shown in Figure 1. It employs a 120 kV dc source connected in series with 50 kV ac testing transformer. The test specimens were placed between the high voltage sources.

In the superimposed ac upon dc voltage test, the direct voltage was increased in steps of 1.0 kV and the alternating voltage was increased at a constant rate I kV/s from 0 up to breakdown. This procedure ensured that breakdown was always caused by a voltage increasing at a constant rate.

The electrode system used is shown in Figure 2, but the upper electrode was 50mm diameter, surrounded by a guard ring to eliminate surface corona discharges. The lower electrode was plane-shaped of 100 mm diameter. Both electrodes were made of brass. .

The individual polypropylene films were of an average thickness of 19.1 ㎛ and a weight of 17.2 g/m² The tested samples consisted of 1,2 or 3 layers of film in mineral oil. With a larger number of layers, the surface corona discharges became so intensive that they rendered impossible the measurement of the breakdown voltage under ac voltage and the combined dc and ac voltages. The polypropylene film is designed specifically for use in power capacitors and other related electrical apparatus. It has a dissipation factor 0.0002, over temperature 24 through 120 °C and frequency 60 Hz through I MHz. Its dielectric constant is 2.3.

Prior to applying the pulsating voltages, the breakdown strength of the test samples was measured separately under dc and ac voltages. Subsequent measurements were carried out under pulsating voltages by varying the ratio of ac to dc voltage. The measured breakdown voltage data obtained under pulsating voltages are plotted in Figure 9 as a function of the ratio of ac to dc voltage components.

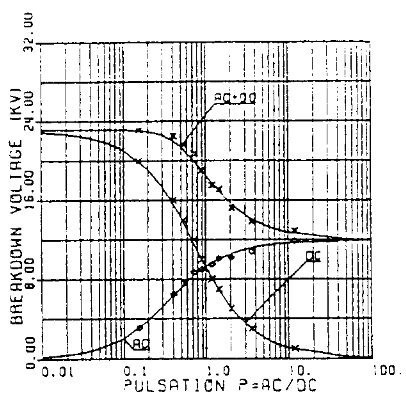


Fig. 9. Breakdown voltage for a double-layer polypropylene film oil-immersed and its components-pulsation ratio relationship.

Upon analyzing the characteristic of the voltage components Vdc and Vac as a function of the pulsation parameter p. It becomes apparent these relations follow the arc cotangent and arc tangent functions, respectively. The obtained breakdown voltage for pulsating voltage is consistent with the data presented previously for paper-oil insulation. The equations for the respective ac and dc voltage components become:

$$Vdc = \frac{2}{\pi} A \arctan \frac{p}{\alpha}$$

$$Vac = \frac{2}{\pi} B \arctan \frac{p}{\beta}$$

The resultant (total) voltage at which breakdown of the sample occurs is given by

$$Vt = Vdc = Vac = \frac{2}{\pi} A \operatorname{arc\,cot\,an} \frac{p}{\alpha} + \frac{2}{\pi} B \arctan \frac{p}{\beta}$$

where A and B represent the direct and alternating breakdown voltages, respectively. Vdc and Vac, the direct and alternating voltage components, when superimposed upon each other, α is the value of p when Vdc=0.5A and the value of p when Vac = 0.5B.

It follows from the last equation that the electrical strength of polypropylene-oil insulation, as was the case of paper-oil insulation, could be calculated and plotted as a function of p, based only on the measured values of breakdown voltage under dc and ac voltages, thus avoiding lengthy measurements under different values of p.

The measured partial discharge inception voltage under pulsating voltage is presented in Figure 10, The partial discharge inception voltage remained constant with varying the pulsation parameter p, at a value of ac voltage independent from the dc voltage. When the breakdown occurred under pulsation voltage and the ac component was lower than the partial discharge inception voltage, the breakdown was not preceded by partial discharge.

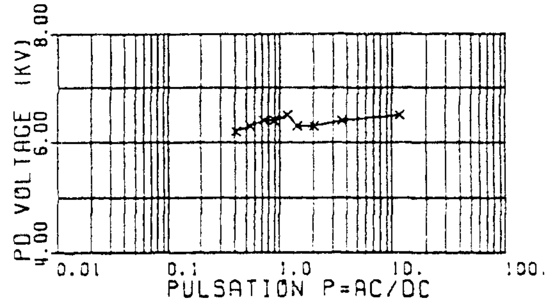


Fig. 10. Partial discharge inception voltage for two polypropylene films oil-immersed - pulsation ratio relationship

CONCLUSIONS

Electrical breakdown strength of paper-oil insulation and polypropylene film immersed in oil studied under pulsating voltages showed that:

1. The dependence of *Edc* and *Eac* components as a function of pulsation parameter *p* follow the arc cotangent and arc tangent function, respectively. The total electric breakdown strength can be expressed by the sum of the component functions.

2. The electrical breakdown strength under pulsating voltage *Ebt* always falls between the dc and ac breakdown strength.

3. Samples with high moisture content may at certain values of pulsation *p* exceed the dc breakdown strength. This occurs when the ac breakdown strength exceeds the half value of dc strength.

4. The decrease in electric strength with increasing water content can be fitted to the relation

$$Eb = CmD$$

5. The partial discharge inception voltage under pulsating voltage remained independent of the parameter *p*.

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