Effect of ageing on the impulse breakdown strength of oil-impregnated pressboard used in power transformers

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Abstract: This paper presents the lightning impulse voltage test results of service-aged pressboards taken from a failed power transformer after 29 years' service. Impulse voltage tests have revealed that there is a significant reduction of breakdown voltages, most probably due to the degradation of mechanical strength. The minimum impulse electric strength may reduce approximately by 30% after 29 years' service. Test results on the service-aged pressboard also indicate that when the moisture content in pressboard is less than 4%, there is no significant correlation between the reductions of the impulse electric strength with increasing moisture content.

Introduction

Oil-filled power transformers have a composite liquid-solid insulation structure, where the oil-impregnated pressboard is used for both mechanical and electrical purpose. Pressboard itself is also a composite structure consisting of solid cellulose fibers with insulating oil medium [1]. Pressboards are gradually aged due to thermal stress, moisture and acidity; and the degradation of pressboards affect the lifetime of power transformers.

The key property of a pressboard as electrical insulation is its dielectric strength. It has been reported [2] that there is a reduction of switching surge breakdown voltage in aged transformer oil-impregnated pressboard insulation, due to a deposit of insoluble ageing products in areas of high electric stresses and the stimulation of surface discharge occurrence. The minimum breakdown voltage at switching surges may reduce approximately by 15% after ageing. Investigation also found [3] that at high water content in pressboard (>4%), the electrical strength at the oil/pressboard interface was strongly reduced.

In this paper, we aim to examine ageing effect on the breakdown strength of oil-impregnated pressboard under lightning impulse voltage. As it is believed that older transformers more than 30 years usually have about 3% to 4% moisture content in the solid insulation, emphasis here is focused on the moisture effect on the impulse electric breakdown strength of aged pressboard.

Experimental procedure

Setup: Experiments were setup with a standard 1.2 x 50 lightning impulse voltage wave produced by a SGV 2000 kV (150 kJ) Impulse Voltage Generator and a glass vessel for up to 500 kV. Sphere-to-cylinder and cylinder-to-cylinder electrodes [4] are used, as shown in Figure 1. ASTM D3426-97 standard [5] was applied for conducting dielectric strength test of pressboards. All tests on the aged pressboards were conducted in transformer mineral oil at room temperature of about 20ºC, relative humidity of 55%-70% and Barometric pressure of 1029 mbar.

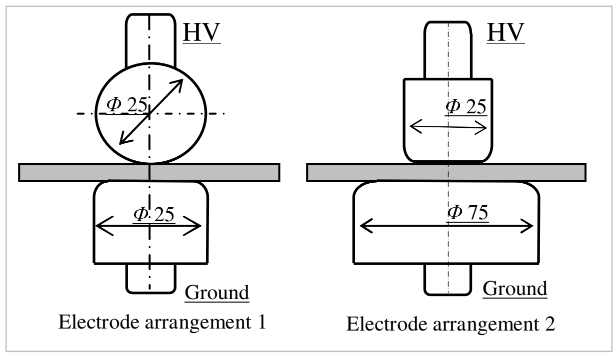

Figure 1 Electrode arrangements used in this study

Pressboard sample: Aged pressboard samples were taken from a failed power transformer after 29 years' service. The transformer was scrapped in February 2005 and since then the pressboard specimen has been stored in a cupboard in laboratory. The measured thickness of aged pressboard is 1.8 mm. It is noted here that the virgin pressboard sample of 1.8 mm thickness is unfortunately not available for a comparative study.

Preprocessing procedures: The samples were first cut to size, and was conditioned under room temperature and a relative humidity of about 55% for 24 hours; then dried in an air-circulating oven at 105°C for 48 hours and in a vacuum-oven at 105°C and about 7 mbar for a further 24 hours. The oil-impregnation was performed with dried and degassed transformer mineral oil under vacuum at 80°C for a further 48 hours, according to BS/IEC 60641-2 (2004) [6]. The moisture content in fully oil-impregnated pressboard sample was about

0.2%, which was measured by the Karl-Fischer titration method (684 KF Coulometer + 832 KF Thermoprep). Subsequently, the dried and fully-oil-impregnated samples were re-moistened by keeping them (always immersed in oil) in the desiccators with a controlled relative humidity of 98%. All samples were kept in mineral oil until testing.

Experimental results

Lightning impulse voltage test results of the service-aged pressboard using sphere-to-cylinder electrodes are summarized in Table 1. The corresponding moisture contents measured for each tested pressboard sample are included Table 1 as well.

Table 1: Lightning impulse voltage test results of the 29 years service-aged pressboard using sphere-to-cylinder electrodes

Sample Nr.	Moisture content in board (%)	Breakdown voltage (kV)	Time to breakdown (μs)
1	0.08	134.24	31.82
2	0.22	115.35	27.48
3	0.2	124.71	14.14
4	0.15	138.81	19.30
5	4.05	129.65	29.56
6	2.09	139.50	1.83
7	1.64	132.49	0.76
8	1.73	150.06	3.06
9	1.17	130.10	29.75
10	1.45	146.62	1.41
11	1.05	143.33	1.09
12	1.92	150.06	32.32
13	1.43	120.38	45.24
14	1.06	129.61	38.96
15	1.83	120.15	37.56
16	0.98	119.15	24.83

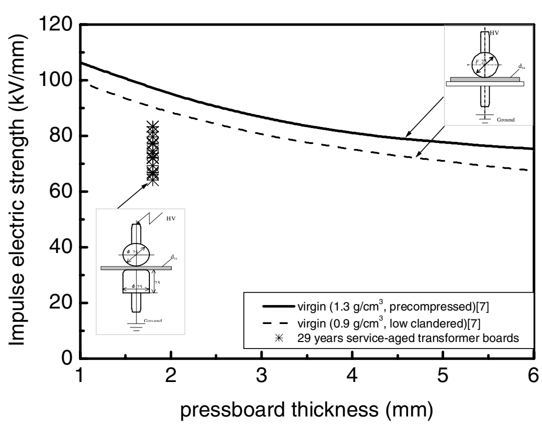

Figure 2 Impulse electric strength values as a function of the pressboard thickness

Discussion of the results

Before discussing the significance of these results, it is interesting to compare the above data with the results of virgin oil-impregnated transformer board reported in the literature by other laboratories. In Figure 2 such a comparison is presented using the data published in [7]. The impulse voltage used in both studies is same, and the electrode arrangements used in both studies are closely similar. The impulse electric strength data of virgin pressboard in [7] was produced by a sphere-to-plate electrode, which gives slightly lower measured values than the sphere-to-cylinder electrode arrangement used in the present study. It is noted here that the measured impulse electric strength values in both studies are to be considered as apparent impulse electric strength only, calculated as $F_{ies}=V_i/L$, here V_i is the measured voltage at breakdown and L is the thickness of the pressboard.

Thickness dependence of the impulse electric strength of transformer board

It is well recognized that the dielectric strength of solid insulation materials depends on the thickness of sample. For examples, Cooper et al. [9] have shown that the impulse electric strength of polythene is given by

$$F_{ies} = 692.34 - 51.29 \ln L \quad (1)$$

Where L is the thickness of polythene in units of millimeters (mm) and F_{ies} in kV/mm. Similarly, it is not difficult to show that in Figure 1, the impulse electric strength of virgin, low-density calendered pressboard (0.9 g/cm^3) can be given by

$$F_{ies} = 100.29 - 18.14 \ln L \quad (2)$$

The impulse electric strength of virgin, high-density precompressed pressboard (1.3 g/cm^3) can be given by

$$F_{ies} = 107.29 - 18.14 \ln L \quad (3)$$

Here L is the thickness of pressboard in units of millimeters (mm) and F_{ies} the impulse electric strength of pressboard in kV/mm.

As it is generally believed that transformer pressboards are *gradually* aged resulting in change of dielectric characteristics, equations (2) and (3) may therefore constitute a foundation to assess the impulse electric strength of service-aged pressboard in terms of thickness as well as density.

Influence of electrode arrangement on the impulse electric strength of service-aged pressboard

Table 2 summarizes the apparent impulse electric strength of 1.8 mm thick service-aged pressboard samples obtained by using two different electrode arrangements in Figure 1. Clearly, the opposing cylinder electrodes gives slightly lower measured values than the sphere-to-cylinder electrodes. This result is in good agreement with the existing finding [1] that the IEC opposing cylinder electrode always gives lower measured values than the opposing sphere electrode.

Effect of ageing on the impulse electric strength of oil-impregnated pressboard

As shown in Figure 2, the minimum impulse electric strength has reduced approximately by 30% after 29 years' service. The significant reduction in impulse electric strength seen in Figure 2 can be most probably due to a reduction in mechanical strength of aged pressboard, as examination of the pressboard has found that compared with virgin pressboard, the bending as well as the tear strength of aged pressboard has been significantly reduced.

Effect of moisture content on the impulse electric strength of service-aged pressboard

Figure 3 plots the impulse electric strength data of Table 1 for the 29 years service-aged pressboards as a function of moisture content in pressboard. The results indicate that when the moisture content in pressboard is less than 4%, there is no significant change in the impulse electric strength of service-aged pressboard with moisture content increased. Such a finding is not surprising since a similar trend has been found in our test results of the same aged pressboard samples under alternative current (AC) voltage. It is interesting to note that there are some similar reports on moisture effects on the dielectric characteristics of pressboard insulation in the literature. For example, in a laboratory model study about PD signatures of wedge type discharges in transformer insulation, Berg and Lundgaard [10] have found that the overall shape of the discharge signature (Q-φ-N distribution) did not change until the moisture content in pressboard reaches 4%. Also, in a study about moisture effects on the electrical strength of oil and pressboard insulation used in power transformers, Krause et al. [3] have found that under AC voltage condition the detrimental impact of moisture on the electric strength at the interface of oil/pressboard is perceptible for moisture level of large than 2% and is significant only at high moisture level between 4% to 6%.

Table 2: Comparison of impulse electric strength for service-aged pressboard samples using different electrode configurations

Electrode configuration	Impulse electric strength (kV/mm)
Electrode arrangement 1 (sphere-to-cylinder)	71.27 ± 6
Electrode arrangement 2 (opposing cylinder)	58.31 ± 6

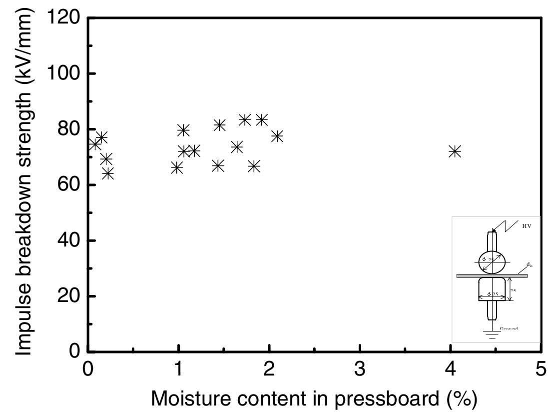

Figure 3 Apparent impulse electric strength values versus moisture content of the 29 years service-aged pressboard samples

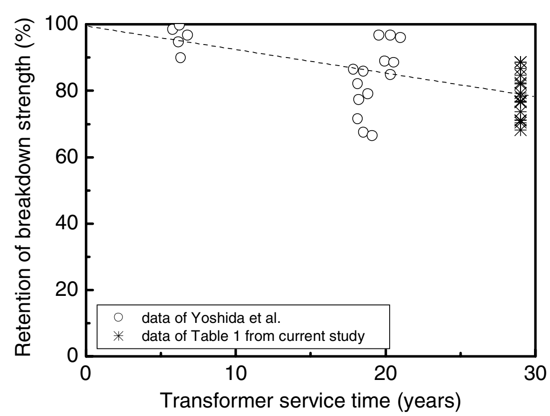

Figure 4 Comparison of current test results in the retained apparent impulse breakdown strength of service-aged pressboard samples with that reported data by Yoshida et al. [8]

Comparison of current test results with reported data in the literature

Figure 4 shows a comparison of test results from the present study in the retained apparent impulse breakdown strength of service-aged pressboard samples with data reported in the literature [8]. As reported by Yoshida et al. [8], their retention values of breakdown strength shown in Figure 4 were values of insulating papers/pressboards of various parts of various transformers; the average value of the breakdown strength may reduce approximately by 5% after 6 years' service and by 15% after 20 years' service. In our impulse voltage test results the average value of the impulse electric strength of aged pressboards reduces approximately by 21% after 29 years' service. Clearly, the current impulse voltage test results on the 29 years service-aged pressboard are in very well agreement with reported data reported by Yoshida et al.

Conclusions

This study has focused on the ageing effects on the breakdown strength of oil-impregnated pressboard under lightning impulse voltage condition, and has particularly stressed the effect of moisture on the impulse electric strength of service-aged pressboard. The finding can be summarized as follows.

(1) Impulse voltage tests on service- aged transformer pressboard samples have revealed that there is a significant reduction of impulse breakdown voltage values. The minimum impulse electric breakdown strength may reduce approximately by 30% after 29 years' service. The most possible reason resulting in the reduction of impulse electric breakdown strength is due to the degradation of mechanical strength of aged pressboard.

(2) The present results also indicate that when the moisture content in pressboard is less than 4%, there is no significant change in the impulse breakdown strength with increasing moisture content in pressboard.

Acknowledgement

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