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# The influence of pressboard parallel to the field on AC-breakdown in oil gaps.

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| OLJEISOLASJON | GRENSEFLATE |
| PRESSPAN | GJENNOMSLAG |

**Referat:** Rapporten består av en artikkel til 4. INTERNATIONAL SYMPOSIUM ON HIGH VOLTAGE ENGINEERING i Athen, September 1983. Ved laboratorieforsøk er det funnet at presspan parallellkoplet med en oljestrekning mellom papirbespunnede ledere senker den elektriske holdfastheten. Forurensninger og vann i oljen forsterker denne reduksjonen, men har ingen virkning for et oljegap uten presspan. Prosjektbeskrivelse og resultatene for de fleste forsøkene er også gjengitt i EFI-TR nr. 1965. "Langsgradienter i impregnert elektrisk isolasjon (Forsøksresultater)".

# THE INFLUENCE OF PRESSBOARD PARALLEL TO THE FIELD ON AC-BREAKDOWN IN OIL GAPS

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## Abstract

In an oilinsulated system (e.g. transformer) the introduction of supports and spacers parallel to the electric field between the conductors is reported to lower the AC withstand voltage. Various theories concerning this problem are reviewed. Breakdown tests on oilimpregnated systems of parallel paperwound electrodes, between which pressboard is introduced confirms these reports. The reduction in breakdown voltage depended on the pressboard geometry. Increased water- and celluloseparticle content of the oil made little difference to the clean oil gap, but amplified the reduction effects from the spacers on the breakdown voltage.

## Keywords

AC-breakdown, oil insulation, solid, interface, particles, humidity.

## 1. Introduction

It is known that a tangentially stressed surface of a solid insulation parallel to an oil insulation may reduce the AC-withstand voltage compared to that of a pure oil-gap.. The mechanisms of breakdown are not yet fully understood, neither in a pure oil gap nor along a solid spacer. Various theories have been presented regarding this subject, and a large amount of experimental data is available.

In the breakdown of a clean oil gap the particle- and water-content in the oil are known to play an important role [1]. Dielectophoretic forces are pulling particles into regions with high electric field strength [2]. Explanations such as particles forming bridges across the gap are given [3], and a statistical approach based on volume and area-effects is possible [4].

The reduction in breakdown voltage resulting from solid insulation in the stressed oil region can be explained by field enhancement in the oil due to rough surfaces of the solid material [5]. It is also observed that electro-hydrodynamical movement in the oil can be modified by the solid, thus leading to vortexes and bubble generation at highly stressed locations in the insulation [6].

The scope of this work is to investigate the magnitude of the reduction in breakdown voltage caused by pressboard in an oil gap, and which parameters influence this reduction. The experiments are designed to be relevant to transformer insulation by using paper wound electrodes and relatively large stressed oil-volumes. The level of partial discharges in the objects was also investigated, to see if there exists a correlation between this parameter and the breakdown voltage of the objects.

## 2. Experiments

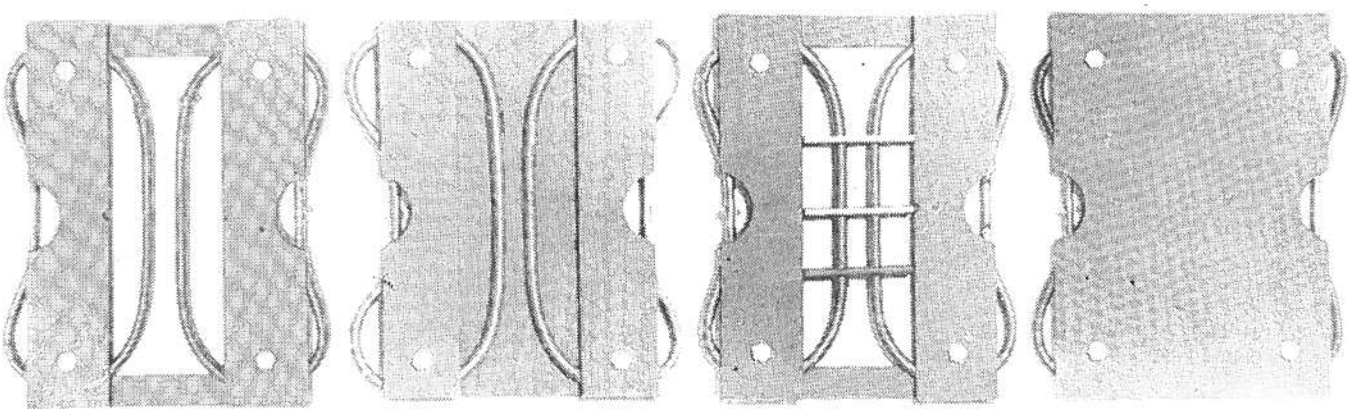
### 2.1 Test objects

In their basic form the test objects consist of two parallel paperwound coppercylinders bent at the ends to avoid field enhancement. Their diameter is 5.64 mm, the paperthickness (24 layers of Kraftpaper) is 1.5 mm. The electrode separation is 20 mm (Cu/Cu) and the length of their parallel sections is about 150 mm. The electrodes are fixed to a pressboard frame, and the electrode gap is shortcircuited by solid material (pressboard) in three different ways. The object types are shown in fig. 1. Number 4 doubleboard, is similar to number 2, singleboard, except that both sides are covered with a board.

The four objects types are different in respect to possible oil- and particle-movements and the field enhancement resulting from the pressboard [table 1]. The field strengths are calculated by means of a data programme using the finite element method.

### 2.2 Test equipment

The test cell consists of a 600 liter tank on which a high-voltage bushing is mounted. The cell is placed at an inclined angle, so that the test objects can be manipulated from the inspection port without being exposed to air. A filter and a drying and degassing equipment, in which the oil can be continually processed, are connected to the test cell. The test cell and the instrumentation are shown in fig.2. An air-gap is mounted in parallel to the bushing. When breakdown occurs in the test cell the air-gap will be triggered and then discharge the test circuit, in order to minimize the contamination of the oil in the tank. Furthermore there is a drying and impregnating tank, in which the test objects are treated. This tank is connected to the oilprocessing unit.



1 2 3 4

Figure 1: Test objects, 1 Open, 2 Singleboard, 3 Spacer, 4 Doubleboard.

Table 1: Test object characteristics. Fiels enhancement is given relative to homogeneous field.

| Object | Maximum field enhancement in oil | | Oil and Particle movement |
|---|---|---|---|
| | Magnitude [%/mm] | Position | |
| Open | 46% | front of electrode | free |
| Single-board | 58% | wedge between electrode and board | oil movement altered |
| Spacer | 180% | wedge under spacer | oil movement altered |
| Double-board | 58% | wedge between electrode and board | oil movement altered particle attraction prevented |

## 2.3 Test procedure

Each test series consist of 10 objects. One series at a time is impregnated[7] and loaded into the test cell. The objects are mounted at an inclined angle, backboard down. They are brought to breakdown using stepped AC-voltage (25kV/1 min). The maximum test voltage is 425kV.
During the experiments the humidity and particle content in the oil are sampled before each voltage test. To be able to measure the low concentrations of water in the oil at 20°C, which is the actual temperature during the experiments, samples of oil and paper are heated in order to increase the watercontent in the oil. The humidity in the oil is then measured using Karl Fisher's method, and the moisture content at 20°C computed from equilibrium curves for water i oil/paper-systems. The lowest achievable humidity is about 0.6 ppm in the oil, giving 0.8% in paper at equilibrium. During some test series the humidity is raised to about 6 ppm in the oil (3% in paper) by adding a calculated amount of water to the objects before impregnation, in order to check the influence on the withstand voltage of the objects. After impregnation the oil is circulated past the objects until equilibrium is established.
With well-filtered oil the particle content is kept at about 50 particles greater than 5µm pr. ml. During some series this is increased about 10 times by adding cellulose particles. The distributions of the particle-sizes are shown in fig. 3. We use the notation dry & clean, when both particle and watercontents are at the lower level.

During the test the partial discharges in the objects are measured with a Kreuger bridge. The position of the breakdown relative to the phase of the applied voltage is checked with a transient recorder. A video-camera was used to monitor movements of particles in the stressed oil volume.

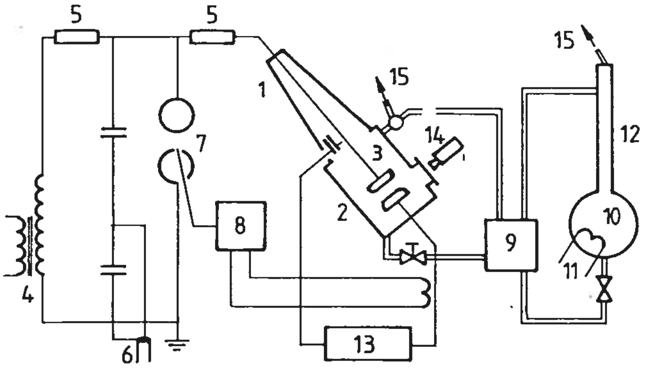



Figure 2: Test equipment and instrumentation.
1 HV-bushing, 2 Test cell, 3 Object, 4 Transformer, 5 Damp.res., 6 Volt. meas., 7 Shortcirc.gap, 8 Trig.circ., 9 Pump and filter, 10 Oil tank, 11 Heater, 12 Drying column, 13 Kreuger bridge, 14 Video camera, 15 Vacuum.

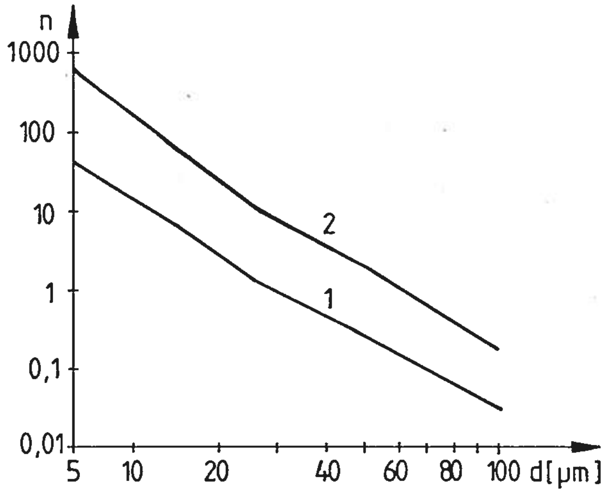



Figure 3: Cumulative distribution of number of particles (n) versus diameter(d) of particles in 1ml of oil.
1: At low level.
2: With water and particles added.

## 2.4 Statistical treatment

In the analysis of the results the Weibull distribution is assumed. The cumulative distribution is given by:

$$p(U) = 1 - \exp\left\{-\left(\frac{U}{U_0}\right)^b\right\}$$

$U_0$ denoting the voltage that give 63.2% breakdown probability, and b is the shape parameter of the distribution. Results are fitted to this distribution by the maximum likelihood method using a computerprogramme. The confidence-bounds at different percentiles are also calculated [8].

## 3. Results

The results from the different test series are listed in table 2. Here the distribution parameters are given with the 90% confidence limits. The confidence bounds for the entire distribution are widening at higher and lower percentiles. This can be seen from fig. 4. The confidence bounds will always behave this way, but an increase in the number of observations will bring them closer to the expected distribution. Even if the breakdown voltages at the lower percentiles are of largest technical interest, we will not make any further comments on them, due to these wide confidence bounds. All our considerations are based on 63.2% breakdown probability($U_0$). An increase in level of certainty will widen the confidence bounds. The higher the level of certainty is without resulting in overlap in the confidence bounds, the more significant the difference between the two distributions will be.

Taking the open objects in clean & dry oil as a reference, the reduction in breakdown voltage ($U_0$) re-

Table 2: Results from breakdown tests: Weibull parameters.

| Objects | Oil condition | $U_0$[kV] | $U_0$: 90% conf. [kV] | b | b: 90% conf. |
|---|---|---|---|---|---|
| Open | Clean & Dry | 409 | 393 - 426 | 16.8 | 8.9 - 23.3 |
| Backboard | - " - | 361 | 333 - 391 | 8.1 | 4.5 - 10.8 |
| Double-board | - " - | 348 | 311 - 390 | 5.8 | 2.9 - 8.4 |
| Spacer | - " - | 340 | 323 - 360 | 12.2 | 6.6 - 16.5 |
| Backboard | Water added | 349 | 325 - 376 | 10.4 | 5.4 - 13.9 |
| Open | Water & part. added | 400 | 387 - 413 | 19.9 | 10.4 - 27.9 |
| Backboard | - " - | 310 | 288 - 333 | 9.15 | 5.0 - 12.5 |
| Spacer | - " - | 286 | 277 - 296 | 20.0 | 11.4 - 26.6 |

sulitng from the introduction of pressboard parallel to the oil-gap is between 12% and 17%. The reduction is largest and most significant in the spacer objects.No overlap exists in the 99% confidence intervals. The reduction is of the same magnitude for the single- and double-board objects.Their 90% confidence bounds do not overlap the 90% confidence bounds for the open object.
For the single-board object an increase in humidity seems to have only little impact on the breakdown voltage. It is still of the same magnitude as when tested in clean & dry oil. On the other hand an increase in both humidity and particle content results in a significant reduction (12%) of $U_0$ compared to the same object tested in clean & dry oil. There is no overlap in their 90% confidence bounds.
The reduction of $U_0$ resulting from adding particles and water is even greater for the spacer objects. The reduction is 16% compared to the same object in clean & dry oil, and there is no overlap in their 99% confidence bounds. The entire distributions are shown in fig. 4.

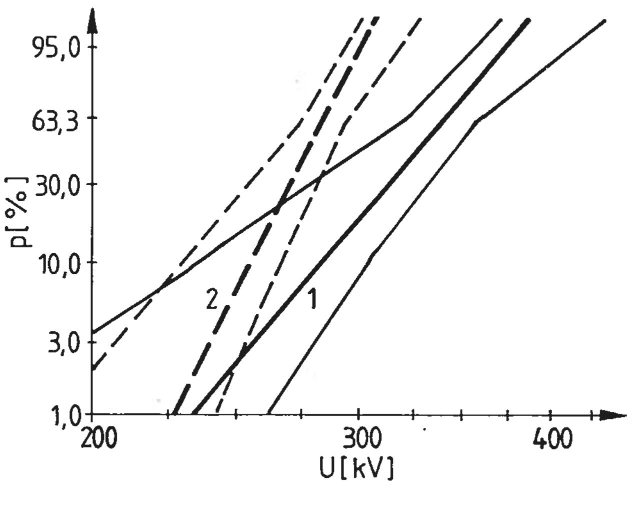



Figure 4: Weibull distribution of breakdown probability(p) versus voltage(U) with 90% confidence-bounds, for spacer objects.
1: In clean & dry oil.
2: In oil with water and particles added.

On the contrary, addition of both water and particles does show little effect on the open object.There is no significant difference in the withstand voltage for this object in the two oil qualities. Addition of water and particles reduced the scatter in all object types.
In the open objects the breakdowns are distributed evenly along the parallel parts of the electrodes. This indicates that edge phenomena do not dominate the breakdown mechanism.The single-board objects behave in the same way. In some of these the flashover left no trace on the pressboard surface. In the spacer objects, nearly all the flashovers were located at the outer surface of either of the outer spacers. The breakdowns, as registered with the transient-recorder, occurred within 1.6 ms on each side of the crest voltage. There were no significant correlation between the inception voltage for partial discharges and the breakdown voltage for objects in good condition.
In some preliminary experiments not tabled above, we observed a number of very small metal particles;left overs from the production of the test-cell. For these series both the open and the single-board objects had breakdown values being 16% lower than the values obtained in the main series reported in this paper.
Tests of the dielectric strength of the oil with VDE-electrodes 1.2 mm apart resulted in average values of 48±5kV in dry & clean oil and 46±4kV with water and particles added. This reduction (4%) was highly significant according to Student's t-test.

## 4. Discussion

As seen from the results it is obvious that the presence of pressboard in an oil-gap may reduce the with-stand voltage. Like-wise the magnitude of this reduction may be dependent on the condition of the oil to a higher degree than in a similar pure oil-gap. The total reduction resulting from both the pressboard and particles and humidity in the oil is 24% for single-board objects and 30% for spacer objects. Neither of these have overlap between their and the open objects (clean & dry oil) 99% confidence limits on $U_0$.
The reduction in breakdown voltage for the open object resulting from increased contamination in the oil is of the same order as the reduction measured using the VDE-electrodes.
As shown above the reductions in breakdown voltage are most significant for the spacer object, as is also the effect of moisture and particles. This may be caused by different breakdown mechanisms in the single-board and spacer objects, which is indicated by a more defined breakdown location and less scatter in breakdown values for the spacer object.A possible explanation may be the greater field enhancement in this object type. Curvature in the electrodes may increase the oil volume in the wedge at the outer spacer, thereby increasing the breakdown probability. The role of water and particles in the enhanced reduction in withstand voltage for these objects is difficult to elucidate from these experiments. Tests have not been done with only water added to the oil, and we therefore do not know whether it is both particles and humidity or only one of these factors that govern this mechanism.
The field enhancement is equal in the single- and double-board objects.It is slightly greater in these than in the open object. It is not likely that this small increase in field enhancement is causing the reduced breakdown voltage in these objects. The results with single-board objects indicate that particles do play an important part in the mechanisms resulting in the reduced withstand voltages. The results with double-board objects indicate that at

least with a low level of contamination dielectophoretic attraction of cellulose particles into the stressed gap do not play an important role. This is in contradiction to the results reported recently[9]. In an object similar to our double-board the breakdown voltage was increased compared to that of a pure oil-gap. There are differences between these experiments and ours, in respect to object dimensions, humidity and particle-content, and this may explain the discrepancy.
The effect of the difference in permittivity between oil and pressboard is not known. Tests with solid insulation not giving rise to field enhancement have to be done in order to obtain information about the eventual importance of permittivity matching. It is also desirable to make tests with a quantified amount of metal particles added to the oil to gather more information about the large reduction in breakdown voltage indicated in our preliminary tests.

## 5. Conclusion

The results of our experiments show that the AC-breakdown voltage in a relative homogeneous field between paper insulated conductors is significant reduced after introduction of pressboard. The breakdown voltage in a system including pressboard is more sensitive to the condition of the oil than a system without such solid insulation.

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