THE BREAKDOWN VOLTAGE OF INSULATION OIL UNDER THE INFLUENCES OF HUMIDITY, ACIDITY, PARTICLES AND PRESSURE

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The breakdown voltage of mineral insulation oil was systematically investigated under the influences of moisture, acidity, pressure and particles. The standards IEC156/95 (VDE0370/Part5/96 and ASTM D1816) specified the test conditions. Moisture provides charge carriers, therefore a moisture saturation of 0 to 20 % decreases the breakdown voltage from 72 down to 61 kV. Acids as aging products decrease the dielectric strength too for the same reason. Not the total acid number TAN, but the low molecular acids effect the major decrease. Since the breakdown process starts with a microscopic bubble, an increasing pressure increases the breakdown voltage too. The observed asymptotic behaviour seems to come to a maximal end value of the breakdown voltage at around 150 kV. Under-inflation supports bubble generation, decreasing the dielectric withstand strength. Dry particles (cellulose fibres) decrease the breakdown voltage only at under-inflation, nearly no influence was observed at atmospheric pressure.

Mineral oil, breakdown, particles, acidity, humidity, pressure

1 BREAKDOWN IN INSULATION OIL

1.1 INTRODUCTION

Insulation oil in power transformers serves as a heat transfer medium and as an insulating liquid. Two reasons motivated for the investigation of its insulation properties: Firstly power transformers are often operated under aged conditions. Thus the moisture content in oil increases, aging products become dissolved and particles are dispersed. Secondly, transformers are operated under novel environmental conditions, were low or high pressures exist. A safe service necessitates the thorough investigation of these influences.

1.2 THEORETICAL CONSIDERATIONS

Insulating liquids derive their dielectric strength from the much higher density compared to gases. The breakdown process starts with a microscopic bubble, an area of large distances between corpuscles, where ions or electrons can initiate avalanches. These microscopic bubbles originate from current impulses on an electrode. The next current impulse injects charge carriers into the bubble, leading to current amplification and finally to breakdown [1]. From these considerations, one expects the following impacts:

- Moisture delivers charge carriers and therefore decreases the dielectric withstand strength.
- Aging byproducts such as acids also deliver charge carriers through dissociation. Additionally they are surface-active, decreasing the surface tension. Thus they support bubble evolution following into a decreased dielectric strength.
- Pressure influences bubble evolution too. With increasing pressure the breakdown voltage should increase. For pressures below the atmospheric pressure the breakdown voltage should decrease.
- Particles will move into highly stressed areas depending on their permittivity in relation to that of oil. A decreased breakdown voltage is expected of they are highly conductive or wet.

2 INFLUENCE OF HUMIDITY AND ACIDITY

2.1 MEASUREMENT SETUP

A conventional dielectric test system „Baur DTA 100 E“ measured the breakdown voltage at different moisture contents and acid numbers. The system operates fully automatically, which is very convenient for long test series. Special advantage is the fast breakdown detection and current disconnection in less than 1 ms, which together with a low energy in the test circuit prevents carbonation of the mineral oil. Even hundreds of tests in the same oil sample do not lead to a decreased breakdown voltage due to combustion products.

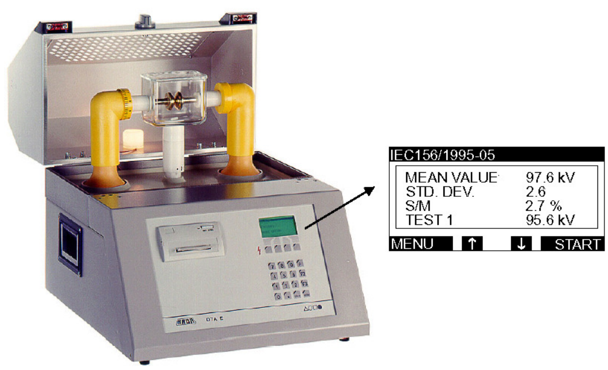

Figure 1: Automatic insulating liquid test set Baur DTA 100 E

The tests were carried out according to IEC156/95 Fig.II (VDE0370/Teil5/96 and ASTM D1816), i.e. spherical electrodes with 25 mm radius. Figure 1 shows the automatic test system.

An automatic potentiometric titration system "Titrino SM 702 with Exchange Unit 806" made by Metrohm measured the acidity of the oils (Figure 2). Here the Total Acid Number TAN was determined by a volumetric titration with potash to neutralize the carboxylic acids.

Figure 2: Volumetric titration system Metrohm Titrino SM 702 with Exchange Unit 806

The titration took place as follows: At first 10 g of the oil were dissolved in 40 ml of solvent toluene / ethanol in a ratio of 5 to 4. Potash (KOH, 0,1 mol/l) was added as titre with volume increments of 0,001 ml or 0,005 ml depending on the expected acidity. The system detects, when the acid-base-equivalence-point EP is reached by a voltage measurement in the solution. From the volume of potash at the EP equation (1) calculates the acidity as TAN.

$$TAN = \frac{(EP1 - C31) \cdot C01 \cdot C02 \cdot C03}{C00} \qquad (1)$$

TAN – total acid number
EP1 – equivalent point
C31 – blind value of the solvent toluene/ethanol
C01 – 0,1 mol/l, concentration of titre
C02 – 1
C03 – 56,106 g/mol, molar mass of titre
C00 – weight of the oil sample

The humidity of the oils was determined as the moisture content relative to saturation (RS in %) by capacitive sensors Vaisala HMP 228. In order to obtain dependable results, the sensors were carefully calibrated by saturated salt solutions with lithium chloride and sodium chloride.

The moisture content relative to saturation (%) gives more information about the crucial effects of moisture on the breakdown voltage than the conventionally used moisture content relative to weight in ppm. Therefore it was forborne to measure the ppm-moisture. Nevertheless this value can be calculated by sorption isotherms as published in [2].

2.2 INVESTIGATED INSULATION OILS

New mineral insulation oil type Nynas Nytro 3000 and service aged Shell K 6 SX from 1964 were investigated. Both oils were free of particles and gas saturated, the temperature was 20-21°C. In order to obtain oils with various acidities both oils were mixed in six steps, see the following table and the acid titration results in Figure 3.

Oil	Ratio of Nynas to Shell	Total acid number
A1	100/0	0,0097
B2	80/20	0,101
C3	60/40	0,2027
D4	40/60	0,2906
E5	20/80	0,4034
F6	0/100	0,4866

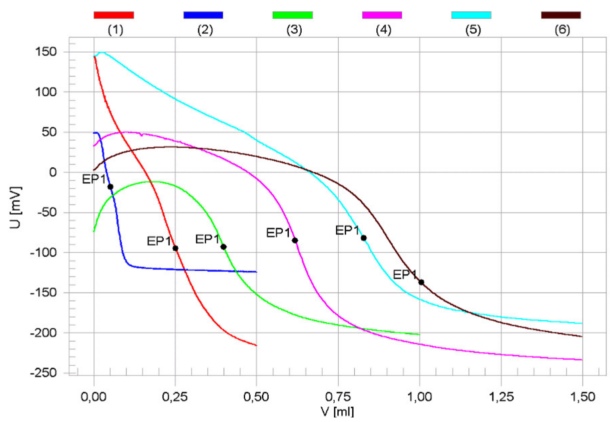

Figure 3: Results of the TAN determinations in the six investigated insulation oils

To investigate the influence of a low molecular carboxylic acid, formic acid HCOOH, which is an aging product too, was added to the new Nynas Nytro 3000. This resulted in a TAN of 0,27.

The humidity of the investigated oils was varied in four steps: 0-5-10-20 % of relative moisture saturation. This covers the range typical for power transformers. To obtain various moisture contents, each of the six oils was set by immersion of cellulose. According to thermodynamic equilibrium and moisture adsorption capacities the relative saturation of the cellulose determines the relative saturation of the oil [2]. E.g. to obtain 10 % of relative saturation in oil, insulation paper with 10 % of relative moisture saturation was added. Subsequent heating cycles affect a fast diffusion and a homogeneous moisture distribution.

2.3 RESULTS AND DISCUSSION

A very high scattering of the results signifies the measurement of the breakdown voltage. The first 40-100 breakdown tests were significantly lower than the later reached value. This might be explained by particles in the oil and at the electrodes. Figure 3 illustrates this phenomenon.

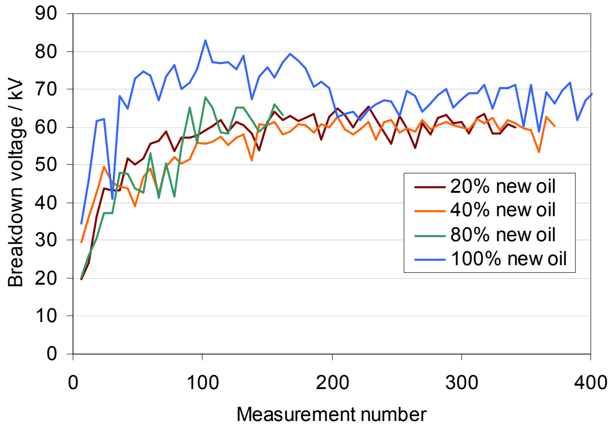

Figure 4: Scattering of the breakdown voltages

Figure 5 depicts the breakdown voltage in mineral oil as a function of relative moisture saturation and total acid number. Every measurement point is the average of around 150 single breakdowns, whereas the first results with the huge scattering were rejected.

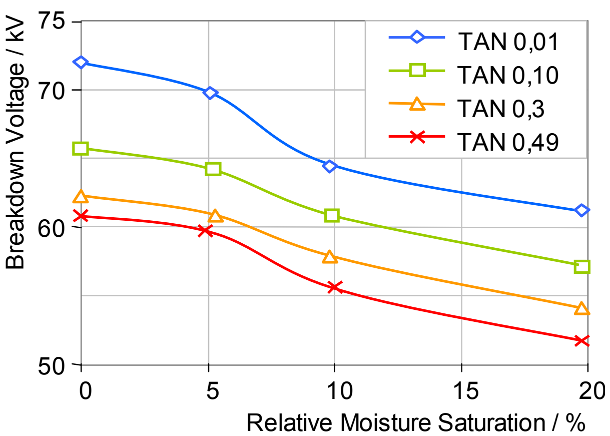

Figure 5: Breakdown voltage in mineral oil as a function of relative moisture saturation and total acid number

It is obvious, that with increasing relative moisture saturation from 0 to 20 % the breakdown voltage for new oil decreases from 72 to 61 kV. With increasing acidity (TAN) from 0,01 to 0,49 and constant relative saturation of 0 % the breakdown voltage decreases from 72 kV to 61 kV.

Figure 6 shows the influence of additionally dissolved low molecular acid compared to a new and a service-aged oil. The relative moisture saturation in all oils was 10 %. Here formic acid was added to new Nynas Nytro 3000, leading to a TAN of 0,27. Because of the strong acid the breakdown voltage decreases to 38,7 kV, which is much less than that of service-aged oil, although the acidity of the latter is higher with 0,49. One can conclude, that not the total acid number, but rather the low molecular acids contribute to the decreased breakdown voltage. This has to be considered when comparing these results to others.

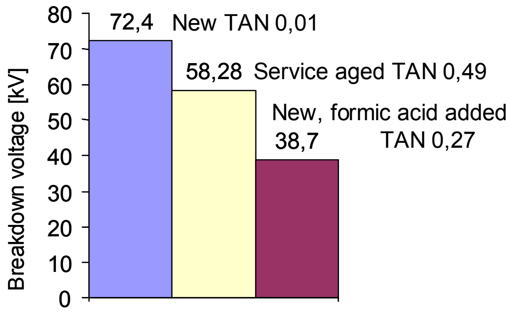

Figure 6: Breakdown voltages for new Nynas Nytro 3000, service aged Shell Diala D with TAN = 0,49 and new Nynas Nytro 3000 with formic acid added, TAN = 0,27

3 INFLUENCE OF PRESSURE AND PARTICLES

3.1 MEASUREMENT SETUP

The breakdown voltage of insulation oil was measured with three different test setups for three pressure ranges. For an oil pressure of 1-21 bar and for 1-100 bar two special measurement cells were constructed. The automated test system Baur DTA 100 E with a modified test cell measured at oil pressures of 0,1-1,5 bar.

In this context a pressure of 1 bar equals the atmospheric or standard pressure.

Figure 7 shows the measurement setup for 1-21 bar oil pressure. A high voltage transformer generates the AC test voltage, which is connected over protective resistances with the measurement cell. At the ground connectioin of the cell a current probe observes the short circuit current.

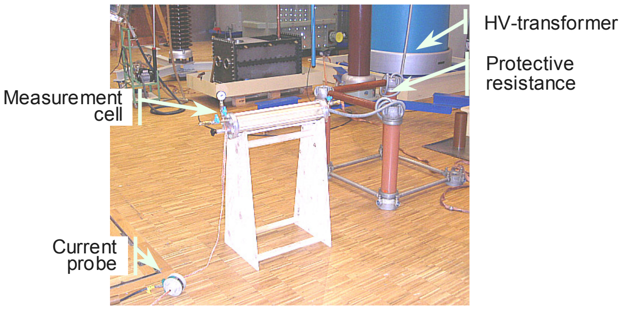

Figure 7: Setup for 1-21 bar oil pressure

A test cell for overpressure was constructed made of epoxy-glass resin. The oil volume amounted 1,1 l. Electrodes are made of stainless steel with a shape according to EN 60156 / VDE 0370 T.5 (spherical with radius 25 mm) and a gap of 2,5 mm.

The very high pressure of up to 100 bar required a second test cell. Here electrodes made of bronze alloy were used. Figure 8 shows test cell and electrodes.

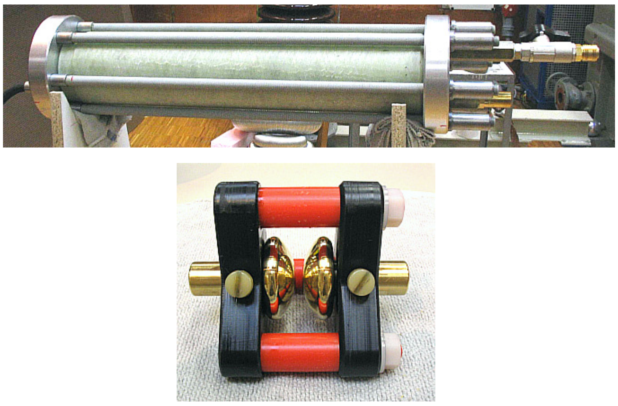

Figure 8: Test cell and electrodes for oil pressure 1-100 bar

A conventional AC test transformer generated the test voltage. A capacitive voltage divider together with a digital oscilloscope measured the breakdown voltage.

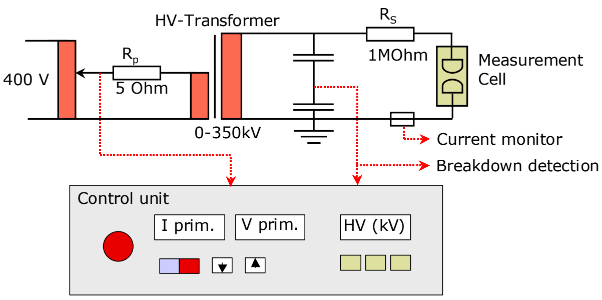

Figure 9: Circuit diagram for the investigations at 1-100 bar

At breakdown tests of liquids it is very important to limit the short circuit current, since otherwise particles from oil combustion will influence the test results. The following means diminish this potential error:

- A series resistor R_p at the LV side of the HV transformer having 5 Ohms decreases the current.
- A series resistor R_s at the HV side having 1 MOhm damps additionally.
- An electronic circuit detects the breakdown by high frequency components in voltage and current. Thus the electric arc extinguishes at the latest 30 ms after breakdown. The electric charge per breakdown is less than 800 µC.

For the low pressure range of 0,1-1,5 bar the automatic test system as described in section 2.1 was used. Its original measurements cell became pressure-proof by a new lid with connections to a vacuum pump and a pressure gauge, see Figure 10.

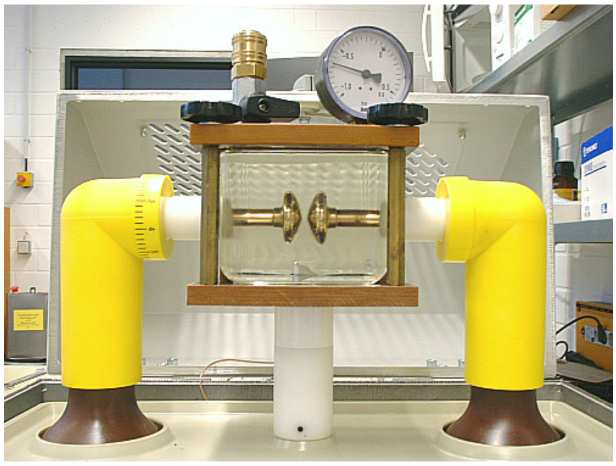

Figure 10: Automatic test system Baur DTA 100 E with modified measurement cell having here 0,3 bar pressure

3.2 INVESTIGATED INSULATION OILS

New mineral insulation oil type Nynas Nytro 3000 (not inhibited) and Nynas Nytro 3000 X (inhibited) were investigated. Both oils were free of particles and gas saturated. Degassing with a conventional drying and degassing plant showed no influence on the breakdown voltage. The relative moisture saturation was 4-6 %, the temperature 20-22°C.

To investigate the influence of particles, dry pressboard fibres were dispersed in a concentration of 20 and 75 g/t oil.

3.3 RESULTS AND DISCUSSION

Figure 11 depicts exemplarily voltage and current during a breakdown at the setup for the investigations up to 100 bar. The left figure shows the voltage, the right one the current with a scale of 1 V = 1 A.

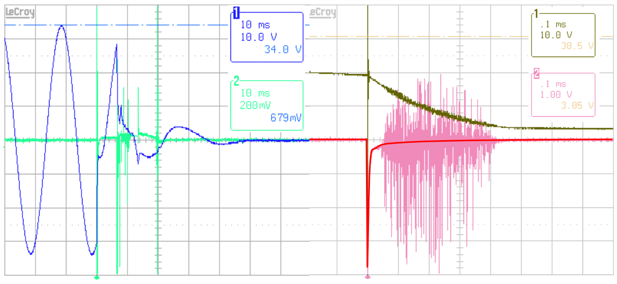

Figure 11: Voltage (left) and current of a breakdown at 1 bar

Figure 12 depicts the breakdown voltage of insulation oil as a function of pressure with linear scaling of the x-axis. This diagram combines the results from all the three measurement setups used for the pressure investigations. The number of single breakdowns for each measurement point were 200-420 for the pressure range below 1 bar and 75 for the pressure range above 1 bar. The results show a considerable standard deviation caused by the stochastic nature of breakdown processes, but a small 5 % confidence belt.

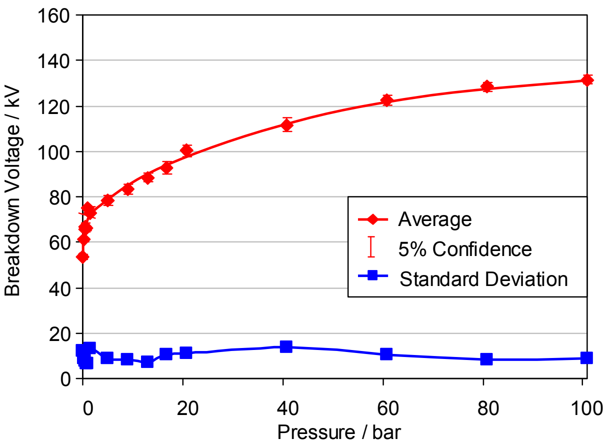

Figure 12: Breakdown voltage of insulation oil as a function of pressure with linear scaling of the x-axis

Just as the theory lets one assume, an increasing oil pressure causes an increasing breakdown voltage up to an asymptotic end value. The breakdown process starts in microscopic bubbles, induced by current injection [1]. A high pressure hinders bubble evolution. On the other hand under-inflation supports it, resulting in a decreased breakdown value. Figure 13 enables for a better view of the low pressure range because of its logarithmically scaled x-axis.

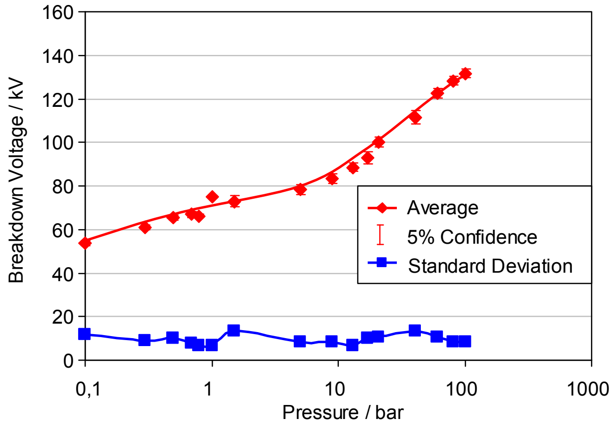

Figure 13: Breakdown voltage of insulation oil as a function of pressure with logarithmic scaling of the x-axis

Oil inhibition has only a slight influence on the breakdown voltage. The asymptotic maximum value for the uninhibited oil seamed to be around 140 kV, whereas that of inhibited oil came to nearly 150 kV.

Figure 14 shows, how dry cellulose particles influence the breakdown voltage of new oil. For the low pressure range there is a decrease, but for atmospheric pressure and above the influence is small only. The reason for the influence is, that particles enable bubbles to evolve. This clearly visible effect happens at under-inflation only. It must be mentioned, that here only dry cellulosic fibres were added, for wet fibres the influence will be more dramatically.

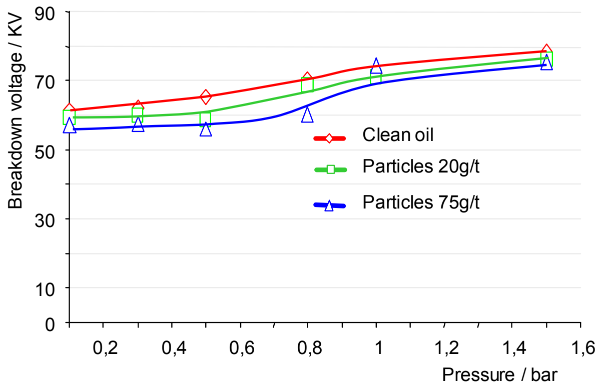

Figure 14: Influence of dry cellulosic particles on the breakdown voltage of new oil

During the measurements at high oil pressure a phenomenon was observed: the oil regained its insulation capability, the breakdown in oil did disappear in the next half-cycle of the test voltage,. These "partial breakdowns" occurred typically at 70-85 % of the average breakdown voltage at a specific oil pressure. Figure 15 illustrates this behaviour, please mind the contrast to Figure 11, where a full breakdown in oil is depicted.

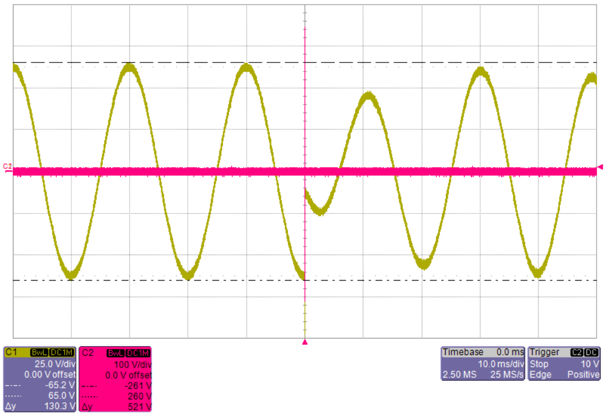

Figure 15: Voltage at the oil gap at a "partial breakdown"

The ratio of full breakdowns to "partial breakdowns" depended on the oil pressure, as shown in Figure 16. At atmospheric pressure all breakdowns were full, at 60 bar 80 % of the breakdowns were "partially". A possible explanation of the pressure dependence is, that the high pressure quenched the electric arc in the oil gap. Thus the oil regained its insulation capability in some milliseconds.

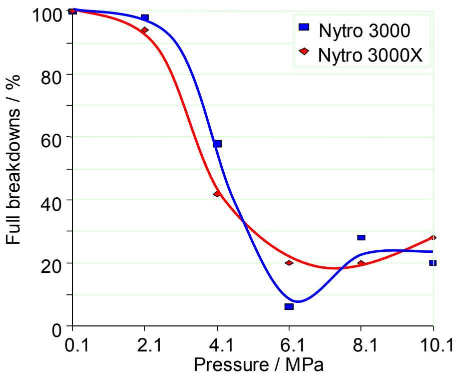

Figure 16: Ratio of full to partial breakdowns as a function of oil pressure

4 SUMMARY AND CONCLUSIONS

The breakdown voltage in mineral insulation oils was investigated under the influences of moisture, acidity, pressure and particles using electrodes according to IEC156/95 Fig.II (VDE0370/Teil5/96 and ASTM D1816).

- The breakdown process starts with a microscopic bubble.
- Moisture provides charge carriers, therefore a moisture saturation of 0 to 20 % decreases the dielectric strength from 72 down to 61 kV.
- Acids as an aging product decrease the dielectric strength too for the same reason.
- Not the total acid number TAN, but the low molecular acids cause the major effect.
- An increasing pressure increases the breakdown voltage too. The asymptotic behaviour seems to come to a maximal end value of around 150 kV.
- Under-inflation supports bubble generation, decreasing the dielectric withstand strength.
- Dry particles (cellulose fibres) decrease the breakdown voltage only at under-inflation, since they support bubble generation. There is nearly no influence at atmospheric pressure and above.

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