Measurement of Electrical Parameters of Breakdown in Transformer Oil

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Abstract. *The initial state of breakdown development is explained on the basis of bubble theory. Application of HV-DC voltage to electrodes immersed in oil results to creation of small channels, in which streamers can develop. In the next phase a plasma channel between the electrodes can be formed. The electrical resistance of plasma channel changes from a few ohms to a few hundred milliohms due to Joule heating caused by high arc current which flows through the plasma. The dynamics of the arc current depends on the parameters of outer circuit and is represented by RLC circuit.*

Keywords: plasma channel, arc resistance, arc current, RLC circuit

1. Introduction

The electrical breakdown in transformer oil and characteristic properties of this process are very important for many applications. Insulating liquids such as transformer oils are critical components for high voltage and pulsed power system. It was reported in numerous publications that dielectric breakdown is based on complex interactions of hydrodynamic and electronic phenomenons [1,2].

In present it is well known the initial stage of breakdown in transformer oil can be described using bubble mechanism. This theory assumes that a bubble of gas is formed by vaporization of liquid by local heating in the strong field region at a surface of the electrode. So the formed bubble will grow and a breakdown will take place inside the bubble. The breakdown processes are also dependent on mechanisms, which play role on interface of the liquid and the surface of electrodes. During breakdown a plasma channel with high initial resistance value is formed. This stage of breakdown - the creation of the plasma channel is similar for various types of liquid or gaseous at enough high applied voltage, although times and processes leading to this stage of breakdown are different.

The aim of the research reported in this article is to describe the time development of breakdown and its current in transformer oil using electrical detection techniques.

2. Experimental setup

Fig. 1 shows the schematic diagram of the experimental setup, which includes HVdc power supply TESLA BS 221 (max voltage 10 kV and current 3 mA), electrode system, electric and optical diagnostics. Sphere-to-sphere Cu electrodes with radius 1 cm were used as the electrode system. The distance of electrode was measured by metric gauge blocks with accuracy of 0.01 mm. New and unfiltered transformer oil - ITO 100 was filled into discharge chamber (0.2 dm^3) and electrodes were cleaned after series of 5 breakdowns. Time intervals between breakdowns were 15 minutes. The capacitor bank contained up to 4 HV capacitors connected in parallel, with nominally capacitance 0.05 μF. This allowed capacitances of between 0.05 and 0.2 μF to be used. The applied voltage and current were measured using a high voltage probe (E253/01, 10 MHz) and a Rogowski coil (Pearson Current monitor 110A, 10 kA, 20 MHz, 50 ns). Development of current and voltage were measured using 150 MHz external oscilloscope ETC M621.

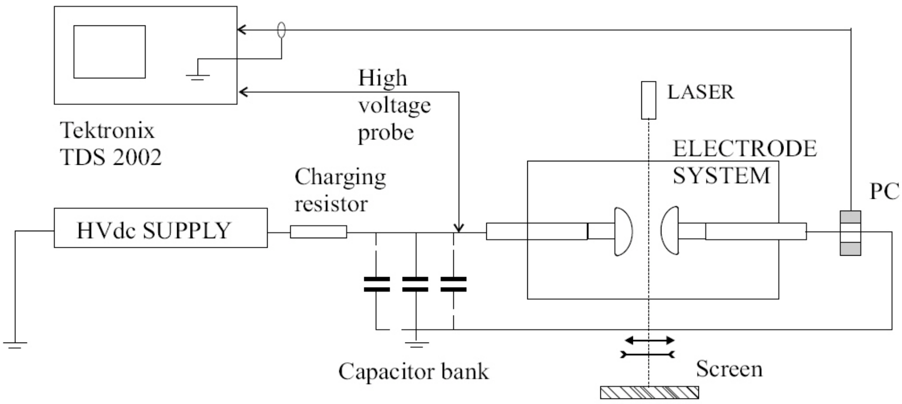

Fig. 1. Experimental setup

3. Results

Various transport phenomena were observed at electric field below 10^6 V/m. At around 25 % value of breakdown voltage (3×10^6 V/m) a small channel with diameter of some micrometers was detected between electrodes. Number of channels rose with increasing voltage. Their shapes were not stable and they were changing and moving. Shapes of these narrow channels illuminated by the laser are displayed in Fig. 2. Number and distribution of channels were dependent on electrode distance and applied voltage. Scattering of laser light on the interface of channels and the oil was caused by lower density of channels than that of the oil. The channels were concentrated along the electrode axis at voltage over the breakdown voltage.

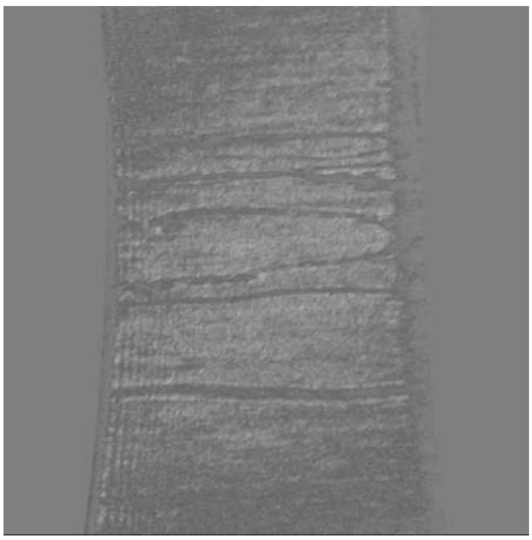

Fig. 2. The picture of discharge gap at the applied voltage 1.2 kV and gap distance 0.4 mm.

Development of the arc current at various capacitances is presented in the Fig. 3. For this case and type of electrode configuration there is almost homogeneous electric field with the electric intensity 74 kV/cm. The arc current is characterized by under-damped oscillation and its angular frequency depends on the value of capacitance, as it can be seen in Fig. 3. At equal capacitance only amplitude and duration of arc current changed with applied voltage. The measurements were also made at various electrode distances (0.1, 0.2 and 0.3 mm) and similar developments of arc currents as were observed in the Fig. 3. Simple measurements in transformer oil were also made by Marton [5], in water by Timoshkin et al. [1] and in air by Kijonka et al. [3].

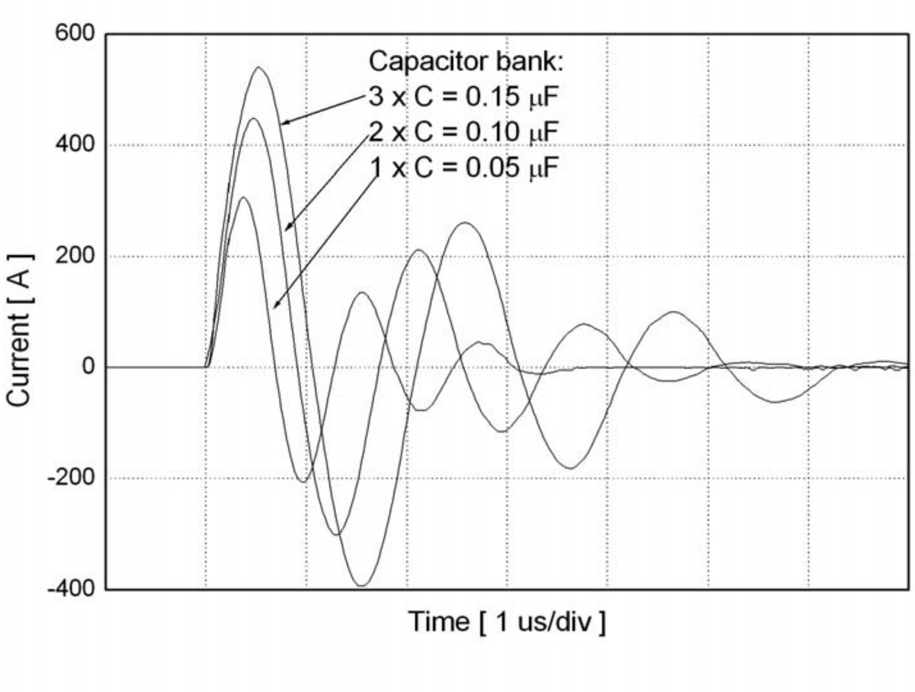

Fig. 3. Development of arc current and voltage across gaps at voltage 3000 V in ITO 100 and gap distance of 0,3 mm

During breakdown the experimental setup can be described by a electrical circuit, in which the arc current flows. Time dependence of the arc current can be fitted by function Sine Damp:

$$I(t) = I_0 e^{-\alpha t} \sin(\omega t), \tag{1}$$

where

- I_0 the amplitude of current,
- α the damping ratio,
- ω the angular frequency of under-damped oscillation.

These parameters are determined by interpolation of measured pulses of arc current. Similar development of current can be observed in RLC circuit. On the basis of this similarity, corresponding values R, L and C* of the electrical circuit were calculated using the previous parameters and the breakdown voltage U_B as:

$$L = \frac{U_B}{I_0 \omega}, \quad R = 2\alpha L, \quad C^* = \frac{1}{L(\omega^2 + \alpha^2)} \tag{2, 3, 4}$$

where

- R the total resistance of the electrical circuit.

Table 1. Electrical parameters of arc discharge

C [μF]	I_0 [A]	α [μs^{-1}]	ω [rad μs^{-1}]	R [mΩ]
0.05	303	0.719	4.976	1162
0.10	450	0.484	3.955	753
0.15	542	0.378	2.998	561
0.20	630	0.352	2.548	165

This circuit can be divided into two parts: external part with $R_{circuit}$ (HVdc power supply, capacitor bank, connecting cords and experimental equipment) and the arc resistance of the plasma channel R_{pl} (t): $R = R_{pl} + R_{circuit}$. Capacitance C* calculated using previous formula was equal to the capacitance C of capacitor bank with accuracy better than 2%. Fitted parameters I_0, α, ω and calculated R are listed in the Table 1 for different capacitances C. The same identifications as in work [1] were used. Resistance R of the electrical circuit reduces with increasing input energy.

4. Discussion and Conlusion

From electrical point of view the whole breakdown can be represented by RLC circuit. Parameters of this circuit were calculated from experimental results using the theory of RLC circuit. During this stage, energy stored in capacitor bank was discharged to the system and under-damped arc current oscillations (Fig. 3, Eq. 1) were observed. The model of RLC circuit was also used in [1]. After transient phase, the value of arc resistance $R_{pl\text{-}const}$ was order of severel mΩ, so it had minimal effect to development of the arc current. Development of the arc current depends on capacitance of capacitor bank (see Fig. 1) and parameters of outer circuit [4]. Similar development of the arc current was observed in oil by Marton et al. [5]. The breakdown was accompanied with other various processes as: acoustical effect, light flash, shock and acoustic waves. Many bubbles of various magnitude were observed after breakdown.

The breakdown characteristics of oil ITO 100 were measured. At voltage over the breakdown voltage the arc channel was created. Its arc resistance changed from a few ohms to a few hundreds milliohms due to Joule heating caused by the arc current flowing through the arc channel. On the basis of experimental results it can be said that breakdown in transformer oil is represented by RLC circuit on a microsecond scale. The development of the arc current is modified by parameters of outer circuit and effect of nonlinear characteristics of breakdown was neglected.

References

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