Jozef KUDELČIK, Miroslav GUTTEN, Pavel VIRDZEK

University of Žilina, Slovakia

Measurement of electrical parameters of breakdown in transformer oil

***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.*

*Streszczenie. Początkowe stadium przebicia w oleju transformatorowym jest analizowane przy wykorzystaniu teorii bąbli. Przyłożenie dużego napięcia DC powoduje powstawanie kanałów. W następnej fazie powstaje kanał plazmowy między elektrodami. Rezystancja kanału plazmowego zmienia się od kilku omów do kilku miliomów na skutek ogrzewania łukowego. Parametry wyładowania łukowego zależą też od zewnętrznego obwodu RLC. (**Badanie parametrów elektrycznych przebicia izolacji olejowej**)*

Keywords: plasma channel, arc resistance, arc current, RLC circuit.
Słowa kluczowe: kanał plazmowy, izolacja olejowa

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 phenomenon [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.

Theory

The development of breakdown can be characterized using some parameters as: resistance, its radius and temperature, dissipated energy and pressure of the plasma channel. Their time development can be described using an analytical approach, which combines energy based hydrodynamic equations, channel radiation and heat conduction and change of the pressure in the channel. The Braginskii model [3] for air is combination of these parameters into self-consistent calculations, where the channel radius is allowed to grow through hydrodynamic expansion driven by the electric energy delivered in Joule heating.

To describe time-dependent channel resistance, an analytical model has been developed based on the Braginskii hydrodynamic energy balance equation and an empirical link between the plasma channel resistance and its internal energy. The Braginskii equation, as proposed in [3] and discussed by Engel *et al* [4], states that the electrical energy delivered to the plasma channel, $E_{el}(t)$ through Joule heating is divided between the internal energy, $W_{in}(t)$, of the plasma–vapour mixture inside the cavity and the mechanical work done by the expanding cavity. $W_{in}(t)$ can be determined from:

$$W_{in}(t) = \frac{p(t)V(t)}{\gamma - 1}, \tag{1}$$

where $V(t)$ is the volume of the plasma channel, $p(t)$ is the pressure in the channel and γ is specific heats.

Energy partition in liquid dielectric spark discharges has been studied by several researchers [1, 2, 3, 5, 6]. It was shown by these authors that the main components of the discharge energy are the internal energy of the plasma–vapour mixture inside the transient cavity and the mechanical work done by the cavity. A simplified version of the energy balance equation [1] for the spark channel which can be written in terms of electrical power deposited in the channel:

$$p(t)\frac{dV(t)}{dt} + \frac{dW_{in}(t)}{dt} = R_{pl}(t)[I(t)]^2 \tag{2}$$

Here $R_{pl}(t)$ is the resistance of the plasma channel and $I(t)$ is the time varying discharge current. The first term in this equation represents changes in the kinetic energy of water as it moves in response to the expansion of the plasma cavity and the second term expresses changes in the internal (potential) energy of the cavity.

During the breakdown process resistance of the plasma channel, its temperature and radius and pressure inside the channel exhibit a highly dynamic behaviour. The plasma channel decreases from its initial value of a few Ohms to a minimum value occurring at the current peak when the magnitude is a few hundreds milliohms [1]. Martin et al [6] applied the breakdown model developed for gases by Braginskii to water. In work by Warme [5] it was made combination of these models into Braginskii-Martin's model and it was used for water. To describe this time dependent plasma channel resistance, model derived in work by Warme [5] was used, which is based on Braginskii-Martin analytical model [5]. This model calculates physical parameters of arc channel using system of three differential equations (the energy balance equation for spark channel which is written in term of electrical deposited energy in channel; the energy balance between energy change of plasma channel to channel radiation and heat conduction; the change of pressure in channel by shock approximation) [7]. The solution of this system gives time development of $p(t)$ is pressure, $A(t)$ is area and $T(t)$ is time dependence of temperature of arc channel.

Experimental setup

Fig.1 shows the schematic diagram of the experimental setup, which includes HVdc power supply TESLA HVdc power supply TESLA HT 55-I (max voltage 60 kV and current 2,5 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 2 HV capacitors connected in parallel, with nominally capacitance 0.05 μF. This allowed capacitances of between 0.025 and 0.01 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 M520.

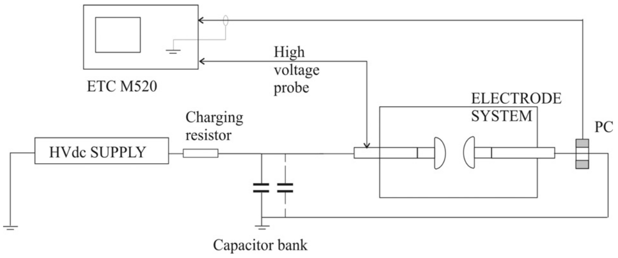

Fig.1 Experimental setup

Rogowski coils are used for detection and measurement of electric currents. The operating principle is that if an air-cored coil (Fig. 2.) is placed around the conductor in a closed path, the magnetic field produced by the current induces an output voltage U_1 in the coil that is proportional to the rate of charge of the encircled current I, given by the expression: $U_1 = -M\ dI / dt$, where M is the mutual inductance between the Rogowski coil and the conductor. If the coil is connected to an integrator (Fig. 2.), the output reproduces the current waveform. Because the output from the Rogowski coil is proportional to the time derivative of the current, an integrator is needed to convert the *di/dt* signal back to the format of *i(t)*.

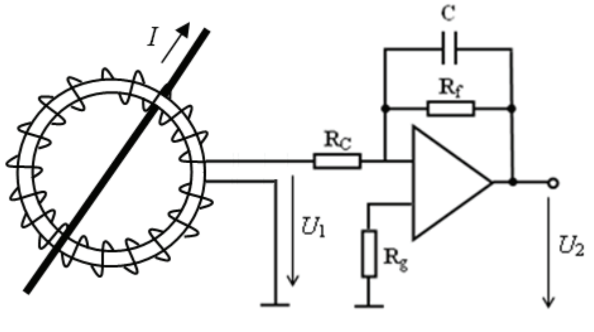

Fig.2 Principle of Rogowski coil

Results

Various transport phenomena were observed at electric field below 10^6 V/m. At around 25 % value of breakdown voltage (30 kV/cm) 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.3. 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.3 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. 4. 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 to 0.6 mm) and similar developments of arc currents as were observed in the Fig. 3. Simple measurements in transformer oil were also made by Marton [8], in water by Timoshkin *et al.* [1] and in air by Kijonka *et al.* [9].

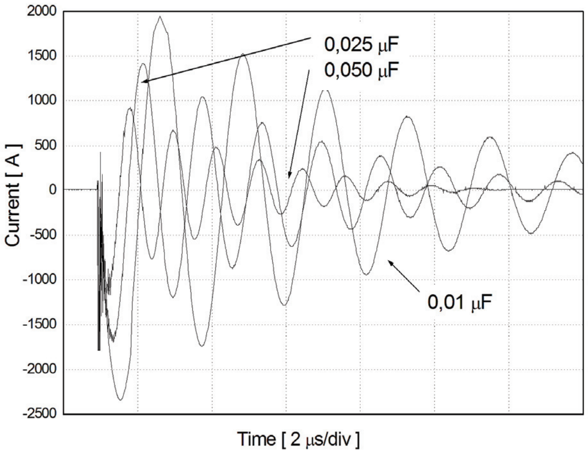

Fig.4 Development of arc current and voltage across gaps at voltage 9200 V in ITO 100 and gap distance of 0,4 mm

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:

$$I(t) = I_0 e^{-\alpha t} \sin(\omega t), \tag{3}$$

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:

$$L = \frac{U_B}{I_0 \omega}, \quad R = 2\alpha L, \quad C^* = \frac{1}{L(\omega^2 + \alpha^2)} \tag{4,5,6}$$

where *R* the total resistance of the electrical circuit.

Table1

C [μF]	I_0 [A]	α [μs^{-1}]	ω [rad μs^{-1}]	R [mΩ]
0.025	1 250	0.309	5.375	849
0.05	1 850	0.212	3.909	540
0.01	2 200	0.133	2.825	391

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.

From previous results it can not be determined resistance $R_{pl}(t)$ of the plasma channel in transformer oil. There are no works concerning the calculations of the time dependence of the plasma channel resistance in transformer oil. In the case of water, the empirical expression relating resistance of the plasma channel to its internal energy $W_{in}(t)$ [1,10] can be used

$$R_{pl}(t) = \frac{Al^2}{W_{in}(t)} = \frac{Al^2(\gamma - 1)}{p(t)V(t)}, \tag{7}$$

where A is a spark constant and *l* is the length of the discharge channel. This empirical expression could be characteristically for various types of liquids and the spark constant changes in dependence on the type of liquid.

From the measured arc current fitted by SineDamp (3) (Table 1) and the initial condition ($p(0) = 10^5$ *Pa*, $A(0) = \pi (10^{-6})^2$ *m*^{2}, $T(0) = 300$ *K*) we get by solution of systems of differential equations [7] time development of *p(t)* is pressure, *A(t)* is area and *T(t)* is time dependence of temperature of arc channel The arc radius was then calculated as $r(t) = \sqrt{(A(t)/\pi)}$ for different conditions which are shown in Fig. 3. From this figure it can be seen, that the arc radius rises with time, what is similar with results of other studies [1, 5, 11]. Time dependence of the plasma channel resistances was calculated by equation (7) (A = 2,5 10^5 V/m^2 [1,12]), when they are known time development of p(t) is pressure, $V(t) = A(t)\, l$ is volume of arc channel. It can be observed (Fig. 5) that resistance of the plasma channel drops rapidly during the first two microseconds and then it reaches at minimum value, which is the order of several hundreds mΩ (R, Table 1). The minimum resistance of the plasma channel decreased with increasing values of peak arc current, the number of capacitors connected in parallel and energy dissipated in the plasma channel. It can be seen from comparison with Fig. 3, that significant decrease of the plasma channel resistance was associated with initial increase of the arc current to the peak value. The increase of resistance after 5 ms is associated with decay of arc channel.

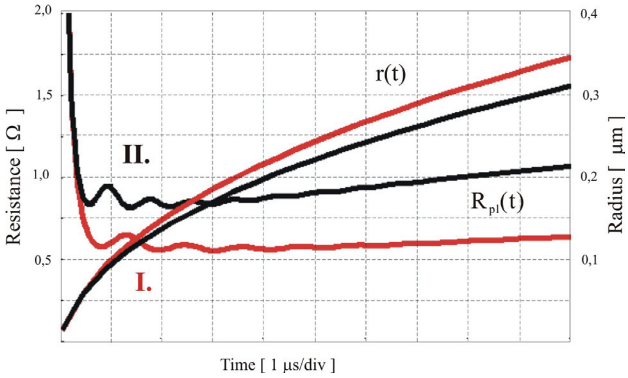

Fig. 5 Theoretical development of resistance $R_{pl}(t)$ and radius r(t) of the plasma channel at voltages 9.2 kV (I. 0,1 μF; II. 0,025 μF) and electrode distance 0.4 mm.$

Discussion and conclusion

The application of the high-voltage to electrodes immersed in a dielectric transformer oil ITO 100 results in breakdown if its magnitude exceeds a breakdown voltage. From the works [1, 2, 11] it is known that breakdown in transformer oil can be described by the bubble mechanism that leads to streamer propagation between the electrodes. After the streamer bridges the inter-electrode distance the current increase (see Fig. 3) and the plasma channel is created. This channel has very small radius, conduction and relatively large value of initial resistance $R_{pl}(t=0)$ (see Fig. 5). Time dependence of resistance and radius of plasma channel were calculated by the system of differential equations [7] and (7). From Fig. 4, 5 the results show that the development of the plasma channel is associated with the fast decrease of its resistance $R_{pl}(t)$ from few ohms to few hundreds milliohms during the first half period (~1 μs) of the current. This decrease is caused by Joule heating from high current which flows through the plasma channel. Resistance of the plasma channel is indirectly proportional to *p(t)* and *V(t)*. Joule heating causes, during the first microsecond of breakdown, a big increase of temperature from 300 K to more than 11000 K, the consequence of this is big decrease of the plasma channel resistance. This decrease is also connected with the increasing radius of plasma channels as is it shown in Fig. 5 and in works [1, 7]. The plasma channel resistance is stabilized 2 µs after the start of breakdown (Fig. 5) and the magnitude of this value is dependent on the applied voltage and capacitance. The correct computation of time development $R_{pl}(t)$ is confirmed by similarity in the development of experimental and theoretical dissipated energy during breakdown [7]. Development of resistance of the plasma channel in oil (Fig. 5) has the same characteristics as development of the plasma channel resistance in air [13].

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. 3) 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. 3) and parameters of outer circuit [14]. Similar development of the arc current was observed in oil by Marton *et al.* [8]. The breakdown was accompanied with other various processes as: acoustical effect, light flash, shock and acoustic waves. Many bubbles of various magnitudes were observed after breakdown.

The breakdown characteristics of oil ITO 100 were measured. The physical parameters of the breakdown process were calculated on the base of the Braginskii-Martin's model. From these parameters time dependence of radius, resistance, pressure, temperature of channel and dissipated energy of the plasma channel were calculated. Development of the resistance and radius of plasma channel are presented. The 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.

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***Authors**: [1]RNDr. Jozef Kúdelčík, PhD., [1]RNDr. Pavel Virdzek, [2]doc. Ing. Miroslav Gutten, PhD., [1]Department of physics, [2]Department of Measurement and Application Electrical, Faculty of Electrical Engineering, University of Žilina, Univerzitná 1, 010 26 Žilina, Slovakia, Email:* kudelcik@fyzika.uniza.sk, gutten@fel.uniza.sk