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## To cite this version:

J. Kúdelčík. The resistance of plasma channel in transformer oil. European Physical Journal: Applied Physics, 2010, 50 (1), pp.11002. 10.1051/epjap/2010016 . hal-00581866

**HAL Id: hal-00581866**

**https://hal.science/hal-00581866v1**

Submitted on 1 Apr 2011

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**EPJ manuscript No.**
(will be inserted by the editor)

# The resistance of plasma channel in transformer oil

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Received: 17.11.2008 / Revised version: date

**Abstract.** The initial state development of breakdown is explained on the basis of bubble theory. Application of dc voltage to electrodes immersed in oil results in the creation of small channels. In the next phase an arc channel between the electrodes is formed. Resistance of the plasma channel changes from a few ohms to a few hundreds milliohms due to Joule heating caused by high arc currents which flows through this channel. The dynamics of the arc current depends on the parameters of the outer circuit and is represented by the RLC circuit.

**PACS.** 52.80.Wq Discharge in liquids and solids – 77.22.Jp Dielectric breakdown and space-charge effects

## 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 systems. It has been reported in numerous publications that dielectric breakdown is based on complex interactions of hydrodynamic and electronic phenomenon [1–3].

At present it is well known the initial stage of breakdown in transformer oil can be described using the bubble mechanism [4–8]. This theory assumes that a bubble of gas is formed by the vaporisation of liquid by local heating in the strong field region at the surface of the electrode. Therefore the formed bubble will grow and a breakdown will take place inside the bubble. The breakdown processes are also dependent on mechanisms, which play a role on the interface of the liquid and the surface of the electrodes (Lippmann's phenomena, Auger's effect) [9]. During breakdown a plasma channel with a high initial resistance value is formed. At this stage of breakdown the creation of the plasma channel is similar for various types of liquid or gas at a high enough applied voltage, although times and processes leading to this stage of breakdown are different [6,10,11].

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The plasma channel is developed and is mainly dependent on the input energy and the experimental conditions. This phase of breakdown can be characterised using some parameters and one of them is resistance to the plasma channel. With gas there are many models which describe the arc resistance [10,11]. For liquid at present only theoretical models of arc resistance in water [2,3,12,13] are present. Timoshkin *et al.* [2] described the formation and development of a highly conductive plasma channel between electrodes immersed in water. The processes in water were described using an analytical approach, which combines energy based hydrodynamic equations and the equation describing the current in a under-damped circuit. The model is based on the self-consistent calculation of the plasma channel at time-varying resistance. Minimum values of the dynamic plasma channel resistance were of the order of several hundreds m$\Omega$. Timoshkin model is based on Braginskii model [14], where the channel radius is allowed to grow through hydrodynamic expansion driven by the electric energy delivered in Joule heating. Although many of the channel heat transfer processes and conductivity variations with temperature are examined in his paper, the final model makes use of fixed channel conductivity. Discussion of these models versus experiments can be found in Meek and Craggs [15]. Martin [16] applied the breakdown model developed for gases by Braginskii to water. The solution of Martin-Braginskii's model for water was made to by work Warme [3]. Gurovich *et al.* [12] derived normalisation differential equations in their model which describe the processes of underwater wire initiated discharge. In these equations the energy conservation law for wire material evaporation and the dependence of plasma conductivity on the energy dissipated in the discharge are implied to calculate the time varying resistance of the plasma channel.

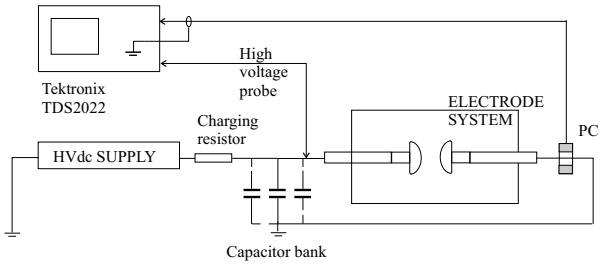


**Fig. 1.** Experimental setup.

The aim of the research reported in this article is to describe the time development resistance and radius of the plasma channel in transformer oil using electrical detection techniques and theoretical articles.

## 2 Experimental set-up and procedure

Figure 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 and electric diagnostics. Sphere-to-sphere Cu electrodes with radius $1\,cm$ were used as the electrode system. The distance of the electrode was measured by metric gauge blocks with an accuracy of $0.01\,mm$. New and unfiltered transformer oil - ITO 100 was filled into the discharge chamber ($0.2\,dm^3$) and electrodes were cleaned after a 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 ca-

pacitance $0.05\,\mu F$. This allowed capacitances of between 0.05 and $0.2\,\mu F$ 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 $110\,A$, $10\,kA$, $20\,MHz$, $20\,ns$). The signals were recorded using Tektronix $TDS2022$, $200\,MHz$ digital oscilloscope. Time resolution is enough for measurements of the whole breakdown process from the point of view to the change of plasma channel resistance.

Development of the arc current at various capacitances is presented in the Fig. 2. For this case the type of electrode configuration there is almost a homogeneous electric field with the electric intensity $74\,kV/cm$. The arc current is characterised by under-damped oscillation and its angular frequency depends on the value of capacitance, as it can be seen in Fig. 2. At equal capacitance only the amplitude and duration of the arc current changed with applied voltage. The measurements were also made at various electrode distances (0.05, 0.15, 0.20 and $0.03\,mm$) [17,18] and similar developments of arc currents were observed as in Fig. 2. Simple measurements in transformer oil were measured by Marton *et al.* [19], in water by Timoshkin *et al.* [2] and in air by Kijonka *et al.* [20].

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

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

where parameters $I_0$, $\alpha$, $\omega$ were determined by the fitting of measured arc currents. Similar developments of current

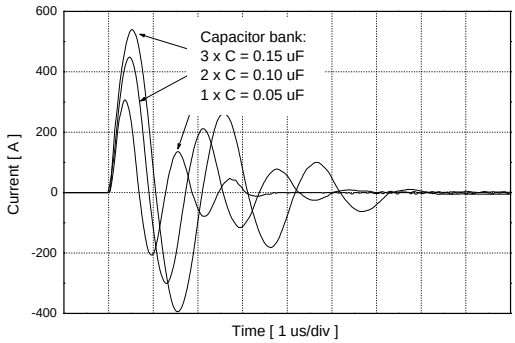


**Fig. 2.** Development of arc current at various capacitances at voltage $U_B = 1480\,V$ in ITO 100 and electrode distance $0.2\,mm$. The pulses increase in amplitude with increasing capacitance.

can be observed in the 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:

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

$R$ is the total resistance of the electrical circuit. This circuit can be divided into two parts: the external part with $R_{circuit}$ (connecting cords and experimental equipment) and resistance of the plasma channel $R_{pl}$(t): $R = R_{pl} + R_{circuit}$. Capacitance $C^*$ calculated using equation (2) was equal to the capacitance $C$ of the capacitor bank with accuracy better than 2%, so during the breakdown some additional capacitances were not created. Parameters $I_0$, $\alpha$, $\omega$, $L$ and $R$ are listed in the Table 1 for different capacitances $C$. The same identifications as in work [2] were used. In general values $R$, $L$ and $C^*$ calculated from previous equations can be a function of time during breakdown. These time dependencies can not be found from

**Table 1.** Electrical parameters of arc discharges. $C$ is capacitance of capacitor bank at which the next values in the column were determined: dissipated energies in the breakdown calculated from data of experiments and results of Braginskii-Martin model based on the equations $(3-5)$ are denoted as $W_E$ or $W_T$, respectively; $I_0$, $\alpha$ and $\omega$ are max current, attenuation coefficient and angular frequency of fitted arc current by equation (1); $L$ and $R$ are values of the RLC circuit which characterises the arc current and $R_{pl-const}$ is the established value of resistance of the plasma channel in $5\,\mu s$.

| $C\,[\mu F]$ | 0.05 | 0.10 | 0.15 | 0.20 |
|---|---|---|---|---|
| $W_E\,[mJ]$ | 132 | 299.1 | 358.4 | 587.0 |
| $W_T\,[mJ]$ | 168 | 312 | 421 | 506.0 |
| $I_0\,[A]$ | 303 | 450 | 542 | 630 |
| $\alpha\,[\mu s^{-1}]$ | 0.719 | 0.484 | 0.378 | 0.352 |
| $\omega\,[rad\,\mu s^{-1}]$ | 4.976 | 3.595 | 2.998 | 2.548 |
| $L\,[H]$ | 0,807 | 0.779 | 0.741 | 0.759 |
| $R\,[m\Omega]$ | 1162 | 753 | 561 | 534 |
| $R_{pl-const}\,[m\Omega]$ | 943 | 729 | 557 | 478 |

RLC theory, but time dependence of the plasma channel resistance is calculated in the next part of the article. This part showed that the arc current of breakdown has similar characteristics as the current in the RLC circuit.

From previous results resistance $R_{pl}$(t) of the plasma channel in transformer oil can not be determined. 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 to the resistance of the plasma channel to its internal energy $W_{in}(t)$ [2,21] which can be used $R_{pl}(t) = A\,l^2/W_{in}(t)$, where $A$ is a spark constant and $l$ is the length of the discharge channel. This empirical expression could be characteristic for various types of liquids and the spark constant changes in dependence on the type of liquid.

During the breakdown process resistance of the plasma channel exhibits a highly dynamic behaviour and 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 [2,22]. To describe this time dependent plasma channel resistance, model derived in work by Warme [3] was used, which is based on Braginskii-Martin's analytical model [16]. This model calculates physical parameters of the arc channel using a system of three differential equations (the energy balance equation for spark channel which is written in terms of electrical deposited energy in channel; the energy balance between energy change of plasma channels to channel radiation and heat conduction; the change of pressure in channel by shock approximation):

$$p(t)\frac{dA(t)}{dt} + \frac{d}{dt}\left(\frac{p(t)A(t)}{\gamma - 1}\right) = I^2(t)R_{pl}(t) \tag{3}$$

$$T(t)\frac{d}{dt}\left(\frac{p(t)A(t)}{T(t)}\right) = \frac{\gamma - 1}{\gamma}(Q_R + Q_T) \tag{4}$$

$$p(t) = 2\rho_0\frac{1}{4\pi A(t)}\left(\frac{dA(t)}{dt}\right)^2 \tag{5}$$

where $p(t)$ is pressure , $A(t)$ is area and $T(t)$ is time dependence of temperature of arc channel and $\rho_0 = 3000\,kg.m^{-3}$ is the density of the transformer oil. Based on the literature a specific heat ratio of $\gamma = 1.35$ has been based chosen for the present model. Time development of the arc current (Fig. 2, equation (1)) and the initial condition ($p(0) = 10^5\,Pa$, $A(0) = \pi(10^{-6})^2\,m^2$, $T(0) = 300\,K$)

were needed for the solution of this system (3 - 5) by Mathemetica. This model also takes into consideration thermal diffusion $Q_T$ and radiation $Q_R$, described by the next equations [3]:

$$Q_T(t) = 1.3(\frac{2\pi^3}{3e^2})\sigma_0(kT(t))^3$$
$$Q_R(t) = \sqrt{4\pi A}\,\sigma_S T(t)^4$$

Time dependence of plasma channel resistance was calculated by equation:

$$R_{pl}(t) = \frac{l}{\sigma(T)A(t)} \tag{6}$$

where $l$ is the electrode distance (the length of the discharge channel) and for channel conductivity the following equation was used: The linear Fedorov approximation defined as: $\sigma(T) = \sigma_0\,(kT(t))$ ($\sigma_0 = 1.6 \times 10^{23}\,S/J.m$, $\sigma_0$ is the Stefan-Boltzman constant and $k$ is the Boltzman constant).

From the measured arc current and solution of systems of differential equations (3 - 5) time development of the area of arc channels $A(t)$ was calculated. The arc radius was calculated as $r(t) = \sqrt{A(t)/\pi}$ for different conditions which are shown in Fig. 3. From figure it can be seen, that the arc radius rises with time, what is similar with results of other studies [2,3,6,22]. Time dependence of the plasma channel resistances calculated by equation (6), for the same conditions as in Fig. 2, are illustrated in Fig. 3. It can be observed that resistance of the plasma channel drops rapidly during the first two microsecond and then it establishes a value $R_{pl-const}$. This value is also presented in Table 1 for time $5\,\mu s$ and is like resistance $R$ determined

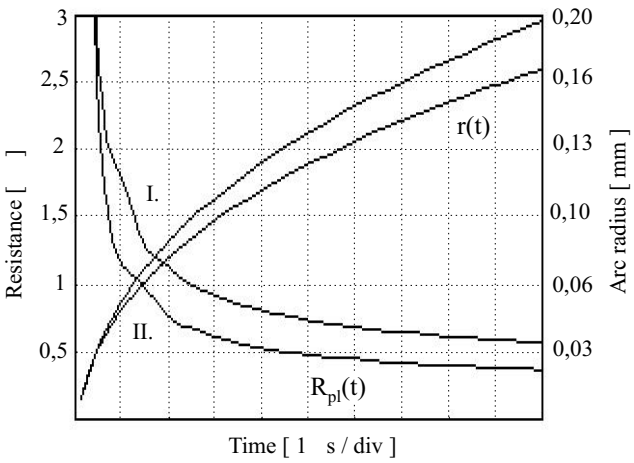


**Fig. 3.** Theoretical development of resistance $R_{pl}(t)$ and radius $r(t)$ of the plasma channel for conditions in Table 1 ( I. $C = 0.1\mu F$, II. $C = 0.2\mu F$) at voltage $U_B = 1480\,V$ in ITO 100 and electrode distance $0.2\,mm$.

by equation (2). It is evident from the Table 1 that 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 (Fig. 3). It can be seen from comparison with Fig. 2, that significant decrease of the plasma channel resistance was associated with initial increase of the arc current to the peak value. Similar results for development resistance of the plasma channel in air give models of Rompe and Weizel [11] and Kurshner [22].

The experimental dissipated energy $W_E$ in the breakdown (Fig. 4(a)) was calculated from time integral of the (arc current) $\times$ voltage injected to the gap, where time development of voltage was measured by the high voltage probe. Theoretical dissipated energy $W_T$ (Fig. 4(b)) was again calculated as time integral of the (arc current)$^2$ $\times$ $R_{pl}(t)$. $R_{pl}(t)$ was calculated by equation (6) using results obtained by the solutions of equations $(3, 4, 5)$. Both time

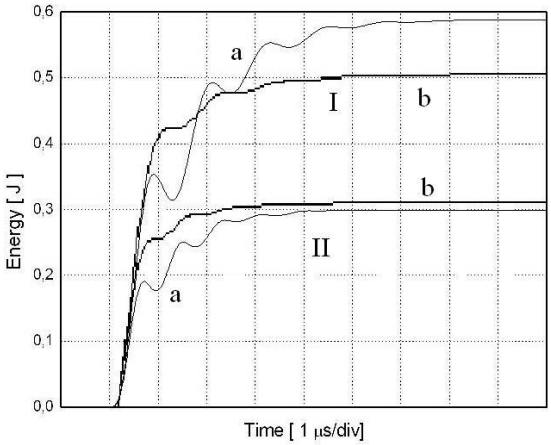


**Fig. 4.** Development experimental $W_E$ (a) and theoretical $W_T$ (b) dissipated energies in plasma channel for conditions in Table 1 ( I. $C = 0.1\mu F$, II. $C = 0.2\mu F$) at voltage $U_B = 1480\,V$ in ITO 100 and electrode distance $0.2\,mm$.

developments of the dissipated energies during the breakdown are presented in Fig. 4. It can be seen from Fig. 4, experimental and theoretical dissipated energies are very similar. The mistake in the determination of theoretical dissipated energy is better then 15%. The total experimental $W_E$ and theoretical $W_T$ energies dissipated during whole breakdown process are presented in Table 1. In time $2\,\mu s$ after the start of the breakdown the dissipated energy reach up more then 85% of final value.

## 3 Discussion

The application of the high-voltage to electrodes immersed in a dielectric transformer oil ITO 100 results in breakdown if the magnitude of the applied electric field exceeds a critical value. From the works [1,2,6,23] it is known that breakdown in transformer oil can be described by the bubble mechanism that lead to streamer propagation between the electrodes. After the streamer bridges the inter-electrode distance the current increase (see Fig. 2) and the plasma channel is created. This channel has a very small radius and conduction and a relatively large value of initial resistance $R_{pl}(t = 0)$ (see Fig. 3). Time dependence of resistance and radius of plasma channel were calculated by the of system of differential equations (3 - 5) and (6) from the work by Warme [3]. From Fig. 2 and Fig. 3 the results show that the development of the plasma channel is associated with a fast decrease of its resistance $R_{pl}(t)$ from a few ohms to a few hundreds milliohms during the first half period 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 $\sigma(T)$ (equation (6)), which is the function of temperature of the plasma channel. Joule heating causes, during the first microsecond of breakdown, a big increase of temperature from $300\,K$ to more then $10\,000\,K$, the consequence this has is to influence a big decrease of the plasma channel resistance. This decrease is also connected with the increasing radius of plasma channels as is shown in Fig. 3 and in works [2, 10,18]. $2\,\mu s$ after the start of breakdown (Fig. 3) the plasma channel resistance is stabilised on the value $R_{pl-const}$ (Table 1) and the magnitude of this value is dependent on the peak current 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 (4). The stabilisation of the plasma channel resistance was caused by input of

85% dissipated energy in the second microsecond of breakdown. In next phase of breakdown there was not enough energy to made any important changes. Similar results were published in [2], too. Development of resistance of the plasma channel in oil (Fig. 3) has the same characteristics as development of the plasma channel resistance in air [11]. The correct results of calculation of system (3 - 5) with used conditions confirmed similar developments of experimental and theoretical dissipated energy in the plasma channel (Fig. 4, Table 1). Similar characteristics of development of breakdown in water were presented in [2,3,6,12,23].

From an electrical point of view the breakdown after connection of electrodes by streamer can be represented by RLC circuit. Parameters of this circuit were calculated from experimental determined time developments of arc current using the theory of RLC circuit. During this stage energy stored in the capacitor bank was discharged to the system and under-damped arc current oscillations (Fig. 2, Eq. 1) were observed. The usage of RLC theory for the final stage of breakdown confirmed similar values of $R$ and $R_{pl-const}$ in Table 1 and development of the plasma channel resistance (Fig. 3) after transient phase. The inductance $L$ and capacitance $C^*$ are of course also time dependent, but their time changes are negligible as at resistance $R$. The model of RLC circuit was also used in [2]. The development of the arc current depends on capacitance of the capacitor bank (Fig. 2), applied voltage and parameters of outer circuit [18]. Similar developments of the arc current were observed in water by Timoskhin *et al.* [2] and in oil by Marton *et al.* [19]. The breakdown was accompanied with other various processes and many bubbles of various magnitude were observed after breakdown.

## 4 Conclusion

The arc current during breakdown in transformer oil I-TO 100 was measured. The breakdown is characterised by plasma channel in which physical parameters were calculated on the base of the Braginskii-Martin model. From these parameters time dependence of radius, resistance and dissipated energy of the plasma channel were calculated. Resistance of the plasma channel changed from a few ohms to a few hundreds milliohms due to Joule heating caused by the arc current flowing through the plasma channel. On the basis of experimental results it can be said that the final stage of breakdown in transformer oil is also represented by the RLC circuit on a microsecond scale. The development of the arc current is modified by parameters of outer circuit and the effect of nonlinear characteristics of breakdown were neglected.

The author wish to thank for the support to the R&D operational program Centre of excellence of power electronics systems and materials for their components. The project is funded by European Community, ERDF - European regional development fund.

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