

PRE-BREAKDOWN CURRENT BEHAVIOR IN DC VOLUME BREAKDOWN IN TRANSFORMER OIL

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Abstract

The phenomenology of pre-breakdown events in transformer oil is investigated using high-speed electrical and optical diagnostics. Data collection using a coaxial test setup terminating into a 50Ω load line to simulate a matched impedance system allows very fast risetimes. Transmission line type current sensors and capacitive voltage dividers with temporal resolution of 300 ps provide information about the discharge voltage and current. Steady, DC currents ranging from a few nA with less than 10 kV of applied voltage, to a few μA prior to full breakdown are measured using an electrometer. Pre-breakdown events are measured with positive and negative charging voltages with respect to ground. Light emission from the discharge is measured using a series of fast photomultiplier tubes, (risetimes 800 ps), that observe positive and negative electrode tips and center of the channel. Preliminary results on self-breakdown (breakdown voltage +44kV) with a 2.35 mm gap show a DC (seed) current of several hundred nA with pre-breakdown spikes of a few mA immediately before final breakdown. Periodicity of the current spikes combined with a general increase in magnitude prior to full breakdown has been observed. Data collection using a negative charging line, with respect to ground with enhanced field at the cathode, indicates current spikes that are typically 25 to 50% faster than spikes using a positive charging line with enhanced field at the anode. Detailed optical diagnostics along with high-speed electrical diagnostics of the pre-breakdown phase will address the physical mechanisms initiating volume breakdown.

I. INTRODUCTION

Electrical breakdown in liquids is of high technical importance and has been studied for several years. It has been reported in numerous publications, that breakdown is based on complex interactions of hydrodynamic and electronic phenomena, leading to a rather complex temporal and spatial structure of the development of a conducting channel. It is generally accepted, that the application of a voltage to a gap in a liquid leads to predischage phenomena, consisting of discrete current spikes and light emission events, which form streamer-like structures

which propagate not continuously, but stepwise. The physical basis of these processes has again been discussed in numerous papers, but a coherent picture for the description is still missing. The use of novel high speed diagnostics methods, such as oscilloscopes with analog bandwidths in the multi GHz regime, and electro-optical devices, such as sub-ns gateable MCPs, might provide additional insight into these processes and might contribute to the development of more satisfactory models describing the physics of breakdown.

To characterize the state of the liquid before breakdown, it is important to have some information on its dc current/voltage characteristics. Especially for polar liquids, such as transformer oil or water, rather complex transport phenomena play a role, starting from convective charge transport at relatively low fields, transport of ionized molecules, as well as charge injection and transport of “free” electrons at higher field amplitudes approaching breakdown. Furthermore, the transition from dc behavior to breakdown has to be characterized.

II. EXPERIMENTAL SETUP

A. Pre-breakdown Setup

The setup incorporates a fast coaxial system with a matched impedance of 52Ω . It consists of two RG-19 transmission lines that connect at feedthroughs on either side of a cylindrical, stainless steel chamber. The inner conductor of each transmission line can be charged independently to 100 kV. This allows either a bipolar configuration or single sided charging of the transmission lines. The test gap is connected to either side of the transmission lines center conductor. A cylindrical grid inside the container connects the outer conductors, maintaining constant impedance. The brass electrodes are hemispherical with a radius of curvature at the tip of 0.3 mm. For some experiments, using single sided charging only, needle electrodes with a radius in the micrometer regime have been used.

To minimize high voltage stress on the feedthroughs, both lines are charged slowly with opposite polarities until breakdown occurs. Therefore the breakdown voltage is twice the single line charging voltage. The matched coaxial setup facilitates fast electrical diagnostics which include a transmission line current sensor [1] and up to four

capacitive voltage dividers with risetimes of less than 300 ps [2].

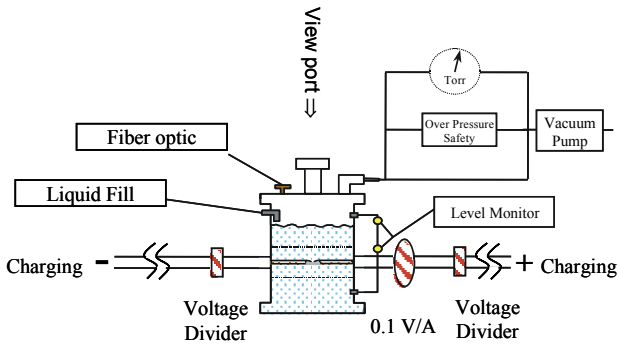


Figure 1. Experimental setup for pre-breakdown tests with coaxial charging lines, and diagnostic devices.

Luminosity measurements were performed with 3 Hamamatsu H6780-04 photosensor modules. The photomultiplier tubes (PMT) have risetimes of 780 ps, a sensitivity of 3×10^4 A/W and a gain of 5×10^5 . The PMT's were focused on the region in front of each tip of the electrodes and the center of the gap, approximately 5 mm apart. A cylindrical lens 5 mm long and 3mm in diameter focuses the light from each location in the channel onto a fiber optic cable that is connected to a PMT. This configuration allows a determination of the starting location for the pre-breakdown pulses as well as an estimate of the speed of propagation across the gap.

The chamber is filled with Univolt 60 transformer oil and then vacuum pumped to a pressure of about 100 torr to remove air bubbles from the oil introduced during the filling stage. After being under vacuum for 24 to 48 hours, after initial filling, the oil is suitable for testing.

B. Steady DC Current Setup

Steady DC current measurements in the nA regime are collected using a Keithley 6514 electrometer. The electrometer as implemented is capable of measuring 1nA with ± 35 pA resolution for this series of tests. Figure 2 is a sketch of the electrical setup for steady DC current tests in transformer oil.

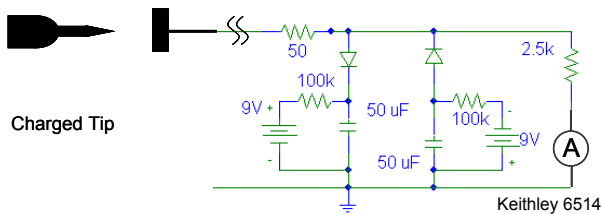


Figure 2. Sketch of setup for DC current with single sided charging and Keithley 6514 electrometer.

The electrometer is slow, with a preamp settling time of milliseconds; therefore it is not capable of resolving the very fast pre-breakdown pulses. Several different geometries

and gap spacing were tested using this configuration, including tip-plane, hemispherical tips, and plane-plane. A tungsten needle with micrometer radius of curvature is charged either positive or negative, while the 1 cm diameter planar electrode is terminated through 50Ω thru the electrometer to ground. DC current measurements are performed on the seconds time scale. A DC voltage is selected then the output from the electrometer is recorded on an oscilloscope. Approximately 50 seconds of data was collected for each voltage setting.

III. RESULTS

A. Steady DC Current

DC current across the gap was measured for several different geometries and biasing configurations; however, the tip-plane results are the focus of this discussion. The voltage was varied up to the breakdown voltage of the geometry in uniform steps. An average current value and standard deviation was determined from the 50 seconds of recorded data for each voltage step. Final breakdown would occur around $1 \mu\text{A}$ for transformer oil regardless of geometry or spacing of the gap.

Figure 3 shows, as an example, several measured current-voltage characteristics for tip-plane geometry for two polarities. For an easier interpretation, the data are presented in form of a Fowler-Nordheim plot, i.e. $\ln(I/V^2)$ is plotted vs. $1/V$. Three runs for each polarity are shown. Other experiments used plane-plane geometry, see below.

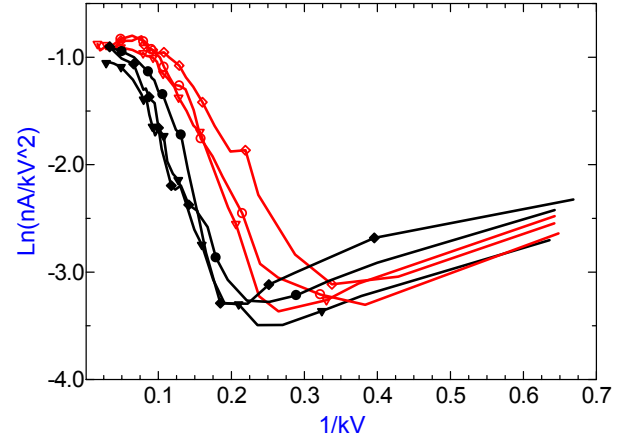


Figure 3. Measured V-I characteristics for tip-plane. 3 negative needle shots (open symbols), 3 positive needle shots (filled symbols).

In the graph, three regimes can be distinguished. Below $1/V=10^{-4} \text{ V}^{-1}$ (i.e. breakdown voltage $V_B=30 \text{ kV} > V > 10 \text{ kV}$) the current is proportional to V^2 , for $1.2 \times 10^{-4} > 1/V > 2 \times 10^{-4}$ ($8 \text{ kV} > V > 5 \text{ kV}$) there is a linear decay showing the validity of a Fowler-Nordheim relationship for this range, and for $1/V > 3 \times 10^{-4}$ ($V < 3 \text{ kV}$), there is, within the error (i.e. reproducibility) limits a linear relationship $I \propto V$ (ohmic behavior).

The basic processes leading to the measured current/voltage characteristics are expected to be electron injection (electron field emission described by the Fowler-

Nordheim equation, or tunneling through a Schottky barrier at the metal-liquid interface [3,4] and current limitation due to space charges. Both electron field emission [5] and tunneling through a Schottky barrier have the same functional dependence of the emission current I on the applied voltage V , i.e.

$$I = KV^2 \exp(-B/V) \quad (1)$$

(K and B are constants), where for the case of Schottky barrier tunneling [6]

$$B = \frac{3\chi d\epsilon}{2\Delta d} \quad (2)$$

(χ =electron affinity barrier, Δd =thickness of oxide layer, d =gap width, ϵ =relative permittivity of oxide). The equations governing the transport of negative charges in a resistive medium,

$$\nabla \vec{E} = \frac{\rho}{\epsilon_r \epsilon_0}, \quad \vec{v} = \mu \vec{E}, \quad \vec{J} = \rho \vec{v} \quad (3,4,5)$$

yield

$$\vec{E} \nabla \vec{E} = \frac{\vec{J}}{\mu \epsilon_r \epsilon_0}. \quad (6)$$

With the boundary conditions $V=0$ at the cathode, $V=-V_0$ at the anode, and $E=E_0$ at the cathode, the voltage/current characteristics can be expressed in parametric form for the one-dimensional case as

$$V_0 = \frac{\mu \epsilon_r \epsilon_0}{3J} \left[\left(\frac{2Jd}{\mu \epsilon_r \epsilon_0} + E_0^2 \right)^{\frac{3}{2}} - E_0^3 \right] \quad (7)$$

$$J = J_E(E_0) \quad (8)$$

where J_E is the emission current density according to eq. (1), i.e. $J_E = I/a$, where a is the active cathode area, and $V=E_0 d$. Similar, but much more complex expressions can be obtained analytically for cylindrical and spherical geometry.

Of practical interest are two limiting cases, the case where the space charge dominates, i.e. where $2Jd / (\mu \epsilon_r \epsilon_0) \gg E_0^2$ which yields

$$V_0 = \frac{2^{\frac{3}{2}}}{3} \left(\frac{J}{\mu \epsilon_r \epsilon_0} \right)^{\frac{1}{2}} d^{\frac{3}{2}}, \quad (9)$$

where the measured current I is proportional to V_0^2 , which allows to determine the mobility μ . The opposite case is the one with low current density and negligible space charge, where $J=J_E(V_0)$ and $V_0=E_0 d$. For this case, a Fowler Nordheim plot ($\ln(I/V^2)$ vs. $1/V$) allows us to determine the field enhancement factor β in eq. (1) or the

Schottky barrier parameter B in eq. (2). For cylindrical and spherical geometry, the dependence $V_0 \propto J^{1/2}$ for the space charge case is still valid, with different dependencies on geometric parameters, however (J has to be replaced by the current per unit length for the cylindrical case, and the total current for the spherical case).

From the plot in Fig. 3 for small $1/V$, it follows that $\mu \epsilon_r \epsilon_0 a/d \approx 1 \text{ nA}/(\text{kV})^2$ which would imply for an area of $a=7 \times 10^{-6} \text{ cm}^2$ (electrode area) a value for the mobility of $\mu=600 \text{ cm}^2/(\text{Vs})$. Note that this mobility would scale with $1/a$, i.e. a ‘‘current flow diameter’’ substantially larger than the electrode area would reduce this value. Literature data for the high-field mobility are around $10^2 \text{ cm}^2/(\text{Vs})$ [6]. The Fowler-Nordheim slope from Fig. 3 amounts to about $15 \times 10^{-3} \text{ V}$, which equals $3\chi \epsilon d/(2\Delta d)$ and would be compatible with a barrier potential depth, χ , of 3 eV, and an oxide layer thickness, Δd , of 0.5 μm . The third parameter which can be estimated from Fig. 3 is the low field dc conductivity, from the slope and absolute values for large $1/V$, for which we obtain a resistance of $8 \times 10^{12} \Omega$. The corresponding charge is probably due to ionization of trace impurities or the liquid itself [6].

Similar V-I characteristics have been measured for a plane-plane geometry (area 1cm, plane distance 0.15 cm) which yields comparable results, but does not reach the space charge saturation level at 30 kV.

B. Pre-breakdown Current Pulses

It has been observed that pre-breakdown pulses are common in various liquid dielectric breakdown mechanisms. Fast current and optical diagnostics allow the measurement of current and luminosity from pre-breakdown events.

Pre-breakdown current pulses range in magnitude from a few mA to a few hundred mA and last from 2 to 5 ns. There could be many pulses prior to the final breakdown event. Figure 4 illustrates a typical test with several pre-pulse events that occur several hundred ns prior to final breakdown. Also the graph shows that there is a steady current measured with the capacitive voltage divider. This connects the DC current of a few μA as measured with the Keithley electrometer to the microseconds leading up to final breakdown. Pulses increase in magnitude closer to the final breakdown. Since the PMT’s observe both electrode tips and the middle of the gap it is possible to estimate how fast the light wavefront passes through the oil to the opposite electrode as well as the point of origin. Figures 5 and 6 are two examples of current and PMT pre-pulses for events early and late in the pre-breakdown event. The light emission is observed first at the negative tip of the electrode and moves across the gap rapidly. The discharge can originate at various locations on the electrode surface due to surface conditioning. The variation in the discharge path means it can occur near the edge of the lens allowing less light to be collected at that PMT.

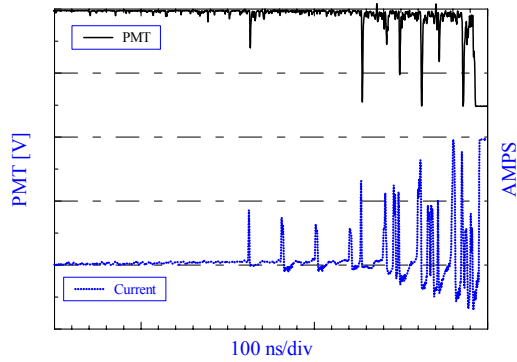


Figure 4. Graph of train of pre-breakdown current and PMT pulses. PMT pulses coincide with current pulses.

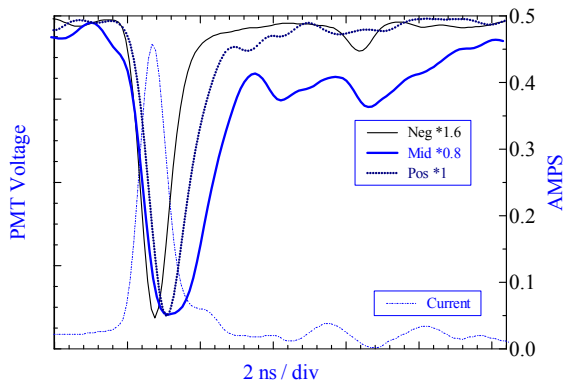


Figure 5. Graph of a pre-breakdown current pulse and PMT pulse 50 ns before final breakdown. Pulses normalized to positive PMT.

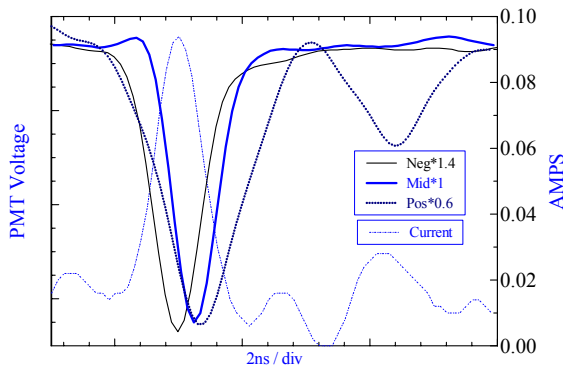


Figure 6. Graph of a pre-breakdown current pulse and PMT pulse 1900ns before final breakdown. Pulses normalized to middle PMT.

Rapid rise of the PMT outputs and magnitude of current pulses indicates that the pre-pulses occur close to final breakdown and previous events have aided in the development of a channel [7].

IV. SUMMARY

Results presented in this paper further describe the formation of pre-breakdown pulses in transformer oil. Fast

electrical and optical measurements demonstrate the presence of pre-breakdown phenomena. The pulses initiate at the negative tip and propagate across the gap. Nanosecond current pulses and localized light emission were measured up to several hundred nanoseconds prior to final breakdown. The pulses are most likely generated by gas discharges in a bubble formed by local heating and vaporization caused by field-emitted electrons injected into the liquid [8]. Electron multiplication and light emission occurs within the gas phase of the bubble. If multiplication does not achieve enough charge carriers for a streamer to form a conducting channel across the gap, then a pre-breakdown pulse is the result. This process will continue until conditions are sufficient to form a streamer across the gap and final breakdown occurs.

A steady DC current of about $1 \mu\text{A}$ prior to final breakdown has been observed and an explanation of the dc voltage-current characteristics is given. For low applied voltages, ohmic behavior dominates, for medium voltages, the current is determined by Schottky-emission, and for high voltages, close to breakdown, space charge limitations are dominant.

V. ACKNOWLEDGEMENTS

This work was solely funded by the Compact-Pulsed Power MURI program funded by the Director of Defense Research and Engineering (DDR&E) and managed by the Air Force Office of Scientific Research (AFOSR).

VI. REFERENCES

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