Currents in AC Stressed Liquid Insulated Needle Plane Gap

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Abstract — **Currents and space charge phenomena in 8 different dielectric liquids have been investigated for an ac stressed needle plane gap. Applied frequencies ranged from 0.1 Hz to 100 Hz. A high resolution analogue-digital converter and an active suppression of capacitive currents were used to extract the small conductive currents. Tip radii and voltages were varied. The currents varied non-linearly with voltage. At low frequencies the perfluorpolyeter and mineral oils had almost symmetrical current in both polarities, while cyclohexane, white oil and esters had asymmetrical current with lower peak current for positive polarity. Above a certain instantaneous voltage level – within the power cycle - the currents increased with the voltage squared, fitting a space charge limited current model. Clear indications of heterocharge space charges were revealed by varying tip radii and frequencies. The heterocharge will result in an increase of the electric field. The results show that at higher voltages a purely resistive model for the liquids becomes invalid. It is also evident that the presence of space charges will influence partial discharge behavior.**

Keywords — Space charges, dielectric liquid insulation, nonlinear current

I. Introduction

Conduction and space charge formation are processes of fundamental interest for designers and users of electrical equipment. For dc insulation the electric field will be resistively distributed, giving stresses quite different from what appears under ac. If the relation between current and voltage becomes nonlinear the behavior of an insulation system cannot be modelled based on simple resistivity of the materials.

If space charges occur in the insulation it becomes even more complicated to calculate stresses. Space charges may occur on many different timescales: From quick corona stabilization around sharp edge defects in a GIS that are active at switching surges and ac, to e.g. Maxwell-Wagner effects that will occur in largely uniform fields under dc stress in transformers.

Generally high voltage insulation systems are designed to achieve a utilization factor [1] as close to one as possible. The insulation system of a transformer is one example. However, in some insulation systems as used in e.g. power electronic components sharp edges are unavoidable. Furthermore, at a microscopic level surface roughness will occur, and defects such as sharp metal debris must also be considered. On this background, studies of current and space charge phenomena around sharp defects on several timescales is of general interest.

This study addresses liquid insulation systems for power electronics for subsea applications. Today, power electronics for subsea applications (i.e. pump and compressor drives) are located in 1 bar containers at sea-depth down to 5000 meter. If one could use ambient pressure there is an opening for cheaper designs and improved functionality. To achieve this all volumes has to be filled with liquid. Thus, if semiconductors – now operating up to 6.7 kV – could be insulated with a liquid this would offer possibilities for simple designs. Power electronics operate with continuous dc stress when in turn-of state and with fast rising and falling pulses when operating. Also the chips and substrates have sharp edges. In this context both capacitive and resistive field distribution becomes interesting, as do space charge phenomena around sharp edges. On this background there, is an interest in studying the general behavior of dielectric liquids, and the development of criteria for choosing a feasible liquid for this application.

Today's test methods for characterization of dielectric liquids have their offspring from transformer applications [2]. IEC 60156 describes how to measure the ac breakdown voltage in a semi-uniform field. The method is mainly sensitive to particles and moisture and does not distinguish between liquids, and is aimed at checking service condition of transformers. IEC 60897 is a test for lighting impulse breakdown voltage of long point to sphere gaps, hardly relevant for millimeter distances of a power electronic circuit. Finally, IEC 61294 describes a test procedure which suggests that liquids can be characterized according to inception voltage of partial discharges (i.e. > 100 pC). It is not clear which functional properties of a liquid it relates to. Earlier studies have indicated that space charges would govern partial discharges in a needle plane gap [3]. IEC 60247 and IEC 61620 describe measurement of conductivity of liquids in uniform fields at low voltages. The suitability of the low field conductivity measurement procedure for higher fields is presently under discussion in CIGRE (WG A2/D1.41).

As a first step to investigate the feasibility of using liquids for insulation of power electronics the current voltage relation of a group of chemically different dielectric liquids were measured using a point-to-plane gap and ac of varying frequency. This gap resembles the non-uniform geometries and small distances on a substrate. Indications of space charge formation was also investigated.

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II. THEORETICAL BACKGROUND

A. The physical idea of space charges in liquids under ac

Applying an ac voltage on a point electrode in a liquid will cause an electric wind [4]. High ac electric fields will produce space charges of alternating polarity in the liquid insulation (Fig. 1). The liquid plume is laminar for low fields and turbulence flows in the liquid occur at higher stresses [5]. The forces acting on an ion will become weaker as it moves away from the electrode. Thus the strongest forces will act at the homocharge close to the electrode. This will result in a steady repulsive force from the tip on the liquid. As voltage polarity varies, regions of ions of alternating polarity will be formed throughout the gap.

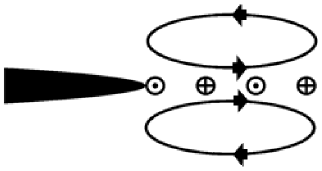

Fig. 1: The idea of alternating space charges from a point electrode and electrohydrodynamic effects under AC stressed voltage. '+' indicates positive charge and '.' indicates negative charge.

B. Dissociative ionization

Dissociation and recombination of ions are important processes in liquids under applied electric field. Impurities and additives highly affect these processes. As a general rule, solubility of electrolytic impurities increases with liquid permittivity, [6]. In the same way, the concentration of free ions decreases with permittivity (ε).

In liquids there will always tend to be equilibrium between molecules and their dissolved ions

$$A^+B^- \underset{k_R}{\overset{k_D}{\rightleftarrows}} A^+ + B^- \tag{1}$$

where the recombination rate k_R and dissociation rate k_D are given by the conductivity and electric field. The recombination constant is given by [7]

$$k_R = q \cdot \frac{(\mu_p + \mu_n)}{\varepsilon_0 \varepsilon_r} \tag{2}$$

where q is the charge, μ is the mobility of positive and negative ions and ε the permittivity. The Onsager relation [7] for the dissociation is

$$k_D = k_D^0 \cdot \frac{I_1(4b)}{2b} \tag{3}$$

where I_1 is the modified Bessel function of first kind and $b = \sqrt{q^3 E / 16\pi\varepsilon_0\varepsilon_r k^2 T^2}$. For weak fields is $k_D = k_D^0$, q is the charge, E the electric field, k Boltzmann's constant, ε_r the relative permittivity and T the absolute temperature. This might be asymptotically simplified to

$$k_D(E) = k_D(0) \cdot e^{\sqrt{E/E_c}} \tag{4}$$

which indicates that dissociative ionization dominates over recombination. The concentration of ions in a liquid according to Denat [6] with conductivity σ, electron charge q_e and ion mobility μ_{ion}

$$n_{ion} = \frac{0.5 \cdot \sigma}{q_e \mu_{ion}} \tag{5}$$

C. Space charge limited current (SCLC)

At low voltages with a low number of charge carriers, the current increases linearly with voltage: Residual ion pairs lead to a current density, with the ion concentration ρ_0, of

$$j_0 = \rho_0 \mu \frac{V}{d} \tag{6}$$

where j_0 is the current density, μ the mobility, V the applied voltage and d is the gap distance.

At higher voltages the current carrier density increases and perturbs the field in front of the electrodes and current becomes space charge limited, equation easily derived from the electrostatic equation $\varepsilon_r \varepsilon_0 \frac{dE}{dx} = \rho(x)$ in a plane-plane configuration

$$j = \frac{9}{8} \varepsilon \mu \frac{V^2}{d^3} \tag{7}$$

where j is the current density, ε the permittivity, μ the mobility, V the applied voltage and d the gap distance.

D. Electrode effects

Electrode effects will occur at sufficiently high electric fields. Electrons might pass from the metal cathode into the liquid by field emission at the cathode, or by tunneling - called field ionization - from molecules in the liquid to the anode. The Fowler Nordheim model [8] gives a current proportional to the field as $E^2 \cdot e^{-\alpha E^{-1}}$, where α is a material dependent constant.

TABLE I. CONDUCTIVITY AND PERMITTIVITY MEASURED WITH IRLAB, WATER CONTENT MEASURED WITH 737 KF COULOMETER KARL FISHER METHOD AND DENSITY MEASURED WITH DENSITO 30PX AND VISCOSITY FOUND IN THE DIFFERENT DATASHEETS

Parameter	Unit	Cyclohexane	Marcol 52	Transformer oil, used	Shell Diala DX	Midel 7131	Galden HT 135	Biotemp	Nytro 10XN
Relative permittivity	[1]	2.01	2.11	2.21	2.18	3.17	1.96	3.07	2.17
Conductivity	[pS/m]	1.043	0.021	22.03	0.159	23.61	0.165	126	0.60
Water content	[ppm]	16.4	10.2	11.9	11.9	201	5.6	60	10
Density	[kg/m^3]	777	830	870	870	970	1710	912	872
Viscosity	[mm^2/s]	1.26@20°C	7.4@40°C	-	8.0@40°C	28@40°C	1.0@25°C	45@40°C	7.6@40°C

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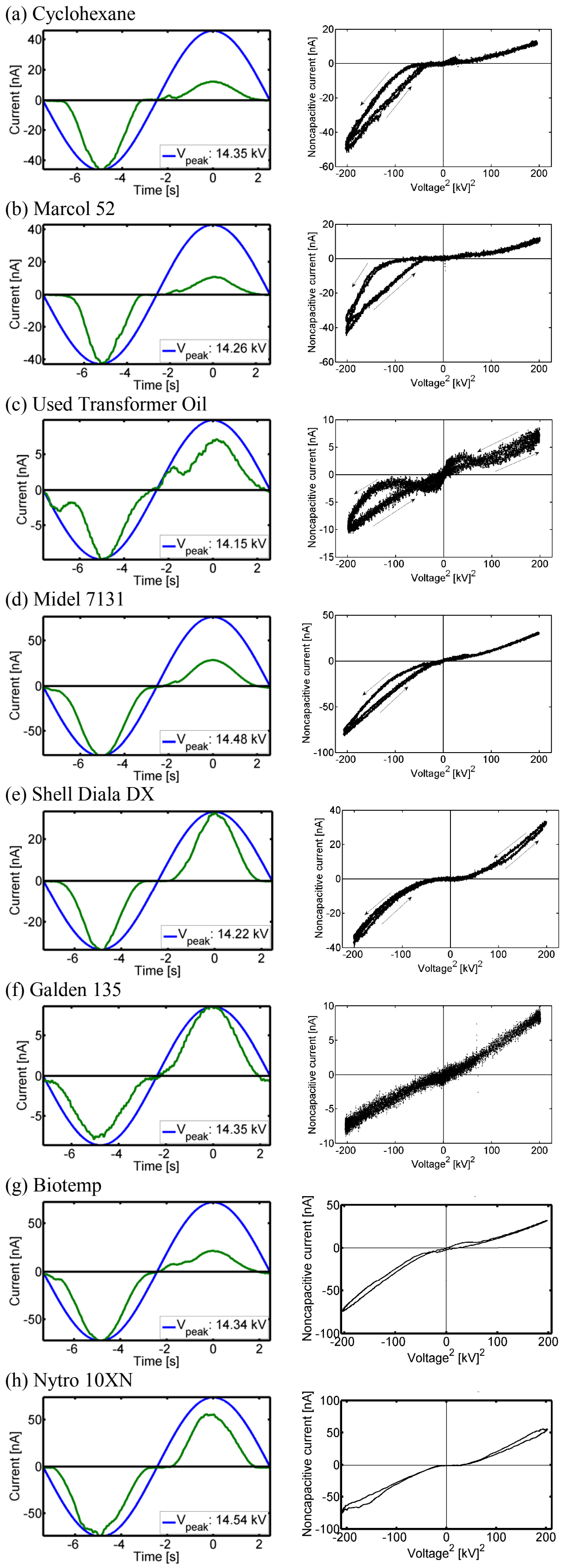

Fig. 2 Applied voltage of 0.1 Hz. Different currents in different liquids with gap distance of 20 mm and tip radius of approximately 5 µm. Left figure is the current vs phase, right figure is the current vs square of voltage.

E. Electrohydrodynamics

Drews et al. [4] studied electric winds in gas. The same phenomenon will occur in liquids [5]. The high electric field creates charges that are transported from the electrode by fluid flow (Fig. 1). The electrohydrodynamic flow moves ion "clouds" into the low field region where forces are weaker. Here the electric field is low and relaxation will occur.

III. METHOD

Measurements were done at voltages up to 14.3 kV, which was below partial discharge inception. At these voltages steady state currents were established. Low frequency voltages were used to reduce capacitive currents that could complicate measurement of the conductive currents.

A. Studied liquids

The liquids were used just as received. Important liquid parameters were measured (Table 1).

B. Setup

The setup consists of a test cell of about 1.6 liter made of Teflon with glass windows and conducting parts of stainless steel. A plane electrode with diameter of 90 mm was used in combination with a guarded needle. Electrode separation was about 20 mm. The plane was connected to a high voltage amplifier, Trek 20/20C-HS, which amplified the signal from a signal generator, type Wavetek Model 187. On the ground side a current amplifier, Stanford Research SR 580, was connected to a 100MS/s, 14 bit oscilloscope for analyses.

C. Mathematical filtering

Large capacitive currents and small conductive currents made it necessary to extract the resistive current from the measured signal. This was done using mathematical filtering in Matlab. Reconstruction of the capacitive current was possible due to the high resolution oscilloscope. The capacitive current was obtained from the fact that the current is equal to the capacitance times the derivative of the voltage. The capacitance was about 0.1 pF for the different liquids, but varied with some percent due to small differences in the tip radius from experiment to experiment. The numeric value of the capacitance was manually adjusted until the reconstructed curve fitted the measured curve. The reconstructed capacitive current was subtracted from the measured signal and the conductive current remained. High frequency components were suppressed above $100f_0$, where f_0 is the ac frequency.

IV. RESULTS

At low frequencies the measured current consisted of a large conductive part and a small capacitive part. This made it easy to remove the capacitive current. The conductive current peaks varied within some percent.

A. Different liquids

Figure 2 shows the measured conductive currents in the eight liquids. To the left, the current is plotted versus phase, or time. To the right, the instantaneous current is plotted versus the square of the corresponding instantaneous voltage level. The conductive current is highly non-linear and tend to asymptotically vary with the square of the applied voltage.

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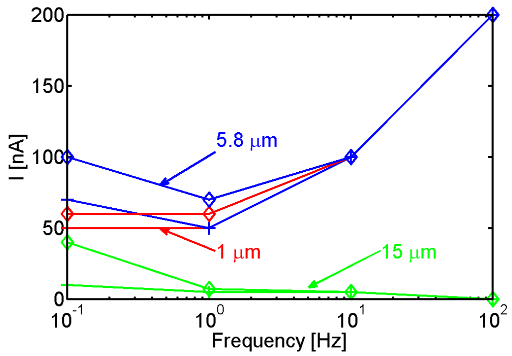

Fig. 3: Current peak vs frequency for different tip radii in Marcol 52, '+' means positive current peak, while '⋄' means negative current peak.

The peak current is different for positive and negative polarity for some liquids. The figures to the right show that there is a slight difference in the current at rising and falling voltage.

B. Different peak voltages

When the voltage was varied the asymmetric current was not seen at the lower voltages, while present at the higher voltages. The assymetric current started at approximately 6 kV in Midel 7131.

C. Frequency dependence

For sharp tips (< 6 μm) the conductive current increases with increasing frequency (Fig. 3), while for larger tip radius it decreases.

V. Discussion

The conductive current in a point plane gap under applied sinusoidal voltage is nonlinear in the voltage. The fact that some liquids showed asymmetric current in the two polarities indicates that a polarity dependent process is involved for these liquids. The presented method clearly differentiates between the different liquids. The 14 bit oscilloscope made it possible to reproduce the capacitive current from the numerical derivative of the applied voltage and thereby easy to extract the conductive current. A better measuring system would allow higher frequencies to be studied.

Figure 2 shows that the current has an ohmic region below a certain voltage level before it tends to increase by square of the applied voltage. This relation is the same as space charge limited current. The model for space charge limited current was originally developed for two plane electrodes, but the relation seems to be the same in divergent fields [9]. The current is asymmetric in most liquids (above a certain voltage level), indicating electrode effects that create charge of one polarity instead of dissociative ionization which creates equal charge at both polarities. Field ionization and field emission are the most likely mechanisms to explain this asymmetry. The tungsten electrode is stressed by a high field at the tip, and electrons are injected into the liquid with field emission, or withdrawn by tunneling electrons into the metal from the liquid, creating ions. The field emission is more likely to occur due to available of more electrons in the electrode at negative polarity than in the liquid bulk at positive polarity. Therefore the negative current should be stronger than the positive current.

The small hump that is observed at the rising edge has unknown origin. One explanation might be the result of an intermediate region between saturation of dissociative ionization and electrode effects similar to what is observed in plane electrodes under dc [10]. The reason why it is only seen at increasing voltage might be related to relaxation time of the liquid at falling voltage.

The applied ac voltage results in a net drift of charge from the point electrode due to the highly inhomogeneous electric field where charges closer to the tip move in a higher field than those at a more distant position. The liquid flow will be concentrated at the highest field region, i.e. the point plane axis, different from what is seen in gasses. Here ions follow the field lines due to few interactions within the gas molecules. Atten et al. [11] described a liquid jet when applying ac voltage. Plumes were also experienced.

Charged particles in liquids have a certain mobility that limits the flow and acts against the electric forces. This means that for higher frequencies (Fig. 3), the injected charges stay close to the electrode and partial discharge initiation is more probable due to heterocharge from previous half cycle enhancing the field.

Pure point plane geometry is only found in laboratory experiments. However, it is rather useful to investigate inhomogeneities and high field phenomena due to the well-defined geometry with analytical solution of the electric field distribution. The geometry of e.g. substrates and IGBT chips are more complex and electric fields are only obtained by numerical methods. Sharp edges, soldering edges and triple points are areas where field enhancement and divergent fields occur. The point plane gap is therefore highly relevant because of the easily obtained inhomogeneous field that might represent the inhomogeneous fields at substrates or defects at substrates.

The maximum electric field in the investigated point plane gap ranges from about 530 MV/m (Nytro 10XN) to 1200 MV/m (Marcol 52) when the space charge limited current starts. This is approximately the same electric field strengths reached at normal operating conditions for IGBT.

Pure dc measurements get steady conditions with homocharges in the liquid bulk. This creates a resistive current that is influenced by the field reduction due to the presence of homocharges. The fields under ac are therefore higher due to the presence of heterocharges. It is therefore important to consider space charges. There is a high stress after a polarity change (or grounding) and streamers are observed to occur [12].

When choosing insulation for power electronics and IGBT or other electronic equipment it is important to know how the insulation medium will act over a long service time. The well-known insulation mineral oils may be replaced with environmental friendly liquids, which do not have the same dielectric performance. It is therefore important to investigate the dielectric properties of new liquids. Application specific test methods for such investigations are needed.

In the experiments we have seen that current densities are governed by electrode phenomena like space charge limited

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currents. Measured low field conductivities will not be relevant for high field conditions. Any attempt to characterize the behavior of a dc insulation system on measured conductivities on materials alone seems hazardous. Attempts to develop IEC 60247 and 61620 towards high field applications must be questioned.

We have in these measurements seen that heterocharge injected form a previous half cycle will influence electrode field and charge injection in the following half cycle. Such space charge perturbation of needle field will certainly also influence inception and level of partial discharges. These effects should be considered before further promoting IEC 61294 as a tool for qualifying dielectric liquids.

VI. Conclusion

- Conductive currents in a point plane indicate that space charges are present. Space charges are important for the electric field distribution in insulation media.
- Different insulation materials have different distribution of space charges, as seen as different current vs phase pictures.
- The conductive current is nonlinear and thereby more rapidly increasing than the voltage.
- The conductive current is asymmetric, which indicates that it matters which polarity to use in power electronics where it usually is on/off voltages.

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