Breakdown Mechanism in Transformer Oil ITO 100

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The DC breakdown characteristics of dielectric liquid – transformer oil were measured. The experimental results showed that the breakdown voltage in transformer oil increases with the external pressure. This pressure dependence indicated the involvement of gas phase process during the development of stage of the prebreakdown process. The initial state of breakdown development on the basis of bubble theory was explained. Using the Braginskii-Martin's analytical model parameters of breakdown channel were calculated. Development of vapor channel after breakdown was recorded by high speed camera.

Keywords: streamer, breakdown, arc channel, temperature

1 INTRODUCTION

The understandings of electrical breakdown characteristics in insulating liquids are very important for many applications, special for transformers. In general, transformer oil in transformers are not chemically pure and have impurities like gas bubbles, suspended particles various size or concentration, fibrous dust from pressboard insulation, etc [1,2]. The presences of these impurities together with aging processes reduce the breakdown strength of dielectric liquids. Several theories have been proposed to explain the breakdown in liquids [3-6].

In present, the initial stage of breakdown in the case of transformer oil can be described using Cavitation and Bubble Mechanism [6, 7, 8]. In many liquids [9, 10, 11] were experimentally observed that the breakdown strength also depends strongly on the applied hydrostatic pressure, suggesting that a change of phase of the medium is involved in the breakdown process, which in other words means that a kind of vapor bubble was formed. Development of streamer in bubble during prebreakdown in transformer oil is presented in works [1, 3, 6, 11]. There are two phase models of charge generation that results in streamer generation. The gas-phase charge generation is described by impact ionization and higher charge mobility. A direct ionization mechanism is caused by electric field dependent molecular ionization characteristic for extremely high electric field and liquid-phase.

2 EXPERIMENTAL RESULTS

Figure 1 shows the schematic diagram of the experimental setup, which includes HT 55-I High voltage test supply (max voltage 55 kV and current 2.5 mA), electrode system and electric diagnostics. 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 digital oscilloscope Tektronix 500 MHz, 5 GS/s. The electrodes were polished by hand using 600 grade emery paper and cleaned with acetone. The distance of electrode was measured by metric gauge blocks with accuracy of 0.01 mm. New and unfiltered transformer oil

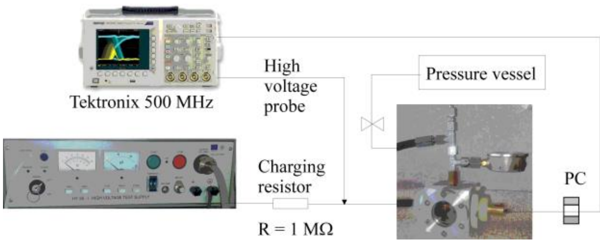

Fig.1: Experimental setup

ITO 100 was filled into discharge chamber (0.6 dm^3). The average dielectric strength or breakdown voltage of oil was determined from series of 7 breakdowns. The maximum and minimum values were not used. From next five values were calculated average value of breakdown voltage and its standard deviation. For all measurements the applied voltage was raised uniformly at of rate 2 kV/sec. After each breakdown oil was stirred by a magnetic stirrer 5 minutes. After stirred all contaminants or previous generated channels were well dispersed inside the vessel. The pressure into discharge was regulated using manual equipment.

The development of arc expansion after breakdown was recorded by high speed camera Olympus ISPEED 3. Advanced features include a high resolution of 1280 x 1024 pixels, the capability of recording up to 150,000 fps as well as full control by the CDU (Controller Display Unit) and the unique i-FOCUS for confirmation of depth of focus and focus within a live image.

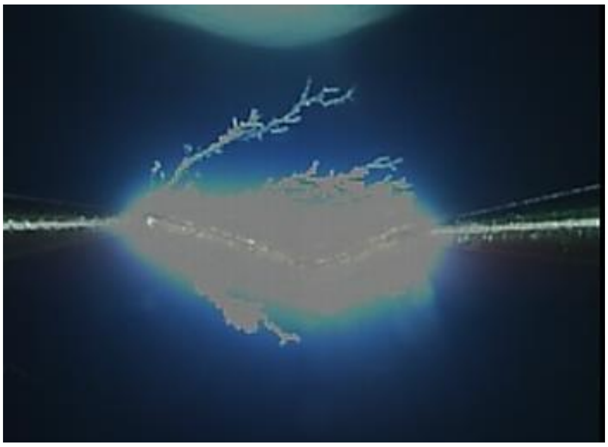

Fig. 2: Arc channel in oil after 20 μs of breakdown with filamentary structure. Point-to-point electrode distance was 8 mm, 55 kV and 20 000 frames per second.

At slow increase of DC voltage various transport phenomena in transformer oil at electric field below 10^6 V/m were observed. At voltage higher than 50 % value of breakdown voltage small channels with diameter of some micrometers between electrodes were detected. Number of channels rose with increasing voltage. Their shapes were not stable, changed and moved. These channels had lower density (no gaseous channels) than the transformer oil [7].

The dependence of breakdown voltage for transformer oil on external pressure at various electrode arrangement and distances are shown in Fig. 3. For given electrode geometry, point-to-plane or sphere-to-sphere (Rogowski profile), the breakdown voltage increases with electrode distance and external pressure. This effect is caused with decreases of electric intensity on electrodes due to their greater distance. The breakdown voltage for point-to-plane is smaller because at the point is higher electric field at given voltage. The strong pressure dependence of breakdown voltage (Fig. 3) indicates that the development of discharge and breakdown are related with gas phase or bubbles [9]. The standard deviation of breakdown voltage was around 5% because there are various factors that influence on the processes lead to the breakdown [3, 12]. A moderate increase of pressure in oil had also significant effect on the conduction current pulses in their amplitude, duration and multiplicity [7].

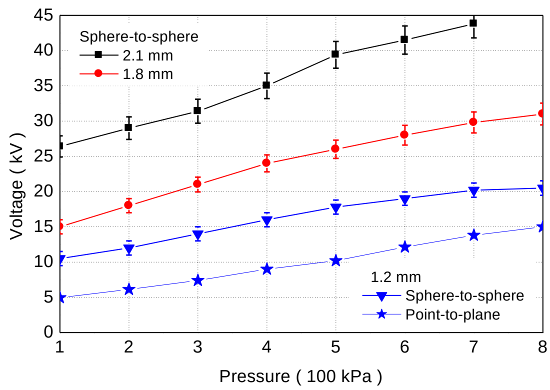

Fig.3: Breakdown voltage in transformer oil ITO 100 for different electrode spaces and electrode arrangement.

During the breakdown process the resistance of the plasma channel, its temperature and radius and pressure inside the channel exhibit a highly dynamic behaviour. To describe time dependent of these parameters Braginskii-Martin's analytical model [7] was used. These system of differential equations were solved for fitted measured arc current and initial conditions ($p(0) = 10^5$ Pa, $A(0) = \pi(10^{-6})^2$ m^2, $T(0) = 300K$ $\rho_0 = 900$ kg/m^3 is the density of the transformer oil) by Mathematica.

3 BUBBLE MECHANISM OF BREAKDOWN

Based on the bubble theory [4, 7, 11] the breakdown process in transformer oil is connected with the expansion of the bubble that leads to streamer generation and propagation between the electrodes and finally to the breakdown. The breakdown phenomena in transformer oil can be divided into several stages, which is also supported by experimental results.

The first stage of breakdown is connected with slowly DC voltage rise. Oil dielectrics are composed of long neutral chains of atoms - molecules that are resistant to ionization. However, during this time polarization processes occur and electrons interact with liquid molecules. Electrons lose their energy until there are trapped in liquid. In the cathode surface their energies increase beyond 3 eV [11] so they have sufficient energy to break the molecular bounds by the process of molecular ionization [6]. Charged molecules created a partial bridge at the surface of the electrode and into space. These bridges can be observed by laser light, because they have other refractive index [7]. Positive ions on the cathode surface effectively lowering the field ahead of then and together with electrons break bonds in the liquid to evaporate and form vapor cavities near the cathode surface. All these processes lead to the formation of small vapor bubbles with surface charge. The pressure in studied range had minimal effect on the processes of bubble creation.

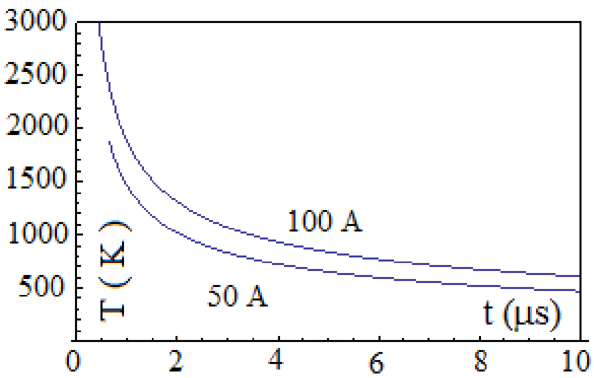

Fig.4: Development of temperature in plasma channel after breakdown during for 10 us. Calculation for current with amplitude 50 and 100 A and time of duration of 1 us.

The bubbles are composed of plasma at the same potential as the cathode and its negative potential is limited only by the positive space charge in the surrounding fluid. It expands due to coulombic repulsion of the electrons within the cavity, which pushes against both the viscosity and fluid pressure. Higher external pressure causes the increase of internal pressure and finally also breakdown voltage. In next stage, it takes the shape of an ellipse and the result of the field enhancement inside is creation of streamer, which propagates across the gap. When the streamer bridges the inter-electrode distance the plasma channel – arc is created. The existence of arc is characterized by an abrupt decrease in voltage corresponding to an immediate increase in current. The final breakdown is characterized by high current which flows through the plasma channel and in short time (1-2 μs) exponentially decreases to zero.

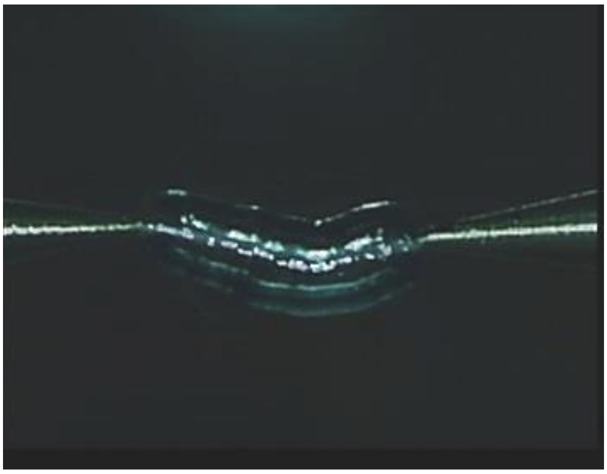

Fig.5: Channel in oil after 120 μs of breakdown with diameter 3 mm.

From the measured arc current and solution of systems of differential equations (1 - 3) time development of the pressure, temperature (Fig. 4) and radius of arc channel were calculated. The arc radius rises with time, what is similar with results of other studies [14, 15]. The resistance of the plasma channel drops rapidly during the first 100 nanosecond and then it establishes at minimum value, which is the order of several Ω. The minimum resistance of the plasma channel decreased with increasing values of energy dissipated in the plasma channel.

There are also next processes that start when current is flowing through channel. Current causes high increase of the temperature (Fig. 4) which evaporates oil around arc channel. This process and high internal pressure start expansion of arc-plasma channel by Joule heating. Immediately, arc rapidly begins to thicken form and becoming luminous in the process (Fig. 2). The energy in the arc is evident by its luminosity and the rapidly expanding gas bubble which it produces. Its lifetime is around 200 μs, but expansion is mainly during the first 20 μs to the diameter 2 mm. The expansion is the result of high pressure and temperature inside channel and expansion speed is 0,1 mm/μs (100 m/s). After this time the current in circuit flows again. In next 100 μs the speed expands is 10 times smaller. After this time the diameter of vapor channel is around 3 mm (Fig. 5). Expansion stops after 140 μs and from this point the channel collapses. This process takes about 60 μs.

4 CONCLUSION

The measurements showed that the external pressure has big influence on the breakdown voltage in transformer oil ITO 100. This pressure dependence indicates the involvement of gas phase process during the development of stage of the prebreakdown process. The bubble mechanism and development of streamer in arc - plasma channel as final stage of the breakdown process in transformer oil was described. The physical parameters of the breakdown process were calculated on the base of the Braginskii-Martin's model. Using high speed camera development post-breakdown phenomena was detected.

Acknowledgements

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