The effect of gas bubbles on electrical breakdown in transformer oil

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Abstract. To study the breakdown of transformer oil with gas bubbles an experimental setup was created that allows to determine electrical and optical properties of the discharge. Oil was sparged with air and sulfur hexafluoride gas. It was found that sparging oil with gas lowers the breakdown voltage of the oil. When a gas bubble is present between the electrodes at a considerable distance from the electrodes at first there is a spherically shape flash observed, resulting in the discharge gap overlapping by a conductive channel. These leads to discharges forming in the discharge gap with the frequency of hundreds Hz and higher. Despite the slightly lower breakdown voltage of oil sparged with sulfur hexafluoride the advantage of this medium to clean oil can serve as a two-phase medium damping properties, which may be sufficient to prevent the destruction of the body in the breakdown of oil-filled equipment.

Transformer oil is widely used as an insulator in various high-voltage machineries. Therefore the studies of discharge processes in oil filled high voltage apparatus where gas bubbles may be present initially or formed there by heating, electrolysis, cavitation *etc* [1] are of great interest. The dielectric strength of gases is much lower than dielectric strength of transformer oil and partial discharge may occur in the gas bubbles at the lower fields strengths than is necessary for a breakdown of oil. The interest in the insulating properties of two-phase media arose due to their damping properties. Propagation of perturbations of various amplitudes in gas-liquid media has been studied extensively since the mid XX century [2–7]. Therefore research in dependency of the breakdown voltage of transformer oil on the concentration of bubbles of different gases (air, sulfur hexafluoride, inert gases) is of interest.

To investigate the breakdown of transformer oil and gas bubbles an experimental stand (figure 1) was constructed, described in detail in [8, 9], which allows to determine the electrical, optical and spectral characteristics of the discharge.

The breakdown of the medium is carried out in a cylindrical chamber made of plexiglass with an inner diameter of 200 mm and 600 mm in height. At a height of 260 mm copper electrodes are located sphericaly shaped segment with a diameter of 36 mm, a thickness of 13 mm and a radius of curvature of 25 mm, interelectrode distance equals to 8 mm. At the electrode level there is a quartz glass viewing window. Microbubble generator ensures a uniform filling of the chamber with 1 mm radius bubbles with a gas share of 10% from total volume [10]. The degree of sparging was determined by the change in the level of pure and sparged oil (figure 2).

To record the electrical characteristics of the breakdown dual kilovolt meter C100 and Oscilloscope Tektronix TDS2014C were used, connected to the high voltage divider resistors

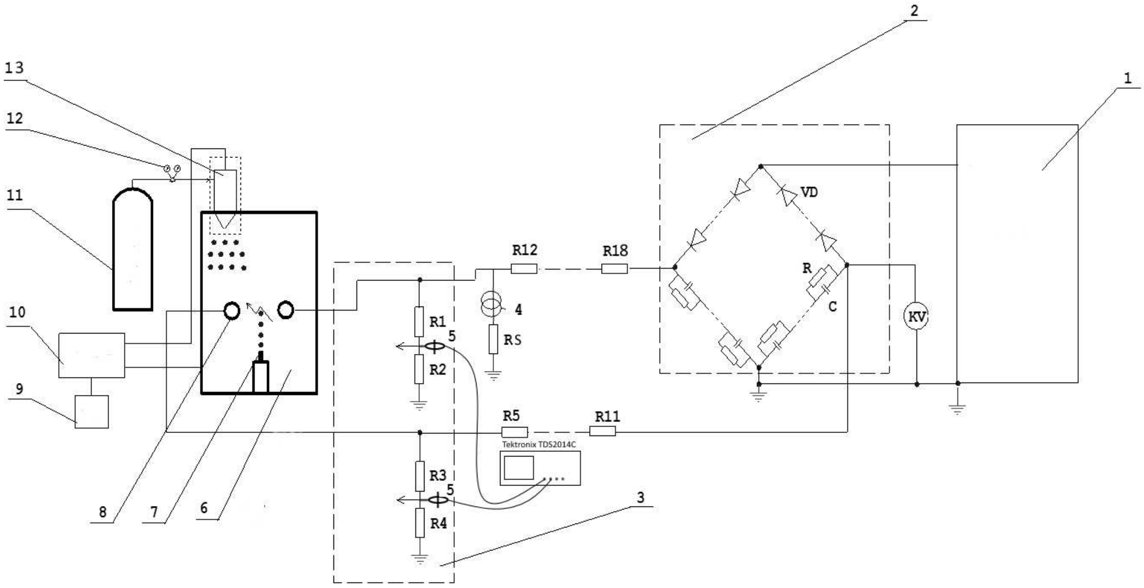

Figure 1. The general schematics of the experimental setup: 1—experimental setup AII-70; 2—diode-capacitor voltage doubler, 3—high-voltage dividers ($R_1 = R_3 = 86$ MΩ, $R_2 = R_4 = 12.7$ kΩ); 4—current probe Tektronix TCP303 or TCP0030A; 5—high-voltage probe Tektronix P6015A; 6—testing chamber; 7—needle to create a line of single gas bubbles; 8—electrodes; 9—centrifugal pump's frequency converter; 10—centrifugal pump; 11—gas cylinder; 12—gas reducer; 13—microbubble environment generator; restrictive resistors $R_5 = R_6 = \ldots = R_{18} = 680$ kΩ, $R = 2.7$ kΩ.

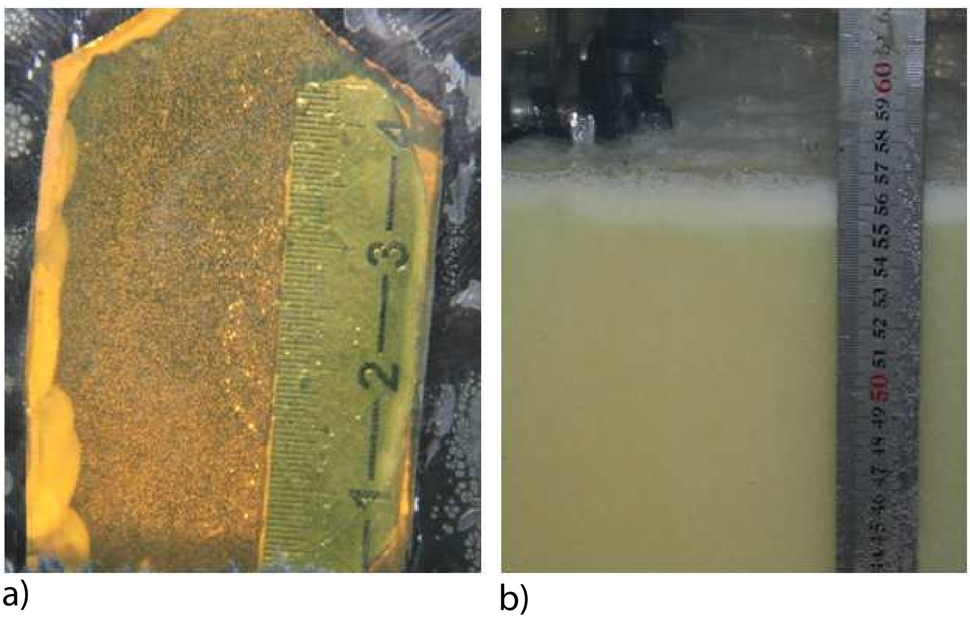

Figure 2. Characteristic size of gas bubbles (a) and level of transformer oil sparging (b).

KEV-20 (86 MΩ each) through extra high-voltage probes Tektronix P6015A. Dividers transient characteristic: $h(t) = R_2/(R_1+R_2) \approx 1.5\times10^{-4}$. The rise time of rectangular signals (frequency of up to 100 kHz) from the GZ-112 generator from 0.1 to 0.9 of their amplitude value is measured

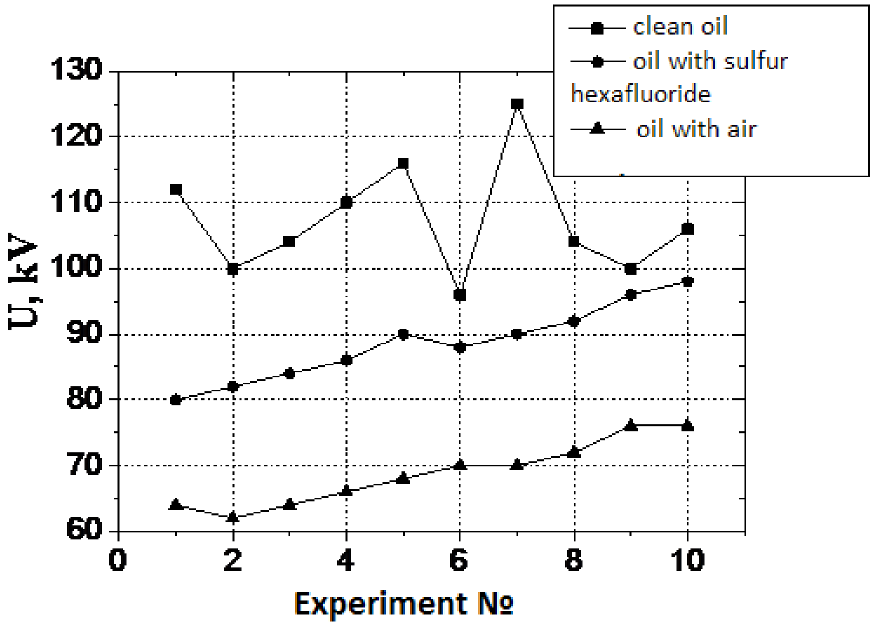

Figure 3. The breakdown voltage of clean and flowing oil, oil sparged with air, oil sparged with sulfur hexafluoride; gas volume fraction of 10%.

from oscilloscope and its value is 150–200 ns, while $RC \approx 2 \times 10^{-7}$ s. Current in circuit is limited by the resistors KEV-2 ($R = 4.76$ MΩ on each shoulder of the voltage doubler). In order to determine the gap closure on the potential free part of the divider (when current readings were performed one of the arms was disconnected and grounded) active current probes Tektronix TCP303 or TCP0030A were connected, as well as 2.7 kΩ bridge. Kilovolt meters C100 is connected to the positive electrode and the full potential difference across the electrodes is defined as twice the value of the kilovolt meter reading, this is valid due to the circuit symmetry. Since kilovolt meter captures the average value, and the rectified signal from the multiplier has a sawtooth shape, deviating from the mean value by ± 5 kV, then the total measurement error on both shoulders is ± 10 kV.

Registration of partial discharge and the beginning of the breakdown is carried out by an optical method using RedLake MotionPro X3-type high-speed camera (with a diagonal of 19.7 mm, a frame rate of 1–10 kHz and a minimum exposure of 1 μs) through a quartz window incorporated in the discharge chamber. The combination of long lens and camera allowed recording the image on a scale of 1:3 for the entire period of observation, with buffer memory of up to 3000 frames.

During a slow increase in the potential difference between the electrodes the discharge was detected by an abrupt voltage drop and the glow in the electrode gap. In the first stage of the research the breakdown voltage was measured for stationary, clean and settled oil (Special drying was not performed and oil in the discharge chamber was in constant contact with the air) and for flowing oil aerated with sulfur hexafluoride or air (for the gassing a fresh oil was used) with the gas volume fraction of 10%. The research has shown that gas bubbles decrease the breakdown voltage of oil (figure 3), with air bubbles decreasing it more than sulfur hexafluoride bubbles.

During the next stage of the research single bubbles of sulfur hexafluoride, air, argon and helium with the radius of R=1 mm with the use of a needle were formed between the electrodes

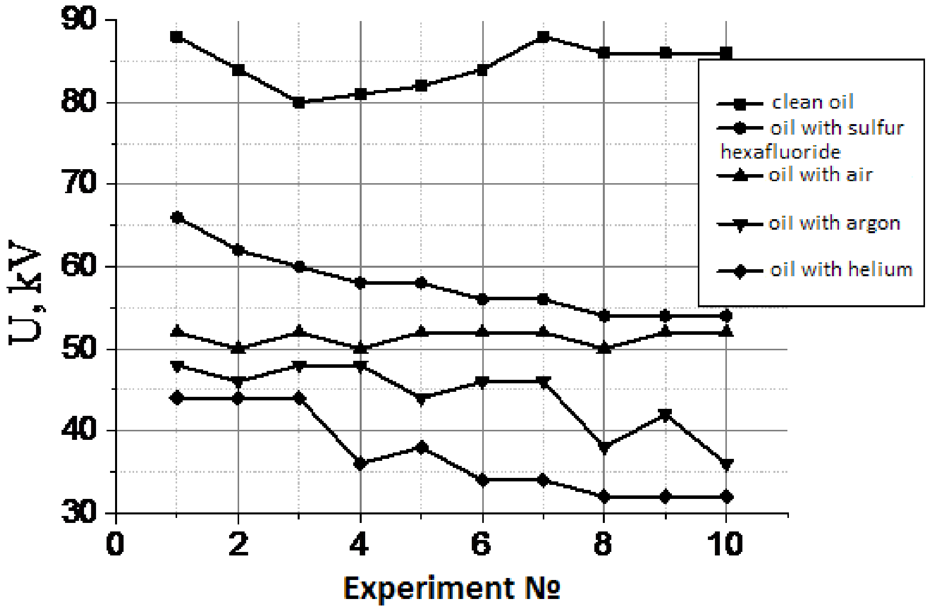

Figure 4. Breakdown voltage of clean transformer oil and oil aerated by single gas bubbles of air, argon, helium and sulfur hexafluoride.

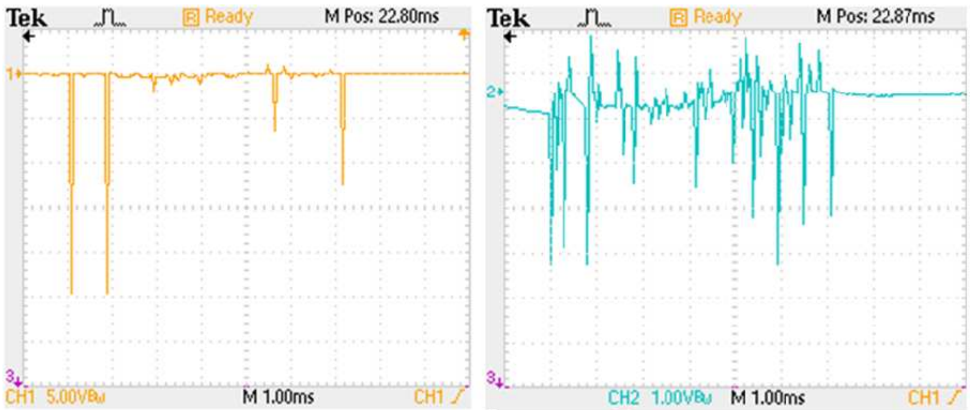

Figure 5. Oscillogram of (a) Channel-1 voltage taken from 2.7 kΩ resistor ($\sim$ 2 mA/div) and (b) Channel-2 discharge voltage taken from 1:6770 voltage divider (6770 V/div).

in order to assess the relative influence of the bubble on the electrical breakdown of the settled, old transformer oil, without taking into account chemical purity or humidity of the oil. In addition, each time a gas from which single bubbles were formed changed, oil was also changed to an identical settled old oil. The voltage between the electrodes was increased gradually until the breakdown occurred.

It was found that the sparging of transformer oil by single gas bubbles also reduces the breakdown voltage of oil (figure 4). For example, the breakdown of the settled oil occurs at $V_{av} = 85$ kV. Sparging by single bubbles leads to a decrease in the breakdown voltage: $\sim$ 58 kV—sulfur hexafluoride, 51 kV—air 44 kV—argon, 37 kV—helium. When the voltage between the electrodes is less than that necessary for the breakdown of the pure oil, the breakdown first

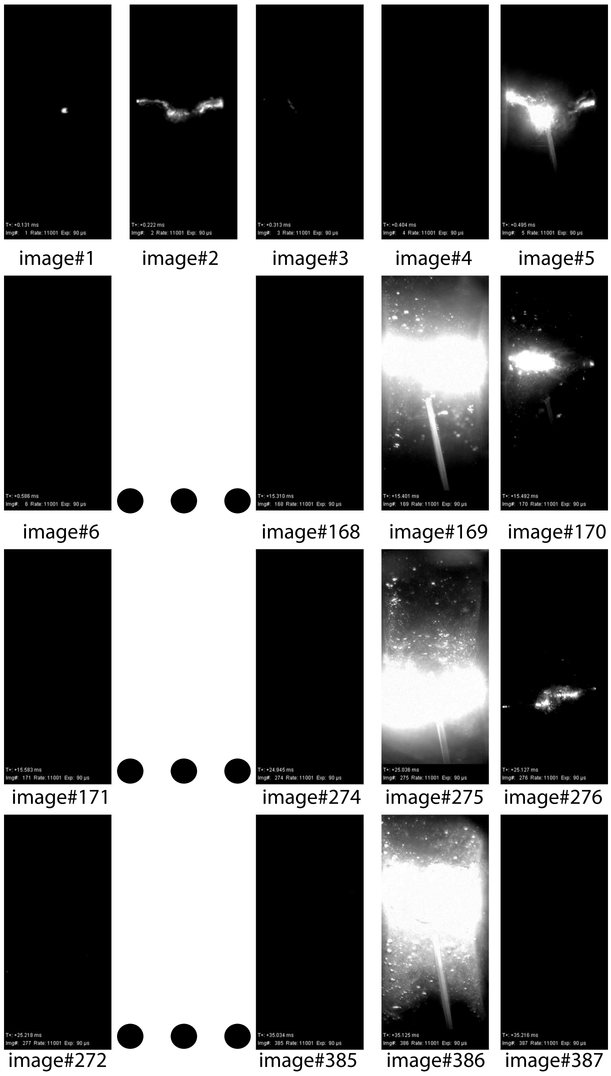

Figure 6. High-speed video imaging of breakdown process in transformer oil with a frame rate of 11000 frames/s and exposition of 90 μs.

occurs in the gas bubble and is not always overlapped by a highly conductive channel in the discharge gap [11].

In the discharge channel with single gas bubbles the discharge is observed with a frequency of hundreds Hz which is confirmed by current and voltage oscillograms (figure 5) and by high-speed video recording of the breakdown process (figure 6). In addition to registering the fact of repeated breakdown, current and voltage waveforms allow us to estimate the amplitude of current and voltage values at the time of gap closure by the discharge channel. For example, for the transformer oil with single air bubbles (figure 5) the maximum amplitude value of the voltage measured from one shoulder can reach $\sim$ 27 kV. By the symmetry of the circuit and using the same divisor full amplitude value of the voltage is about $\sim$ 54 kV on both shoulders. The maximum peak current is about 10 mA.

Each current peak in figure 5 corresponds to a breakdown which is confirmed by a high-speed synchronized recording (figure 6), which shows different breakdowns at high-frequency. When the bubble is present between the electrodes at a considerable distance from the electrodes (2–

3 mm) at first there is a spherically shape flash observed (image 1), resulting in the discharge gap overlapping by a conductive channel (image 2). Figure 6 presents sequential images which show a series of breakdowns (images 1–6, 169–170, 275–276 and 386, the images in between are blank) which confirm that breakdowns occur at the frequency of hundreds Hz until the power is cut off.

The results of experimental studies on the relative influence of gas microbubbles on the value of the breakdown voltage of the microbubble medium disregarding chemical purity and humidity of the original transformer oil have shown that taking into account the measurement errors the closest to the breakdown voltage of transformer oil is a flowing gassed with sulfur hexafluoride gas two-phase medium. Despite the slightly lower breakdown voltage, the advantage of this medium compared with clean oil is a two-phase medium damping properties, which may be sufficient to prevent the destruction of the oil-filled equipment casing in case of the breakdown.

Acknowledgments
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