Gassing in Transformer Oil at Low and High Frequency Vibration

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***Abstract*—Experiments were performed in model of electrical reactor, where low frequency vibration took place and in special cell, where transformer oil was stressed by ultrasound vibration. The reason of gassing in both cases is cavitation. Dissolved gas content is discussed.**

Keywords—transformer oil, cavitation, vibration, bubbles, dissolved gas analysis.

I. INTRODUCTION

It is well known that the vibration take place in oil filled power equipment [1,2]. Moreover the devices with increased vibration (electrical reactors) show increased generation of gases during service. The reason of vibration is magnetic forces in core and winding of power apparatus. Core size decreases due to magnetostriction periodically with the change of alternating current and its relative value ($\delta l_1/L$) depends on the magnetostriction constant λs:

$$(\delta l_1/L) = \lambda s \qquad (1)$$

Here L is magnetic field length (total length of magnetic core).

The second reason of vibration is realized in case of the reactor mainly. Transformers and reactors are very similar devices; magnetic core and windings are permanent parts of their structures. However, there is principal difference between them. This is obvious presence of non-magnetic gaps in the core in case of the reactor. The gap size changes due to magnetic forces during current flow. The magnetic pressure causes mechanical strength inside metal that result in a longitudinal size of core loss and an increasing of the gap. If the gap doesn't have solid ingredient, its relative change could be estimated as

$$(\delta l_2/L) = (B_m)^2/(2\cdot\mu_0\cdot E) \qquad (2)$$

where B_m – core magnetic induction, E – Young modulus. Reactor is usually functioning at currents that produce induction in the core more than 1.5 T, e.g. close to magnetic saturation. Taking into account B_m ~1.5 T, E= $2\odot10^{11}$ Pa, $\lambda s \sim (0.4\text{-}1.5)\cdot10^{-6}$ one could get an estimation of longitudinal core size, $(\delta l_1/L) = (0.4\text{-}1.5)\cdot10^{-6}$, $(\delta l_2/L) = 6\cdot10^{-6}$.

Both these factors will lead to a gap increase at the moment of maximum current. The gap decreases when current decreases. The pressure inside the gap decreases during the gap expansion phase, which could lead to cavitation and gas generation.

Practically the same mechanism of gassing should be if take into consideration the vibration of winding.

As for as high frequency vibration the cavitation is well known mechanism of bubbling at the ultrasound action on water. Action of these waves on gassing in transformer oil is insufficiently known question.

The goal of this paper is gassing research in the model of oil-filled equipment due to vibration and comparison of results obtained with low and high frequency vibration.

II. EXPERIMENTAL SETUP

A. Low frequency

An electric steel maiden pot core with a controlled nonmagnetic gap was used. The total length of the magnetic core was L=12.5 cm. The crosscut gap inside the core was filled with fulled-board, and its thickness determined the gap size. A power supply of 50 Hz frequency was used. The voltage on the reactor model was changed from 0 up to 230 V. Core saturation was measured at a voltage of 70÷100 V depending on the gap size. The core consists of two parts that were pressed opposite each other by means of a frame. A decrease in pressing force allows vibration and local pressure variation in the liquid to go from negative to positive values with a frequency of 100 Hz.

A reactor model was inserted into a hermetically sealed cubic plexiglass cell. Optical recording was performed with the help of a microscope and a video camera connected with a PC. Vibration was detected with the help of a Corsar instrument intended for estimation of the core pressing rate. An instrument sensor was mounted on the cell wall.

B. High frequency

High frequency vibration was obtained with ultrasound setup. As source of ultrasound the generator from ultrasonic bath WUC-A01H was used. The mean power was 60 W at the voltage 220 V. The generator forms pulse train with time duration 1-14 msec and pause 0.4-1.5 msec. The frequency was 29 kHz. The power was controlled by voltage change. The projector has the form of plunger inserted into the syringe. Plunger end emits ultrasound wave into bulk of syringe filled transformer oil. After the ultrasound action on the oil gas content in oil was analized.

Experiments were performed both with degassed and non-degassed oil GK. Time duration of experiments was 2, 4, 6, 8 minutes. Input voltage U_{in} was fixed: 25 V, 40 V, 50 V, 75 V, that correspond mean true power 1.5 W, 3 W, 16 W, 22 W.

III. Results

A. Low frequency

Interface between parts of core is a source of bubbles both in case of non-degassed oil and slackening of the frame tension. Fig. 1, 2 show bubble appearance and moving in front view and top view. Bubble radius varied from 40 to 60 µm, lifting the vertical speed to 0.3-0.4 mm/s due to buoyancy force. It was surprising that the horizontal bubble speed (moving away from the gap) was approximately the same as the vertical one at the first moments of bubble moving. In case of visible gap between parts of core bubbles were absent. When in experiments the oil was degassed no bubbles were registered, however dissolved gases were detected. Fig. 3 shows relative concentrations of so called “diagnostic gases”. These gases usually used as a marker of undiserable processes in oil-filled high voltage equipment.

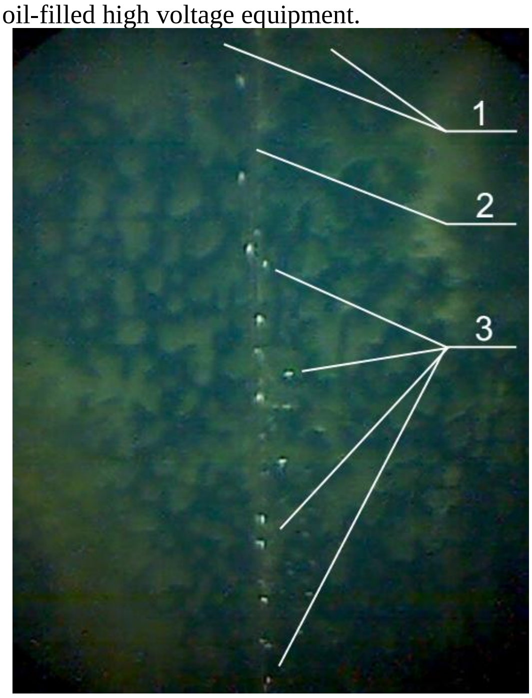


Fig. 1 Appearance and floating of bubbles along the gap between core parts. 1 – core parts, 2 – vertical line where small gap between parts of core, 3 – floating bubbles.

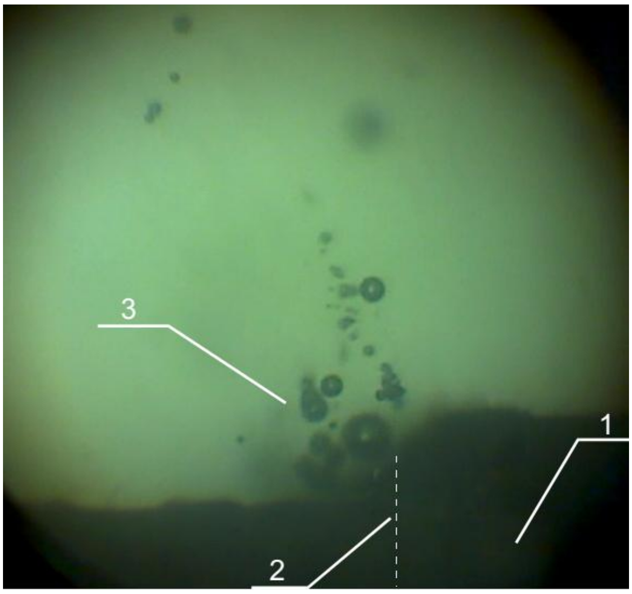
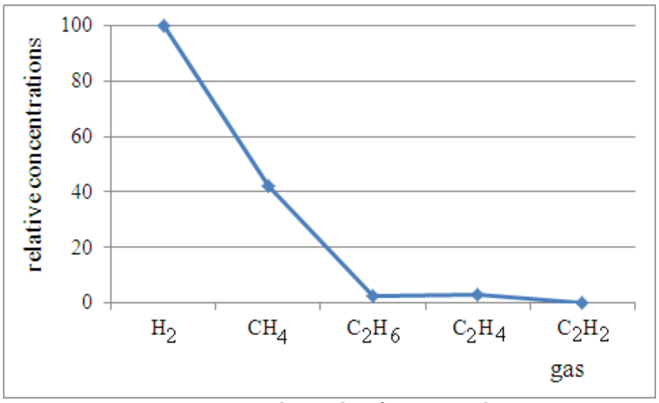


Fig. 2 Appearance and moving of bubbles. Top view. 1- core; 2- joint between parts of core; 3- bubbles.



Fig, 3. New pattern corresponding to low frequency vibration cavitation.

B. High frequency

In experiments the action of ultrasound leads to dissolved gas appearance at the mean power more than 3 W. Fig.4 represents these data for case of non-degassed oil.

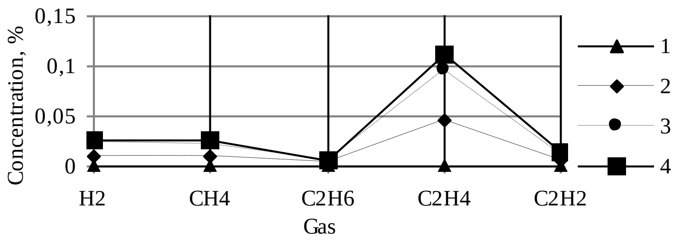


Fig. 4. Dissolved gas concentration at the ultrasound action on non-degassed transformer oil at active power Pa =22 W. 1 – initial concentration; 2-after 2 minutes; 3- after 6 minutes; 4 – after 8 minutes.

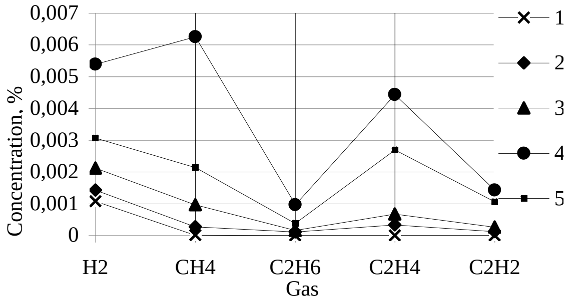


Fig. 5. Dissolved gas concentration at the ultrasound action on degassed transformer oil at active power Pa =22 W. 1 – initial concentration; 2-after 2 minutes; 3- after 6 minutes; 4 – after 8 minutes

IV. Discussion

The model of gas bubble formation consists of cavitation in narrow gaps at the wall vibration. The pressure inside a gap will increase when the gap is reduced and will decrease when the gap is expanded. The pressure inside a gap can be deduced from the solution of a well known one-dimensional problem concerning viscous liquid movement in a narrow gap under the influence of alternating pressure

$$P(x) = P_0 + \frac{12 \cdot \eta \cdot \omega \cdot (a^2 - x^2) \cdot \Delta l}{l^3} \cdot \sin 2\omega t \qquad (3)$$

where P_0 – atmospheric pressure, η – viscosity, ω – circular frequency of vibration (double operation frequency), l – gap, Δl – gap change due to vibration (vibration amplitude), a – depth of gap, x – distance from gap mouth inside gap. Firstly this model was proposed in [2].

One could see from (3) that pressure will have periodically negative values in case of flat narrow gaps. It leads to cavitation and gas formation. The gas content inside a bubble increases due to diffusion of dissolved gases from the surrounding liquid. Then at the period of positive pressure, the bubble collapses. During this action, the gas inside the bubble gets hot; this leads to the deterioration of the transformer oil and appearance of gas, especially hydrogen. If the bubble contains a lot of gas the collapse doesn't lead to bubble disappearance. During the next actions of negative pressure, the bubble increases in size and can be ejected from the microgap into the bulk of liquid. If the gas amount inside the bubble is too low (case of degassed liquid), the bubble dissolves and disappears during the collapse phase.

That is why gassing took place in both the cases of degassed and non-degassed oil, but bubbling took place in the case of non-degassed liquid.

In case of high frequency vibration gassing intensity strongly depends on mean power. For analysis it is more suitable to use sound intensity instead of mean power or power density. Sound intensity I is the power divided on radiating surface.

One could determine mean alternating pressure P according to well known expression

$$I = \frac{P^2}{2\rho c} \qquad (4)$$

Where ρ – oil mass density, c – sound velocity. It could be shown that threshold of intense gassing well correspond to pressure approximately equals to ambient pressure.

When pressure in sound wave become more than ambient pressure, the total pressure in liquid in some moments has negative value. It means that in these moments the cavitation could take place. The mechanism of oil decomposition at the ultrasound action consists of several parts: at the moments of negative pressure the liquid breaks and cavity forms, then dissolved gas diffuses into cavity from surrounding liquids. At the moments of positive pressure this gas filled cavity compresses, the temperature inside bubble increases. That is why the temperature of surrounding liquid increases that leads to oil deterioration.

In our opinion there is principal difference between low and high frequency vibration from the point of view of liquid deterioration. The low frequency vibration could take place in very narrow gaps only. As for as dissolved gas content the prevalent ethylene generation in case of non-degassed liquid subjected ultrasound action the main reason for gas generation is high temperature. Gas content in case of degassed oil is similar to gas content in liquid exposed to partial discharges (low frequency) or arc processes (high frequency).

V. CONCLUSION

Vibration leads to cavitation inside transformer oil. It results in gas generation. Bubbling takes place in the case of non-degassed liquid. The theoretical model doesn't contradict experimental data on the optical bubbles recording and the increase of dissolved gas in oil, especially hydrogen. In real oil-filled power equipment the microgaps could appear after slackening of the mechanical tension in the elements of core and wind due to the alternative forces action at the equipment.

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