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Acoustic Spectra of Ultrasound Induced Cavitations in Insulating Oils

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Acoustic emission measurement results of acoustically induced cavitation bubbles in insulating oil are presented in this paper. Spectral analysis of acquired by a broadband transducer acoustic emission signals is proposed as a diagnostic tool for estimation of aging properties of mineral insulating oils. The article describes the main parts of the designed and built measurement apparatus used for acoustic cavitation investigation in insulating oils. In this note representative results of the experimental data taken from the apparatus are shown.

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1. Introduction

The process of rupturing a liquid by decrease in pressure at roughly constant liquid temperature is called cavitation. The behavior of creation of cavitation voids or bubbles in a liquid is a result of increasing liquid flow in pumps or propellers and decreasing liquid pressure on an orifice. An oscillating cavitation bubble can be also created by acoustic field [1, 2].

Acoustic cavitation is of importance in many technical applications, such as sonochemistry, ultrasonic cleaning, laser surgery in medicine, and lithotripsy. One of the most interesting consequence of cavitation is a sonoluminescence phenomenon in form of multi-bubble sonoluminescence and single-bubble sonoluminescence [3, 4]. An acoustic emission signal from working transformer can be used for monitoring of its condition and recognizing the form of partial discharges generated in insulating oil [5–7].

An imploding gas-vapor bubble during cavitation is a source of broadband acoustic emission signal [7]. A detailed explanation about the acoustic emission by the cavitation bubbles under two distinct cavitation regimes – stable and transient cavitation is given by Leighton [2] and Young [8]. It is generally known that the acoustic cavitation noise spectrum comprises of various frequencies related to the fundamental or the driving frequency. These frequencies are either the sub-

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harmonic ($f/2$, $f/3$, $f/4$, ...), the ultraharmonic ($nf/2$, where $n = 2, 3, 4, \ldots$) or the harmonic (nf, where $n = 2, 3, 4, \ldots$) of the fundamental frequency f. Individual spectral bands of the cavitation radiation are characterized by a finite width and even by definite shape [9]. The acoustic emission signal contains also a broadband noise generated by shock waves of collapsing bubbles of a wide range of sizes [10].

The analysis of hydrodynamic cavitation acoustic emission spectrum can be used for on-line diagnostics of a centrifugal pump in which cavitation is the source of instability of the pump and caused head capacity and efficiency curves [11, 12]. Cavitation noise were also observed in acoustically driven mineral insulating oil filled vessel [13].

The properties of mineral oils used for insulation and cooling in power engineering e.g. power transformers, change in time. Many factors (temperature, humidity, external electrical field) influences the deterioration of the oil [14, 15]. Transformer aging is mainly related to the degradation of the insulation, caused mainly by the thermal stress of the insulating paper, together with the electrochemical decomposition of the oil. The physicochemical processes can be very complex [16, 17].

Dissolved gas analysis (DGA) is the most important tool in determining the condition of a transformer. It is the first indicator of a problem and can identify deteriorating insulation and oil, overheating, hot spots, partial discharge, and arcing. The health of the oil is reflective of the health of the transformer itself. Dissolved gas analysis consists of sending transformer oil samples to a commercial laboratory for testing and therefore is very expensive [18].

2. Measurement setup

A measurement system needed for generating acoustic cavitation in an oil filled round bottomed glass flask and acoustic emission signal measurements was built. Its schematic diagram is presented in Fig. 1.

The main part of used measurement system is a high frequency, high voltage sine wave generator based on a direct digital synthesizer AD9833 with 0.1 Hz frequency resolution tuning. The AD9832 combines the numerical controlled oscillator, SINE Lookup Table, frequency and phase modulators, and a digital-to-analog converter on a single integrated circuit. The chip requires one reference clock and provides digitally created sine waves up to 12.5 MHz. Used 12-bit resolution TLV5638 digital-to-analog converter connected to REF input of the programmable wave form generator enables signal amplitude tuning.

The generated signal drives two round piezoelectric transducers (16 mm diameter and 6 mm thick) glued to the flask in two opposite ends of the flask as showed in Fig. 2. The third transducer used as microphone enables to find the optimal driving resonance frequency. A four channel, 40 MS/s sample rate and 12-bit resolution data acquisition PCI board CH-3160, an acoustic emission broadband

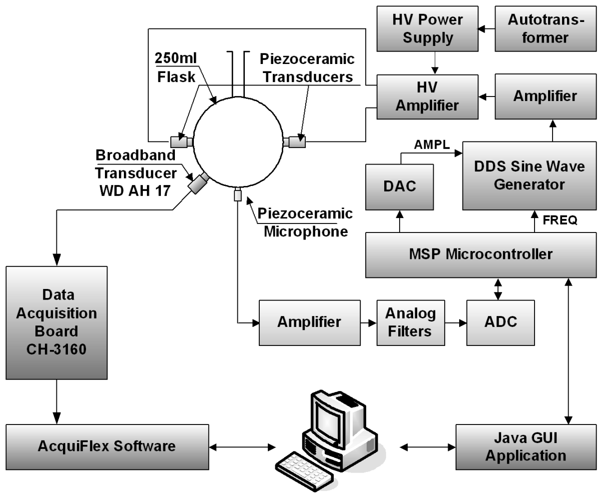

Fig. 1. Schematic diagram of built experimental apparatus.

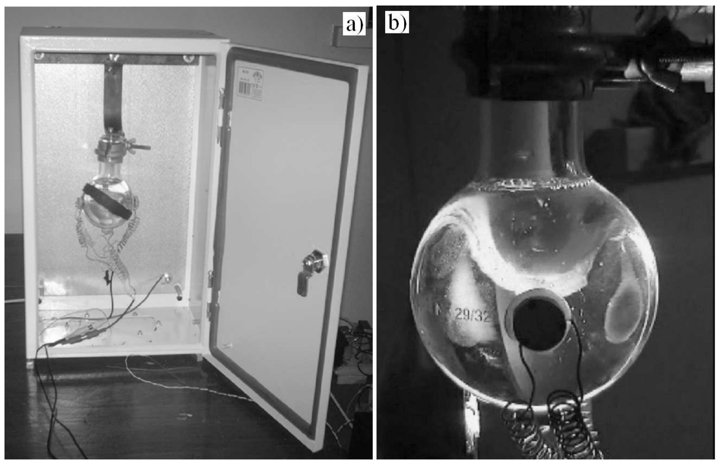

Fig. 2. Used cavitation vessel (insulating oil filled flask): (a) mounting way, (b) acoustically driven cavitation flask.

transducer WD AH 17 and AcquiFlex software were used for acoustic emission signal measurements. A Java application performs a graphical user interface role and together with central control microcontroller were used to automate the measurement process.

Laboratory round-bottomed 250 ml flask were used as a cavitation vessel (Fig. 2a). Two piezoelectric transducers supplied by PI Ceramic GmbH (16 mm diameter by 6 mm thick) were used as ultrasound wave drivers and one as flask vibrations microphone. Figure 2b presents new mineral insulating oil filled flask used for cavitation measurements.

3. Measurement results

The bubble dynamics depends, among other things, on the amplitude of the generated sound field, which is proportional to the amplitude of the signal supplying used transducers. At low amplitude, the gas-vapor filled bubbles are oscillating in phase with the sinusoidal acoustic field. This motion is often called linear and the bubble as stable. When the amplitude of the acoustic field increases the motion becomes nonlinear and the bubbles are called transient. Transient bubble is growing to many times its original size and then a violent collapse takes place during which a shock wave can be emitted. The shock waves are responsible for a broadband acoustic signal called a cavitation noise.

All measurements of acoustic emission signal were carried out for period of 1 s with 1048576 S/s sample rate. The estimated power spectral densities of measured acoustic emission were created using Welch's averaged, modified periodogram method.

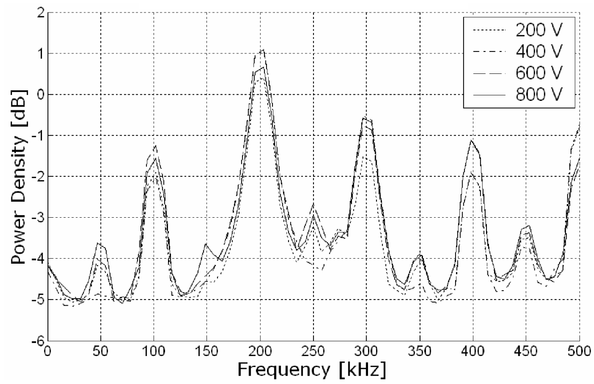

Fig. 3. Power spectrum density of cavitation in insulating oil at 100 kHz frequency signal and amplitude of 200 V, 400 V, 600 V, and 800 V.

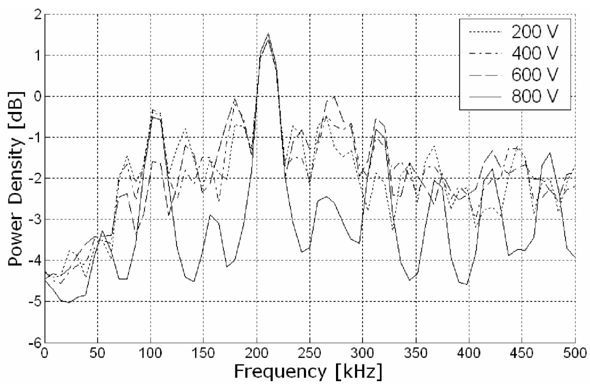

Fig. 4. As in Fig. 3, for 105 kHz frequency signal.

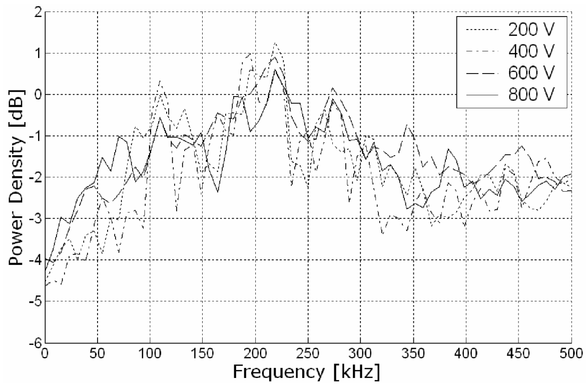

Fig. 5. As in Fig. 3, for 110 kHz frequency signal.

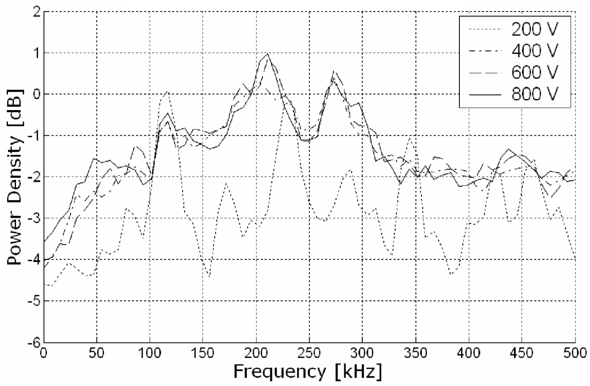

Fig. 6. As in Fig. 3, for 115 kHz frequency signal.

At signal frequency 100 kHz at four sample used signal amplitude values as presented in Fig. 3, no cavitation noise wes present. The presented power spectral density shows only the existence of source frequency and its harmonics. The existing bubbles are oscillating linearly. In Figs. 4 and 5 power spectral densities of cavitation in insulating oil at 105 kHz and 110 kHz are present. The frequency value of 110 kHz caused a strong cavitation noise at all sample signal amplitude values in the whole examined frequency band. The highest amplitude can be observed at 220 kHz. The power spectral density of acoustic emission signal of ultrasound induced cavitation in insulating oil at 115 kHz frequency is presented in Fig. 6. The 200 V amplitude caused a smaller cavitation intensity. In Figs. 7 and 8 a comparison of power spectral densities of acquired acoustic emission signal at 200 V and 600 V are presented. Additionally, a cavitation intensity indicator was evaluated (Pcav).

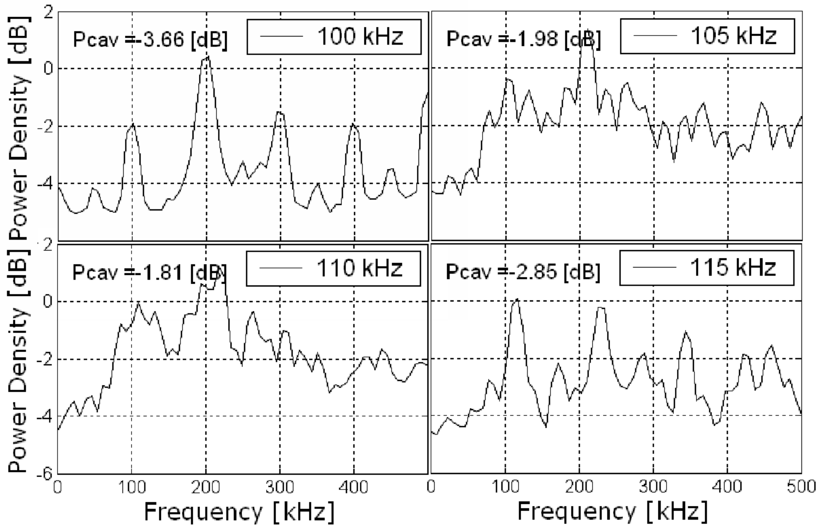

Fig. 7. Power spectrum densities of cavitation in insulating oil at 100 kHz, 105 kHz, 110 kHz, and 115 kHz frequency signal and amplitude of 200 V.

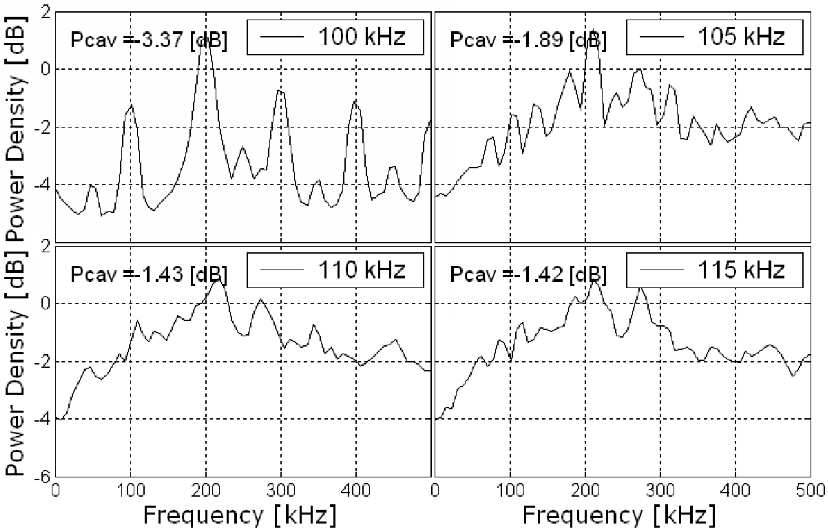

Fig. 8. As in Fig. 7, for amplitude of 600 V.

The carried out measurements of acoustic emission signal of cavitations filled flask caused a need to find a cavitation indicator which will be responsible for representation of the cavitation intensity at given signal parameters i.e. amplitude and its frequency. As a cavitation intensity indicator we used the mean value of power densities of measured signal evaluated from created power spectral densities as follows:

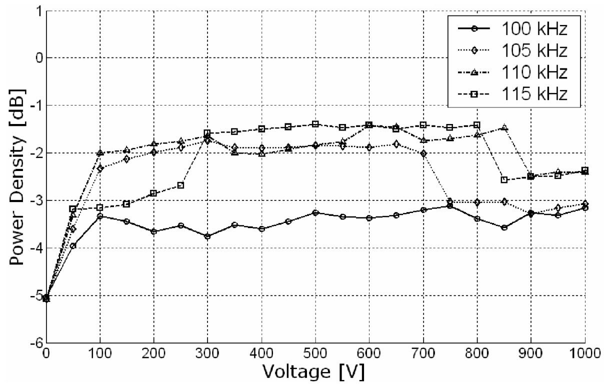

Fig. 9. Cavitation intensity in insulating oil at 100 kHz, 105 kHz, 110 kHz, and 115 kHz frequencies of driving ultrasound as a function of signal amplitude.

$$\mathrm{Pcav} = \frac{\sum_{i=1}^{n} \mathrm{PSD}(i)}{n}, \tag{1}$$

where: Pcav — cavitation intensity factor, PSD(i) — power density of acoustic emission signal at i-th frequency, n — the size of used estimated output frequency vector during the estimation of power spectrum densities.

Using the proposed cavitation intensity factor a cavitation intensity dependence on ultrasound signal amplitude in the range from 0 V up to 1000 V at four sample ultrasound frequency values: 100 kHz, 105 kHz, 110 kHz, and 115 kHz was estimated as presented in Fig. 9. At frequency of 100 kHz a constant power density can be observed at all used amplitudes up to 100 V and no cavitation was present. The most intensive cavitation noise can be observed at frequency of 115 kHz and using the signal amplitudes in the range between 300 V and 800 V. For other frequencies the cavitation was also observed but its intensity is relatively smaller.

4. Conclusion

The objective of this work is to point out the possibility of using acoustic emission signal from cavitation induced by a high energy acoustic field as a diagnostic tool for power transformer lifetime prediction. During the long time of energetic transformer operation the losses of insulation properties of used transformer oils cannot be avoided. The essential factor in transformer oil degradation is the amount of chemical compounds, i.e. oxygen, nitrogen, hydrogen and simple hydrocarbons. An important factor is the humidity content as a result of insulation paper oxidation. All of the factors have also influence on the cavitation bubble dynamics.

The introduced measurement results in form of power spectral densities of detected acoustic emission signal during ultrasound induced cavitation in oil filled vessel can be used for estimation of aging properties of mineral insulating oils.

The results from acoustic emission (AE) analysis have shown a clear relationship between acoustic emission activity and the oxidation time of oil. The older the insulating oil the smaller the power of specific frequency component of detected AE signal. In conclusion, the use of acoustic cavitation can be an essential supplement for existing methods of insulating oil diagnostics.

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