DEVELOPMENT OF ELECTRICAL BREAKDOWN IN TRANSFORMER OIL

J. Kúdelčík[a), M. Gutten [b), M.Brandt [b)

[a) *Department of Physics, Faculty of Electrical Engineering*
[b) *Department of Measurement and Applied Electrical Engineering, Faculty of Electrical Engineering*
University of Zilina, Velky diel, 010 26 Zilina
e-mail: kudelcik@fyzika.utc.sk

Summary Power transformers are key equipment for transfer and distribution of the electric power. Considering the significance of the power transformers in the electric system, their price and possible damages occurred by accidents, it is necessary to pay attention to their higher prevention. To prevent failure states of transformers, we perform different types of measurements. They shall illustrate a momentary state of the measured equipment and if necessary to draw attention in advance to changes of parameters, which have specific relationship to no-failure operation of the equipment. The conditions under which breakdown of composite liquid/ solid insulation can occur, e.g. in transformer, play an important role in designing such insulation. The liquid, mainly mineral oil, generally constitutes the weakest part of insulation and a great amount of work has been devoted to the study of streamers, which appear in the gaseous phase, and most often are triggering the failure of insulation.

1. INTRODUCTION

A partial discharge is localized electrical event of short duration, which occurs in certain material when subjected to high voltages. The sudden redistribution of charges associated with a partial discharge causes a pulse, which can be detected using various external instruments. Energy release is known to be an inherent characteristic of partial discharges. As a result, a quantitative evaluation of the energy dissipated during a partial discharge could serve as a suitable estimation of potential level of destruction involved with the partial discharge. Test done on oil-paper insulation show a nearly perfect correlation between the energy dissipated during the discharge and the deterioration caused to the insulation.

Transformers are major elements in power generation and transmission systems. Partial discharges occurring in power transformers can cause damage of varying severity to the transformer's insulation, which may eventually lead to a failure of the unit. The failure of especially large power transformers is an area if extreme concern for electrical utilities. Failures that occur without any warning cause service disruptions, which are difficult to circumvent and may cost million of dollars in replacement fuels and customer outages. The ability to identify the existence of partial discharges before they pose any danger of failure of the transformer unit is therefore highly desirable. The accurate detection and localization of the partial discharge in transformer could provide an indication as to the integrity of insulation.

The objective of the research reported in this article is to investigate the feasibility and application of examination of transformer oil using electrical detection techniques.

2. DIAGNOSTIC OF POWER TRANSFORMERS

It is in principle about tests applied for test equipment with an aim to detect weak points in insulation system and to determine stage of progressive devaluation of this system as the whole [1]. They are specific terms, which considering the necessity of short-time shut-down of equipment from an operation (it is not recommended to use time demanding methods) and minimisation of number of an operations, which are required to make a machine preparation for a individual measurement.

2.1 Testing methods

a) Insulation Oil Analysis:

- *Breakdown Voltage* - On the basis of the analysis results we can assume if oil contains emulsified water, over-saturated gas or conductive impurities. It does not indicate the stage of operation ageing (Fig. 1).
- *Dissipation Factor* - Loss factor indicates presence of polar and ion substances in oil. Therefore, it indicates oil ageing. Heat dependency (tgδ) may indicate presence of foreign soluble matter in oil.
- *Resistivity* - Resistivity indicates foreign matter of conductive character (including water) present in oil.
- *Relative Permittivity* - This factor provides rough information on oil ageing degree, but not moistening.
- *Ageing Factor* - determines the quality of new oil. Considering operation it serves to define the ageing degree.
- *Interfacial Tension of oil against water* - serves for new oil quality assessment. Considering operation it serves to define the ageing degree. It reacts sensitively onto soluble sediments creation.

- *Density* - represents a quality factor considering both new and used oil. It is essential for surface tension calculation.

Fig.1 Measurement of oil breakdown voltage by testing equipment Megger

b) Thermal and Electric Defects Detection in Oil Transformers:

- *Total Gas Content in Oil* - Considering new transformers this factor impacts assessment of degasification of the insulation system of the machine. Considering hermetic machines it verifies the sealing effectiveness. It represents factor significant for detection of kinetics of the thermal defect (fast or slow process) if we take machines with thermal defects into consideration.
- *Chromatographic Analysis of Gases Dissolved in Oil* **-** method used for determination of thermal and electric defects in transformers filled with oil. It enables to detect the defect location, intensity of the process and kinetics of development (that means the rate of risk taken during consequent operation of the transformers).
- *Chromatographic Analysis of Gases from Gas Relay* - method used for determination of thermal defects

c) Measurement of Power Transformers Insulation Characteristics - measurement of power transformers insulation characteristics (measurement of loss factor, capacities, insulation resistance, polarization index calculation, non-temporal constants in various connections of measured winding) is to detect the operation ageing degree, insulation systems moisturizing and to detect defect creation location in each section of insulation systems.

d) Short-circuit Impedance Measurement under Reduced Voltage - the assessment of short-circuit impedance changes enables to detect potential winding deformations. The maximum of method response deals with radial deformation. Considering axial deformations the response is low.

2.2 The electric fortresses oil examination

The preparation of samples

- Directly before filling examinational container is the sample in container little by shake and the container is turn over a few times up bottom like this, so that is provide by decision what the most homogeneity diversion messies in the fluid without production of air bubbles.
- Is needs to exclude users exposure samples to outside's air.

The examinational container filling.

- Directly before early in the test oneself empty the examinational container and her walls, electrodes and others sections is rinse with testing fluid. The container is emptying and again is slowly filled with testing fluid, like this so that it excludes the generation air bubbles.
- Measurement container is placed into examinational machinery and the mixing is running.

The Voltage Connecting

- The first voltage connecting is begins about 5 min. after overfilling of testing fluid and after its infuse, whether there are not visible bubbles in a blank between electrodes.
- The voltage is connecting at electrodes and equally is going up by 0 with speeds of 2,0 kV/s ± 0,2 kV/s, while is not fall breakdown voltage. The breakdown voltage is maximum achieved voltage and circuit is automatically interrupted by it. (Arc formation).
- Measuring data are recording.
- To execute cycle 6 breakdown voltage with same sample with aborted least on 2 minutes every breakdown voltage before frequently connection voltage. If a blender is used, this blender has to be repeated during the test all the time.
- To calculate the average values of 6 breakdowns and introduction them by kilovoltage (kV).

3. THEORY OF SERIES RLC CIRCUIT

On the basis of presented measurement development of discharge current, RLC circuit can represent the breakdown in oil. In this type of a circuit, the resistance R is significant and the electromagnetic energy of the circuit decreases with time because energy is dissipated as heat from the resistor. Thus in an RLC circuit (Fig. 2) we expect that the charge on the capacitor and the current in the circuit will tend to approach zero as time goes by, but that oscillations in the charge and current may occur while they are dying out.

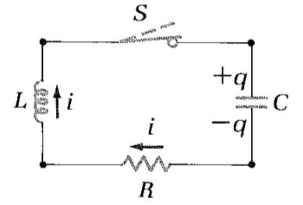

Fig. 2. RLC circuit

As before, a battery with the voltage U_0 charges the capacitor, and then the switch is closed. We let i be positive when the current is clockwise, and we let q be positive when the charge on the upper plate is positive. With our chosen sign convention for q and i, the loop rule gives

$$L\frac{di}{dt}+iR+\frac{q}{C}=0\,, \tag{1}$$

Derivation the previous equation by t and using substitution for i = dq/dt, we have [2]:

$$\frac{d^2i}{dt^2}+\frac{R}{L}\frac{di}{dt}+\frac{1}{LC}i=0\,, \tag{2}$$

This is differential equation of second order, which solution we can find in the form:

$$I(t)=I_0e^{-t/\tau}\sin(\omega t+\phi)\,, \tag{3}$$

The factor $e^{-t/\tau}$ provides the exponentially decreasing amplitude, and the expression sin (ω t + Φ) provides the oscillations. It can show that Eq. (3) is a solution by using it to substitute for i, di/dt, and d^2i/dt^2 in Eq. (2). Further, this substitution will allow to find values for τ, ω and I_0. The results are

$$\tau=\frac{2L}{R}\,, \tag{4}$$

$$\omega=\sqrt{\frac{1}{LC}-\left(\frac{R}{2L}\right)^2}=\sqrt{\omega_0^2-\frac{1}{\tau^2}} \tag{5}$$

$$I_0=\frac{U_0}{L\omega} \tag{6}$$

Depending on the values of τ and ω_0, there are three possible cases: a) If R > √(4L/C), then the circuit is overdamped. b) For the particular case where R= R_{crit} = √(4L/C), the circuit is said to be critically damped. c) In the case when (1/LC) >> $(R/2L)^2$ or R << √(4L/C),), then the circuit is underdamped. The last case occurs of our experiment.

4. EXPERIMENTAL TECHNIQUES AND RESULTS

Figure 3 shows the schematic diagram of the experimental setup, which includes HV power supply, electrode system and electric diagnostic. As the electrode system, we used sphere-to sphere, which were prepared using norm STN 100 and its radius is 3 cm. Electrode distances were measured with accuracy of 0.01 mm. As a dielectric liquid, new ITO 100 was used.

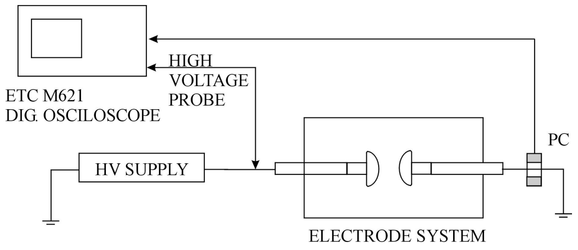

Fig. 3 Experimental setup.

The applied voltage was measured with high voltage probe and the current was measured by means of Pearson coil (110A) with a temporal resolution of approximately 20 ns. Development of current and voltage were measured with using 150 MHz oscilloscope M621 (computer card).

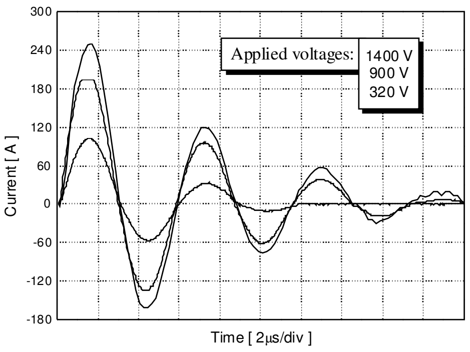

Fig. 4: Development of discharge current at different applied voltages at S = 0,1 mm.

With our oscilloscope, we are able to study breakdown phenomena in insulating oils. We measured the development of discharge current in dependence of applied voltage at various electrode distances. In the Figure 3 the development of discharge current at various applied voltages can be seen. Simple measurement with transformer oil also made Marton [3]. The development of current can be fitted by function: Sine Damp (Eq. 3). This development of current was the same as we could observe at RLC circuit, theory of which was presented in section 3. The measurement was also made at various electrode distances (0.05, 0.15, 0.20 and 0.03 mm). We observed similar development of discharge current as in the figure 3. We made the comparison of development of discharge current at the same applied voltage and at various electrode gaps. We found out that the amplitude of current pulse and its characteristic values depend only on applied voltage, not on electrode gap.

From the knowledge, that RLC circuit can represent development of discharge current, we can use relations (4, 5, 6) to determine its characteristic values: R, L a C. We found out from the data analysis of calculated corresponding values, that capacitance C and inductance L of circuit are constant with the values 252±8 nF, 3.31±0.16 μH, respectively. The value of resistance of breakdown channel was not constant. The calculated values of resistance R are shown in the figure 5 in dependence of applied voltage at different electrode distances. From the Figure 5 it can be evident, that the resistance decreases (by linear or other function) with increasing applied voltage to the electrode gap.

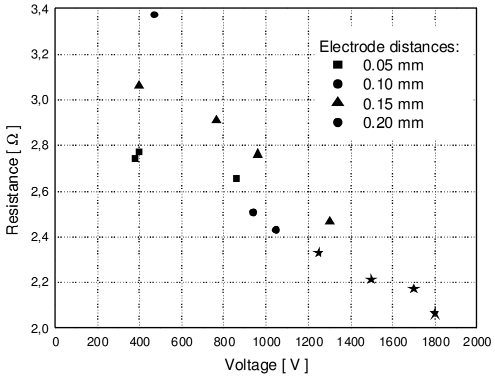

Fig. 5: The resistance of breakdown channel in dependence of applied voltage at different electrode distances.

5. DISCUSSION

From the measured development of discharge current for different applied voltages and electrode distances, RLC circuit can represent the breakdown phenomena. On the basis of this analogy, we can replace transformer oil between the electrodes by RLC circuit. Its characteristic values can be determined by fitting of measured development of discharge current using the function defined in Eg. 3. As a result, there are correspondent values of function for current as: I_0, τ and ω which can be transformed to R, L and C using relations (4, 5, 6). From the calculated values we get, that inductance L and capacitance C are constant and do not depend on the conditions of our experiment. For the value of R this is not true and its value decreases with increasing applied voltage (Fig. 5). The next interesting result is, that the value of resistance of virtual circuit is of order of Ω, while the resistivity of insulating oil ITO 100 at normal conditions is of order of 10 MΩ/mm.

In particular, when considering a high field region very close to a cathode, the first events following a voltage step are now well identified: there is an initial discharge in liquid phase generating a small gaseous bubble, in which subsequent discharge occurs. The dependence of breakdown upon pressure in liquid insulators led investigators to suspect that gaseous bubbles play an important part in triggering of the breakdown. This has been confirmed by recent works [4, 5] which showed that a moderate pressure (up to a few MPa) can suppress the bubble initiated at a sharp electrode leading to the increase of the discharge initiation voltage and therefore to the increase of the dielectric strength of the liquid medium. Several other mechanisms of breakdown initiation are known such as thermal-electric ionization and dissociation, dissociative ionization, impact ionization, tunnel effect, etc.

It is well known that the development of streamers in liquid dielectrics is generally preceded by the creation of a gaseous bubble resulting in local heating of the liquid induced by a current pulse injection [6]. Based on our experimental results we can say, that the breakdown in transformer oil exists in gaseous phase, what is confirmed by more facts. The main is that the resistance of breakdown channel is of order of Ω. The next one is, that the bubble is observed after each breakdown, which is generated in the discharge space. The breakdown causes a local heating of the liquid and as the result it is observed a bubble.

6. CONCLUSION

The breakdown characteristics of dielectric liquid – insulating oil ITO 100 were measured. We are able to measure the development of current of breakdown and applied voltage in μs time scale. On the basis of experimental results we can say that breakdown in transformer oil can be represented by RLC circuit. The resistance of breakdown channel is of order of Ω. The whole evolution of the breakdown takes place in gaseous phase, which is not identical with dielectric liquid.

Acknowledgement

This work was supported by the Grant Agency VEGA from the Ministry of Education of Slovak Republic under contract 1/2017/05

REFERENCES

[1] Gutten, M.: *Diagnostic and Monitoring of Power Transformers, 5th International Conference Elektro 2004, Žilina (2004)*

[2] Čičmanec, P.: Všeobecná fyzika 2, Alfa 1992

[3] Marton, K., et al.: *Proc. DISEE, Inter. Conference, Bratislava (2004)*

[4] Beroual, A.: *J.Appl. Phys., Vol 73 (1993) 4528*

[5] Beroul, A.: *IEEE Elect. Inst. Mag. Vol 14 (1998) 6-17*

[6] Blake, J.R., Gibson, D.C.: *Ann. Rev. Fluid Mech., Vol 19 (1987) 99-123*