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EFFECT OF PARTIAL DISCHARGE ON PHYSICAL AND CHEMICAL PROPERTIES OF TRANSFORMER OIL

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Abstract- The classic definition goes something like this: "partial discharge is an electrical discharge that shunts only part of the insulation between electrodes at different potentials". We have such a definition almost everywhere in the literature: However, from the perspective of engineering diagnostics, we are mostly engineers, this is not a very complete definition. According to this definition, there are a lot of bit processes that are not related to defects, and it turns out that they need to be registered and defined somehow. However, it is not. A corona discharge, for example, in some cases is a hindrance and is not related to a useful signal, and in some cases, on the contrary, it is a corona discharge that is a manifestation of a defect and we need to register it. At the same time, a classical discharge in a small gas cavity somewhere is a manifestation of a defect, and somewhere it can exist in a completely natural way, since it does not consume the insulation resource. Therefore, in my opinion, the definition in the sense of diagnostics should be supplemented: "partial discharge is an electric discharge that shunts only part of the insulation between electrodes that are under different potentials" - a completely classical definition - but at the same time consumes the insulation resource or is a manifestation of a defect. This small addition immediately shows that not all discharge processes related to the very concept of "partial discharge" are useful to us in an engineering sense. The same processes may or may not indicate a defect. It all depends on the equipment and insulation.

Keywords: Partial Discharge, Transformer Oil, Diagnostic, Temperature, Analysis.

1. INTRODUCTION

Power transformers with a service life of 40-60 years require a revision of regulatory documents for technical diagnostics [1-3]. A thermographic inspection and partial discharge measurement every 8 years or before a major overhaul is a big risk of missing early defects and therefore damage to the transformer. In [4], [5] the diagnostic value of control methods and parameters is given. The authors of articles performed the ranking of diagnostic parameters:

- Chromatographic analysis of gases;
- Degree of polymerization of paper insulation;
- Content of furan compounds in oil;
- Surface tension of oil;
- IR spectrometry;
- Thermal imaging control;
- Partial discharges;
- Short circuit resistance;
- Measurement of low-voltage pulses to assess the dynamic resistance of windings;

Measurement of the amplitude-frequency characteristics of the windings to assess the pressing of the windings. It should be kept in mind that partial discharges are a diagnostic parameter and a factor that leads to transformer damage. In, a group of authors believes that the registration of partial discharges in the conditions of high-voltage stations and substations is ineffective.

As for the determination of the violation of the pressing of the windings and the magnetic circuit, the method of the Vibrocenter company is increasingly used because of its simplicity, i.e., the change in the overall level of the tank vibration in the range of 10-1000 Hz. Studies have shown that the reliability of this method is 50-60%, since there are many factors (defects) that cause an increase in vibration in the range of more than 1000 Hz. In addition, the authors of the article do not consider traditional measurements on a disconnected transformer tgδ (dielectric losses) of windings and bushings, insulation resistance of windings and bushings, DC winding resistance, no-load losses from the point of view of their diagnostic value. It can also be agreed that none of the known diagnostic methods can give reliable results when detecting defects. It is advisable to use complex diagnostics without stress relief. A verified analysis of the results of measuring power transformers over the past five years and in 2018 showed that these data on tgδ are not only uninformative, but to some extent even dangerous, since they give false information about the technical condition of the bushings and windings. Studies have shown that 60-70% of damage to windings and bushings occurs due to the intensive development of partial discharges.

The author of the article provides data on the number of damages to transformers and economic losses from their damage, losses from interruptions in power supply and total losses. Total losses can vary from $20 million to $150 million. The purpose of this work is to study under laboratory conditions the influence of impurities on the intensity of partial discharges in an open vessel.

2. STATEMENT OF THE RESEARCH PROBLEM

The partial discharge is the first step in a sequence of events leading to complete insulation failure. Originally, the insulation failure was believed to be a runaway ionization process. Today, photographic evidence has shown the details of the mechanisms of partial discharges and electrical breakdown (4-83, 4-82, 11-81, 4-81). These studies have used a high-speed image converter camera to obtain a series of photographs that show the initiation and development of partial discharges. These events are descri- , bed in the following paragraphs. In the case of a metal in contact with a liquid, the tendency is to reduce the free electron concentration in the metal by injecting electrons from the metal into the liquid, where, unlike the metal, in good insulating oil there are virtually no free electrons.

This injection process occurs even in the absence of any externally applied electric field and provides the liquid with several free electrons. Upon the application of an external electric field, a force acts on the charges and their resultant motion causes the formation of low-density oil regions. It is the presence of these low-density regions which facilitates further charge injection and thus the initiation of a partial discharge. The field-induced charge injection occurs at optimum sites on the interfaces between the liquid and metal surfaces, such as the walls of the transformer tank or the surface of conductive particles in the oil, or at the interfaces of the liquid and an insulator such as the wires of the transformer 21 coils. For the latter to occur, a conductive path through the insulator must be established to allow the transfer of charge from the metal windings to the oil-paper interface. Although the transformer is designed to avoid any large field gradients, the microscopic roughness of the interfaces alters and enhance the electric field at certain points on these surfaces. Thus, the electric field is locally increased and thereby facilitates the charge injection.

Oil-pressboard was commonly used in power transformer for electrical insulation and mechanical support purposes. Physical, chemical, electrical properties of transformer oil are subjected to change with environmental conditions, and these properties depends on the crude oil and on the refine process. Dielectric strength of mineral with pressboard is 200-250 kV/cm and permittivity 4.4 [1]. Moisture and particle in the oil leads to local electric stress which initiates the discharges at interface of the insulation. Naphthenic and paraffinic based liquids have been commonly used as liquid insulation and coolant in power transformers with pressboard material. In recent decades, there has been scientific research into the partial discharge and flashover at oil/pressboard interface of composite insulation system The focuses of the previous studies were formation of carbonization marks along the pressboard surface due to surface discharge phenomena and also change in PD behavior of oil-pressboard samples with the effect of thermal or electrical ageing. However, research in the change of phase resolved PD pattern and apparent charge in pressboard samples impregnated with transformer oils especially in synthetic ester has not been widely reported. Experimental investigations of the change in PD behavior in oil-pressboard insulation with some impurities were performed. The purpose of this study is to find the suitability of synthetic ester as an alternative of mineral oil. The pressboard with different oils and its breakdown properties have been discussed in next session. Followed by detailed experimental methods of oil pressboards. Last session describes the experimental results with some possible scientific explanations.

Chromatographic analysis of combustible gases in oil and physico-chemical tests of oil are performed in Energy System every six months. To date, the following methods of chromatographic analysis of combustible gases are known: IEC 599 method; IEEE methodology; Rogers technique; Schlizenger's method; Dornenburg; Duval. According to the CIGRE working group 15.01, none of the national methods is suitable for universal application [11]. In this regard, the authors tested about 50 samples of transformer oil according to some method and according to Dornenburg.

The signs of thermal defects coincided completely according to the two methods. As for discharges in oil, the methods showed large discrepancies in the results in the classification of defects. It should be noted that discharges of low and high power and an electric arc are distinguished. It must be assumed that under the influence of various discharges and an electromagnetic field, the physical and chemical composition of transformer oil changes. It is possible that with prolonged exposure to low power partial discharges or electrical discharges, these changes accumulate, since oil control is carried out once every six months, oil cleaning is carried out even less frequently. It was necessary to determine under what conditions partial discharges turn into an electric arc in power transformers and whether the physical and chemical composition of transformer oil changes under the influence of partial discharges. Partial discharges have several different types of energies associated with them. The major types of energies of partial discharges and the techniques used for their detection are now discussed. 1) Acoustic detection. Acoustic waves are generated by the expansion of the low-density region formed by the partial discharge. The shock waves have frequency components from the subsonic range (20 kHz). Acoustic measurements have been found to be useful for partial discharge detection in oil-filled transformers, where the transducer can be either placed directly into the liquid or attached to the transformer tank walls.

3. RESEARCH RESULTS

The moisture content [1], [2] and the acidity of the oil increase the aging rate of the paper insulation. Mechanical impurities more than 10 rel. units cause partial discharges. Under laboratory conditions, R-646 oil was tested in an open vessel. It was very important to visually determine the moment of occurrence of partial discharges and measure their intensity with the M4202 device. Organic impurities were used - balls with a diameter of 1.5 and 3.5 mm (decorative eco-soil). Steel balls 2.5 mm in diameter were used as metallic impurities [4]. The AID-70M device could generate voltages up to 70 kV. At the same time, the leakage current between the electrodes in the vessel was recorded. At a low voltage between the electrodes of 3-4 kV, the organic balls performed a chaotic movement between the electrodes. With an increase in the applied voltage, some of the organic balls lined up in a straight line between the electrodes with a minimum distance from each other as Figure 1 [7].

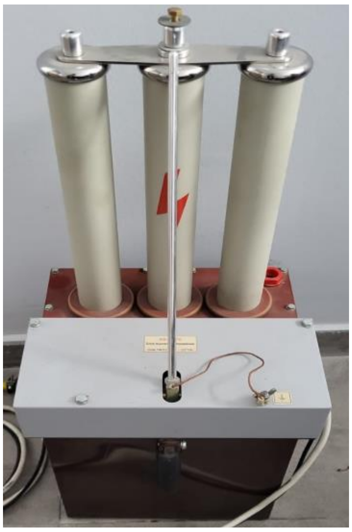

Figure 1. AID-70M high-voltage test facility

In fact, the conditions for the occurrence of an electric arc were formed. With a slight increase in voltage between the electrodes, an electric arc instantly appeared. The distance between the electrodes in the oil varied from 8 to 18 cm. As a result of the experiments, it was found that the occurrence of partial discharges is affected by: the distance between the electrodes in the vessel; oil contamination level; diameter of organic impurities. In particular, the following patterns were identified:
– The smaller the distance between the electrodes in the vessel, the lower the voltage level for partial discharges;
– The greater the level of oil contamination, as well as the diameter of organic impurities, the lower the voltage level, the partial discharges occurred;
– The larger the diameter of organic impurities, the lower the voltage level for partial discharges.

Partial discharges were recorded by the German partial discharge probe M4202 (Lemke-5). Due to the large contamination of the oil, already at a voltage of 4 kV, partial discharges of more than 1000 pC were recorded. After short-term exposure (5 min) to partial and electrical discharges, sample 2 was taken. After prolonged exposure to electrical discharges for 15 min, sample 3 was taken. device "Crystal-2000M". The results of the analysis are presented in table. One [10]. As follows from Table 1, the percentage composition of gases increased significantly in sample 3. Let's check how the ratio of gases has changed, following the accepted methods of IEC.

- Sample 2: C_2H_2/C_2H_4 = 0.247/0.229 = 1.08; CH_4/H_2 = 0.46; C_2H_4/C_2H_6 = 3.55.
- Sample 3: C_2H_2/C_2H_4 = 1.75; CH_4/H_2 = 0.454; C_2H_4/C_2H_6 = 3.2. In this case, low and high energy discharges are also observed.

High-energy discharges turning into an electric arc were visually observed, partial discharges of more than 1000 pC were recorded by the device. Chromatographic control of combustible gases was an additional method for evaluating the effect of partial discharges on transformer oil. The ratio of gases C_2H_2/C_2H_4 has changed significantly, i.e., it has increased by almost 1.7 times. Other ratios of gases practically did not change. It can be assumed that new fractions appeared in the oil under the influence of partial and electric discharges. To make sure that the physical and chemical characteristics of transformer oil have changed, tgδ was checked and the IR spectrum of oil samples was analyzed, tgδ was checked at the Tangens-3M transformer oil electrical loss measurement unit. The measurement results are presented in Tables 2 and 3 [8].

Table 1. Results of chromatographic analysis of transformer oil

Sample transformer R-646 oils	Concentration of gases dissolved in oil, vol. %						
	H_2	CH_4	CO	CO_2	C_2H_4	C_2H_6	C_2H_2
Sample 1: Before the experiment	0.00044	0.00019	0.002	0.105	0.00018	0.00007	-
Sample 2: short-term exposure	0.11058	0.05103	0.065	0.1	0.22905	0.06452	0.24767
Sampler 3 prolonged exposure	0.39237	0.17875	0.0178	0.125	0.69757	0.17738	1.22497

After short-term exposure to partial and electrical discharges, tgδ increased by 3.21 times at a temperature of 19-21 °C. At a temperature of 70 °C - 2.3 times. It was not possible to measure tgδ of the oil of sample 3, since the protection of the device was triggered Tangent-3M. The results obtained when measuring tgδ confirm the hypothesis that under the influence of partial electric discharges, new fractions appear in transformer oil.

Table 2. Test results of R-646 transformer oil before exposure to partial and electrical discharges

Index	Temperature t, °C		
	21 °C	70 °C	90 °C
tgδ	0.00058	0.00606	0.0121
Dielectric constant ε	2.265	2.019	1.878

Table 3. Test results of R-646 transformer oil after exposure to partial and electrical discharges

Index	Temperature t, °C		
	19 °C	70 °C	90 °C
After the first experience. Sample 2			
tgδ	0.0019	0.0139	0.026
Dielectric constant ε	2.29	1.89	1.77
After the second experience. Sample 3			
Instant oil breakdown (see explanation in the text of the article)			

In the course of the research, a comparative analysis of the IR spectra of samples of transformer oil was carried out. IR spectra were taken on a Vertex 70 Fourier spectrometer (Bruker, Germany). The intensity of absorption bands was expressed in terms of the area of absorption peaks (arb. units), which was determined using the OPUS 6.5 software package. Sample 1 was a control sample of oil, samples 2 and 3 were taken from vessels, they were previously subjected to short-term (sample 2) or long-term (sample 3) exposure to electrical discharges. Three main absorption bands can be distinguished in the IR spectra of all samples: 3100–2800 cm^{-1}, 1555–1400 cm^{-1}, and 1655–1555 cm^{-1}. As we see from the data in Fig. 2, all three oil samples have the same absorption frequencies in the IR region (Table 4). However, their relative absorption intensity differs, which means that after the impact of electric discharges, changes in the structure of oil molecules occur. The data of the performed calculations are presented in Table. four. The absorption band in the region of 3100–2800 cm^{-1} (the main peak in the region of 2920 cm^{-1}) is due to the stretching vibrations of aliphatic methylene groups (-CH2-) contained in the oil molecules, the absorption band 1555–1400 cm^{-1} (the main peak in the region of 1460 cm^{-1}) is due to stretching vibrations of methyl groups (-CH3) [12], [13]. The intensity of the band 3100–2800 cm^{-1} was used as the base absorption band [2].

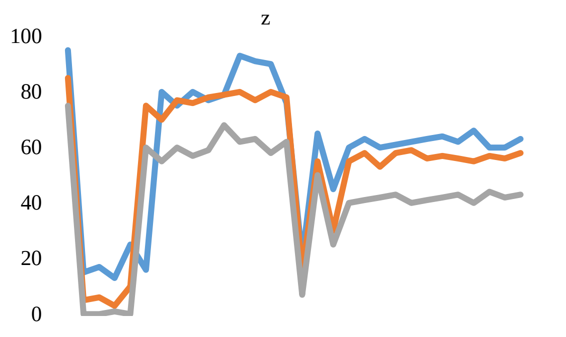

Figure 2. IR spectra of transformer oil:
sample 1: spectrum 1, sample 2: spectrum 2, sample 3: spectrum 3

The intensity ratio of the S1460/S2920 bands in the spectra of samples 2 and 3 is higher (0.0817 for sample 2, 0.0838 for sample 3) compared to the spectrum of the control sample. This fact indicates a higher content of methyl groups (-CH3) in oil samples exposed to electrical discharges (Figure 3). At the same time, the number of multiple bonds in the composition of organic oil molecules also increases. This can be judged from the increase in the relative intensity of the absorption band at 1655–1555 cm^{-1} (the main peak in the region of 1600 cm^{-1}), which refers to unsaturated carbocompounds [12], [13], the data are given in Table 4. The intensity of this band in the control sample is low S1600/S2920 and is there is only 0.0037.

Table 4. Analysis of IR Spectra of Transformer Oil Samples

Transformer oil samples P-646	S_{1460}/S_{2920}	S_{1600}/S_{2920}
Sample 1 - before the experiment (control)	0.0800	0.0037
Sample 2 - short-term exposure	0.0817	0.0038
Sample 3 - long-term exposure	0.0838	0.0041

Based on the data obtained from IR analysis on the structure of oil molecules, it can be argued that when exposed to electric discharges, oil molecules undergo destruction. At the same time, the accumulation of oxygen-containing groups in the composition of oils was not fixed, since in samples 2 and 3 there is no absorption band in the region of 1720 cm^{-1} (Figure 2), which is related to the stretching vibrations of carbonyl groups [12]. Separately, it should be noted that sample 2 contained a separate fraction that differed in color and consistency - a gel-like precipitate. This precipitate was recovered and subjected to IR analysis; the IR spectrum is shown in Figure 3.

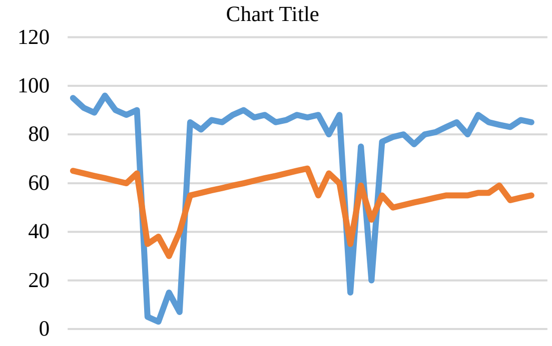

Figure 3. IR spectrum of sample 2 of transformer oil (spectrum 1) and its sedimentary fraction (spectrum 2)

It can be seen from the presented spectrum that the resulting fraction contains water, which follows from the absorption bands in the region of 4000–3500 cm^{-1} and in the region of 1670–1590 cm^{-1} [14]. This means that under the influence of electric charges on transformer oil, the chemical structure of its molecule's changes, and with prolonged exposure, destructured molecules are released in the form of a separate fraction. Partial discharges have several different types of energies associated with them. The major types of energies of partial discharges and the techniques used for their detection are now discussed. Acoustic detection. Acoustic waves are generated by the expansion of the low-density region formed by the partial discharge. The shock waves have frequency components from the subsonic range (20 kHz). Acoustic measurements have been found to be useful for partial discharge detection in oil-filled transformers, where the transducer can be either placed directly into the liquid or attached to the transformer tank walls the main advantage of the used methods is the simplicity of their application. The presence of certain errors is the main shortcoming of the proposed method.

4. RESULT

Thus, as a result of the conducted research, it was established:

1. When transformer oil is contaminated, partial discharges of high intensity occur, which, under certain conditions, turn into electrical sky ranks. It has been determined that the occurrence of partial discharges and their transition to an electric arc are affected by: the distance between the electrodes; oil contamination level; diameter of organic impurities.
2. Under the influence of partial and electrical discharges, the color of the oil changes, new fractions appear, which can reduce the reliability of detecting defects in the chromatographic analysis of combustible gases.

3. When the chemical composition of the oil changes under the influence of partial and electrical discharges, the dielectric loss tangent tgδ of the oil increases by a factor of 2-3.
4. To increase the reliability of detecting defects in power transformers, it is advisable, along with chromatographic analysis, IR analysis of transformer oil, to simultaneously control the intensity of partial discharges.

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