Moisture content as an important integral parameter of transformer oil quality in power transformers of 10/0.4 kV substations

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Abstract. The main element characterizing the transformer efficiency is the state of its isolation, and the first thing is operating oil, which can perform its functions for a long time with timely restoration of its properties. Transformer oil is the main dielectric being in contact with the external environment, interacting with solid insulation and carrying a large amount of diagnostic information. Analysis of the development of transformer insulation damage showed that the main catalyst for accelerating the aging process of the oil is the appearance of moisture in it. This effect is enhanced by oxygen, temperature, the catalytic action of metals, oxidation and other factors. To confirm the influence of moisture content in oil on the deterioration of its properties, a statistical analysis of the oil sample test protocols was carried out. The obtained data allowed us to determine the moisture content as an important integral parameter of oil quality. Recommendations are given on the inclusion of a moisture content parameter in a set of mandatory requirements, in particular, for 10/0.4 kV consumer transformer substations equipped with silica gel air dryers

1 Introduction

Analysis of the reliability of transformers shows that the main criterion for the overall assessment of their ultimate performance is the technical condition of windings, which, in turn, depend on the state of liquid and solid insulation. Often, the insulation works in heavy conditions (high electric field strength, high temperature, dissolved oxygen and moisture molecules, metals, etc.), which degrades its properties. As a result, insulation breakdown and transformer failure may occur [1-5].

A study of technical documentation of damaged transformers shows that in most cases they were operated with oil and solid insulation characteristics that have unacceptable deviations from the standard values. The cause of transformer failures is the late detection of the developing defects.

In order to understand the reasons for it, we consider in more detail the mechanism for the development of damage processes in transformers' insulation as a block diagram (Figure 1) [2,3,6].

Transformers have certain defects during their fabrication. Under the influence of operational impacts, their further development occurs. However, such defects are not determinative if the insulation is damaged. The main role is played by the natural processes of its aging under the influence of operational factors.

Transformer overloads, ambient temperature increase, start-up modes of powerful consumers, short circuits in the networks supplied by transformers result in overheating of the insulation, and its thermal wear is accelerated.

Thermal insulation aging is a determining factor in general wear, which is also affected by oil moisture, oxidation, and other factors that reduce the mechanical strength of the insulation.

The appearance of moisture in the insulation drastically reduces the leakage current resistance caused by free ions, which leads to an increase in dielectric losses. As a result, the thermal breakdown voltage decreases and the insulation is further heated, which leads to an acceleration of the rate of thermal aging [1,2,7].

Aged insulation easily collapses under the action of vibration and electrodynamic forces arising from the flow of large load currents, especially during short circuits in the supply networks, which lead to coils in the windings, interfacial closures and transformer failure [5,8,9].

Since the main part of 10/0.4 kV consumer transformer substations is located outdoors, the insulation is significantly affected by climatic conditions, in particular, changes in ambient temperature (it reach 10-15° C during the day) and moisture. Since the insulation system is composite, the climatic factors first affect the liquid and then the solid insulation of the windings [7].

Moisture is one of the main factors contributing to the intensive aging of insulation in transformers [1,7, 10, 11]. The influence of moisture on the paper-oil

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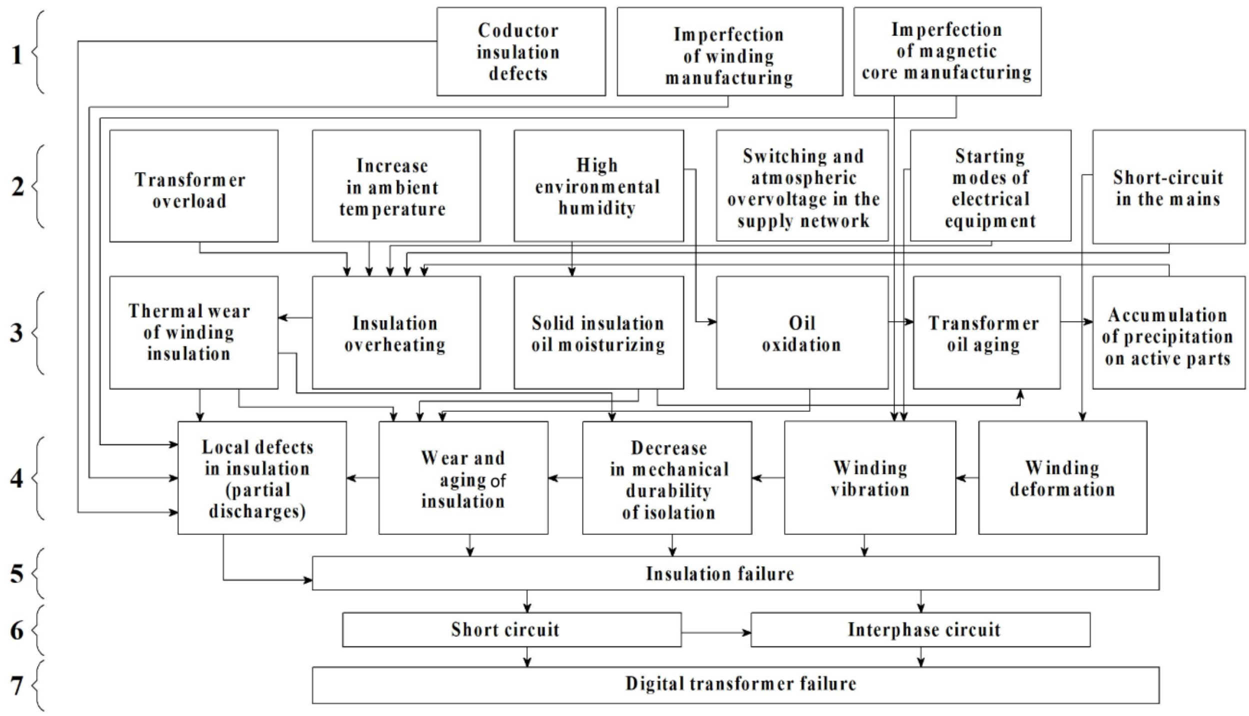

Fig. 1. Diagram of the development of transformer insulation damage: 1 - Initial defects of technological origin; 2 - Operational effects leading to the development of initial defects; 3–7 - Subsequent stages of the development of insulation defects.

insulation of the transformer as a whole and on its individual components will be further considered in more details.

Water in paper can be in three states: in the form of molecules adsorbed on the surface, in the form of free water in capillaries, and in the form of vapors. The amount of moisture in paper depends mainly on the vapor pressure and water temperature in the equilibrium state. The water content increases when vapor pressure increases and it decreases when temperature increases. An increased amount of moisture enhances the paper conductivity, which leads to an increase in dielectric loss [11-14].

Water in oil can also be in three states [4, 7, 10, 14]. Its main part is in dissolved form. A small part is in the form of water molecules and oil, which are strongly interconnected. Moreover, the number of bound molecules increases with increasing the operation time. In addition, water in the oil can be in the form of free drops. This is observed when oil saturation by water reaches a limit. Free water is considered as the most dangerous, since its droplets form chains along the field lines of force for an electric discharge [7, 10, 12].

Paper has a higher hygroscopicity than oil, therefore moisture in the insulation system of a transformer is mainly in paper. Its distribution in paper-oil insulation depends on the temperature inside the transformer. At high temperatures, water absorption by paper is reduced, and the solubility of water in oil increases. At constant temperature and vapor pressure, the moisture between the oil and paper insulation is evenly distributed [10,11,14].

Relationship between moisture contained in paper and the moisture degree of the surrounding oil are presented in Figure 2.

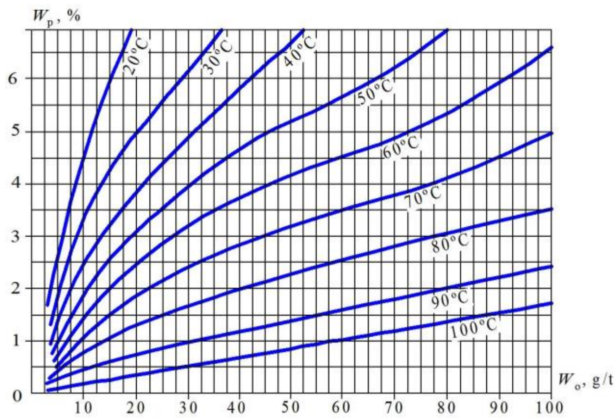

Fig. 2. Relationship between moisture contained in the paper and the moisture degree of the surrounding oil for various temperatures.

During transformer operation, the amount of moisture in its insulation is constantly growing. There are two sources of moisture in the insulation.

One of the main sources is considered to be the direct ingress of moisture from the atmosphere through disturbances in rubber seals (for example, between the tank and the tank lid) or through the oil in the expander in contact with atmospheric air. Due to the imperfection of silica-gel air dryers, atmospheric moisture is introduced from the environment into the transformer, which moisturizes the insulation over time. It can also slowly penetrate into protective systems and

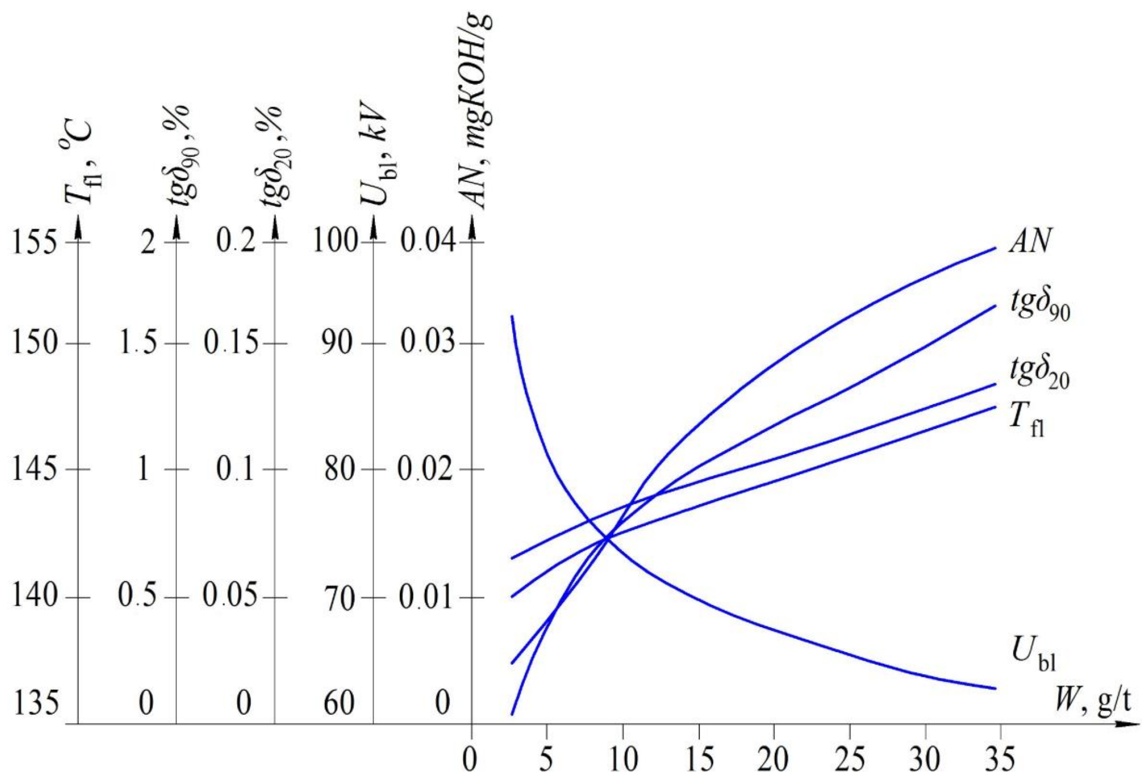

Fig. 3. Relationship between the main parameters of oil quality and the moisture content: U_{bv} is the breakdown voltage; $tg\delta_{20}$, $tg\delta_{90}$ are tangent of dielectric loss angle at temperatures of 20 and 90°C; AN is the acid number; T_{fl} is the flash point in a closed crucible; W is the oil moisture.

connections. The rate of the insulation moisture depends on the transformer load mode and the system of protection against penetration of moisture inside the tank [1, 3, 4, 15].

Another important source of excess moisture content in insulation is paper decomposition. As a result of the impact of elevated temperatures on the insulation paper component, the rupture of cellulose links occurs, at which water and furan components appear [8,16].

In addition, experimental studies show that moisture in the internal insulation accumulates even when the transformer is disconnected for a long time or is weakly loaded. In such cases, the oil absorbs moisture from the environment, which gradually moistens the outer and then the inner layers of the transformer insulation.

The moisture content of the solid insulation of a new transformer when released from the factory is less than 0.5%. After several years of its operation with silica-gel air drying, the humidity of the insulation can increase up to 3–5%, and oil - up to 25 g/t depending on the load conditions and further increase as well [17]. Determination of moisture directly by opening the transformer is difficult and costly. Therefore, the humidity of the insulation of transformers in operation is diagnosed by the moisture content of oil.

The considered processes of transformer insulation damage allowed identifying moisture content as an important parameter leading to accelerated aging of oil, reduction of insulating and mechanical properties of solid insulation, and, as a consequence, transformer damage. To confirm the effect of moisture on the aging of the oil and deterioration of its properties, a statistical analysis of test protocols was carried out for test samples of GK and VG oil in a reduced volume [1]. The protocols are provided by the chemical laboratory of the Central Production Department of the Saratov DG branch of IDGC of Volga, PJSC. According to the results of 700 protocols' processing, graphs were built (figure 3) according to average values, i.e. limit values (the largest and smallest) are discarded from the results.

The results shown in Figure 3 indicate that the moisture content of oil is uniquely related to the main parameters of its quality. All dependencies have a non-linear nature and vary proportionally to humidity.

The highest sensitivity of the parameters to changes in humidity is observed in the area of "dry" oil. For example, a change in humidity from 2.5 to 5.0 g/t on average causes a decrease in breakdown voltage from 93 to 81 kV. In other words, an increase in humidity of 2.5 g/t reduces the electrical strength of the oil by 12 kV. When changing it from 5 to 10 g/t, the acid number, the dielectric loss tangent (at 90° C) and the flash point will be respectively: AN = 0.012 mgKOH/g; tgδ90 = 0.5%,

T_{fl} = 2.7 °C.

Thus, the moisture content in insulating materials results in a decrease in electrical strength, an increase in electrical conductivity and dielectric loss, which leads to an increase in the rate of aging of insulating materials and reduction in their service life. Consequently, the control of moisture content of transformer oil is particularly relevant, since a large number of transformers do not effectively protect the oil from moisture.

2 Conclusion

1. Increased moisture content in oil leads to a decrease in the insulating and mechanical properties of solid insulation.

2. The reason for oil moistening is the decomposition of cellulose insulation and the ingress of moisture from the environment.

3. The solubility of moisture in oil depends mainly on the relative humidity of the atmospheric air, temperature and chemical composition of oil.

4. Experimental studies showed that an increase in moisture content in oil has a certain impact on a number of other oil quality parameters (Ubl, tgδ, AN, Tfl).

5. For transformers operated in the open air, the moisture content parameter should be entered into a set of mandatory ones, which will allow increasing the operational reliability of the transformer through the timely implementation of preventive measures.

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