THE INFLUENCE OF INSULATION AGING PROCESSES ON THE RELIABILITY OF TRANSFORMERS

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Introduction. The reliability and efficiency of the functioning of electrical networks and systems mainly determines the reliability of power transformers. Failures or accidents during the operation of this equipment lead to great losses. Let's give a definition of "transformer reliability". In general, it is understood as the ability of a device to operate reliably with unchanged technical characteristics for the required time and under specified conditions of use.

This problem is extremely urgent: power transformers installed in the 1960s and 1970s operate at substations and they are rapidly approaching the end of their "life". These transformers have not caused many problems over the past two decades, but with every year of the 21st century, their failure rates are becoming more difficult to predict. This means that solving issues of repair or replacement are becoming more and more urgent.

The greatest demands are placed on high-power transformers interacting with generators. Failure of low-power transformers is not so critical, since they are more easily redundant [1]. Accordingly, their breakdown can be felt only by a specific consumer, and not by the entire network. In general, both external influences and abnormal operating modes of the power system itself affect the operation of transformers.

A correctly designed and manufactured machine should be delivered to the customer with a calculated value of the reliability level, which does not depend on the moment of calculation and characterizes the features of a particular design, being its property. The probability of failure-free operation of the weakest link in relation to operational influences serves as an assessment of the level of reliability of a structure. For a power transformer, the weakest link is the set of windings. The forces acting on the winding during the current flow - dynamic, thermal, electrical - during operation should not exceed the permissible values [2].

The main factors responsible for the aging of transformers are: temperature, oxygen and humidity. Other factors may include operation in extreme conditions, as well as unfavorable environmental conditions (for example, high temperature and humidity), frequent short circuits and electrical surges. The cumulative effect of increased temperature over time will adversely affect the life of electrical devices in general and transformers in particular. For the longevity of a transformer, the combination of its elevated temperature and high ambient temperature are adverse factors that accelerate insulation aging. Aging of the insulation can ultimately lead to catastrophic failures in the transformer.

Moisture in the insulation system of a transformer can degrade molecular chains, accelerate the aging process of cellulose and negatively affect the tensile and dielectric properties of the insulation.

One of the sources of moisture is the humidity of the air surrounding the transformer. Improperly made or aging transformer gaskets and seals allow moisture present in the atmosphere to penetrate the insulation as the pressure gradient changes. This moisture ingress accelerates the aging process of power transformers. In addition, water vapor is a by-product of the degradation of paper insulation. The aging of the insulation itself exacerbates moisture problems, as the dielectric strength decreases with each increase in the moisture level [3].

Humidity and oxygen levels depend on temperature, and as the temperature rises, their values increase. High levels of moisture and oxygen can lead to the formation of bubbles, which, if trapped in insulating materials, can lead to voids and local tensions, which in turn can lead to breakdowns and accidents. Water in the insulation can also affect the dielectric properties of the insulation. The insulation power factor increases with increasing moisture content. For reliable operation, the transformer must be within the acceptable humidity range, which depends on the load and temperature. The moisture content of an oil sample is usually measured with the Karal Fischer test. It has been accepted by the industry as a standard test because of its high selectivity, sensitivity, repeatability and reliability.

The aim of the work is to analyze the impact of factors and processes of insulation aging on the reliability of the transformer and formulate basic recommendations for reducing the rate of aging of transformer insulation during normal operation.

Materials of research. The physical parameters and behavior of the insulation degrade over time. Aging of paper insulation and transformer oil leads to the formation of moisture and furans, which can cause further accelerated aging. Overheating of the insulation system, partial discharges and arcing can all lead to gas emissions. Moisture in the insulation of the bushings can lead to their degradation and destruction. Temperature can affect the moisture content and how it passes between the paper insulation and the oil. One way to minimize damage from transformer aging is to continuously monitor gases, temperature and moisture content. This data can assist in identifying the type of fault, its severity and, to some extent, its location.

The mechanical properties of insulating paper decrease significantly with age, although its electrical properties may not show significant changes. The mechanical strength of the insulating paper can be reduced by increasing the temperature in the windings. Mechanical damage to aging insulating paper can lead to electrical breakdown. This, in turn, can adversely affect the insulation performance, which can lead to transformer failure. Consequently, the condition of the insulation should be monitored regularly, as should the assessment of the condition of the transformer as a whole. Insulation paper can be tested directly by measuring its degree of polymerization.

Transformer aging can also accelerate if the transformer is not properly maintained and diagnosed. Correct diagnosis of impairments plays a vital role in prolonging the life of the transformer. The failure rate of transformers caused by dielectric problems can be as high as 75 %. Dielectric problems can be detected by tests for the presence of furan compounds in transformer oil, which are indicative of degradation of the solid dielectric.

The oil/paper temperature of the insulation system can affect the aging process, resulting in heat stress and changes in the mechanical and electrical properties of the material. If transformer faults are detected early, this can significantly reduce unplanned downtime and the costs that come with it. If the properties of the transformer oil, there is a possibility that this deterioration can lead to damage to the transformer. In addition, emissions from transformer oil can seriously damage other insulating materials. Therefore, it is important to regularly check the insulation of the transformer.

One way to determine the nature and severity of a short circuit in a transformer is through dissolved gas analysis. Decomposition of insulating oil and cellulosic materials leads to gas evolution. These flammable gases are generated when transformer oils and cellulosic materials are exposed to excessive electrical or thermal stress. If the short circuit develops slowly, the concentration of gases dissolved in the oil also increases gradually. The initial amount of gases is very small and it takes time for sufficient free gas to accumulate in the gas relay. In this regard, it is important to analyze the transformer oil for dissolved gases.

Resource indicators − full service life and service life before the first overhaul - are calculated until the limit state is reached. The distribution of operating time to the limiting state is the life curve of a transformer and is the basis for establishing estimates of resource indicators. The quantitative value of the service life is calculated according to the parameters of the distribution curve, provided that the average service life corresponds to a probability of 0.632, and the service life before the first overhaul is a probability of 0.8. A mixture of sudden and gradual (wear) failures is characterized by a Weibull distribution with a shape index of <1. Power transformers for the foreseeable period up to 15 years obey the Weibull distribution, the distribution parameters are determined by processing truncated samples. To establish a calendarized transformer life curve, it is necessary to take into account all types of damage that necessitate a functional check, including damage during transportation, installation, from improper actions of operating personnel, natural phenomena, etc. To increase the reliability of estimates, the processing of information on the durability of transformers should be divided into groups according to the voltage class. The decision on the compliance of the indicator with the established norms, limited from below, is taken if the ratio is maintained

$$R_L \geq R_N, \quad (1)$$

where: R_L – lower limit of the confidence interval; R_N – normalized indicator value.

The processing of information from operation is carried out with a frequency of one year and is given in an overview technical report for all manufactured transformers. The operating time is counted from the beginning of the year following the year of manufacture of the transformer. Calculation of the probability of no-failure operation of a transformer based on dynamic, thermal effects and the strength of inter-turn insulation:

$$P_{TD}(t) = P_{INS} \times P_{TRD} \times P_T \tag{2}$$

where: $P_{TD}(t)$ – probability of failure-free operation under dynamic influences; P_{INS} – probability of failure-free operation in terms of turn-to-turn insulation strength; P_T – probability of failure-free operation in terms of thermal effects.

These influences cause damage to the main and coil insulation with small reserves of their electrical strength. Increase in operating voltage. An increase in operating voltage leads to heating of the structural parts of the transformers (core, steel parts). It is dangerous to parts in contact with them.

An analysis of the causes of damage to this equipment, depending on the location of the defect is given in Table 1.

Table 1 − Distribution of faults of transformers

Type of damage	Part from all damage quantity, %
Deformation of the windings	19
Bushing insulator	3
Insulation defects	21
Moistening the insulation	8
Oil	5
Voltage regulator	23
Contacts of windings	15

If the transformer windings are dynamically unstable, the effects of short-circuit currents can lead to unwanted deformations. The phenomenon of overcurrent has perhaps the strongest impact on the reliability of power transformers. It increases markedly as the insulation ages. Hence, the conclusion follows to increase the reliability of the operation of power transformers, it is advisable to slow down the aging process of the insulation system.

Conclusions. If the transformer is regularly and carefully monitored, then the aging process can be controlled and its life prolonged. Longer transformer life, and the associated safety and reliability improvements, can in turn help reduce costs. This is only possible with good diagnostic techniques and realistic interpretation of the data. The usefulness of an old transformer can be improved if proper operating criteria are met and its insulation system is effectively maintained. Resource indicators - full service life and service life before the first overhaul - are calculated until the limit state is reached. The distribution of operating time to the limiting state is the life curve of a transformer and is the basis for establishing estimates of resource indicators. The conformity assessment of products (a set of products) to the specified reliability requirements is carried out according to the results of calculation or reliability tests. It is allowed not to carry out reliability tests separately or to combine them with controlled operation, if the required duration of reliability tests does not allow completing them within the terms of preliminary or acceptance tests, and accelerated tests are impossible for technical or other reasons. The main factors contributing to the aging of transformer oils are high temperatures, oxidation with atmospheric oxygen, as well as the ingress of various harmful impurities (for example, aging products, solid insulation), water and gases.

Timely use of insulation protection technologies helps prevent the development of irreversible processes and maintain the state of the insulation environment at a high operational level. As a result, the reliability of power transformers is increased, and the insulating oil lasts longer, which saves money on the purchase of fresh raw materials.

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