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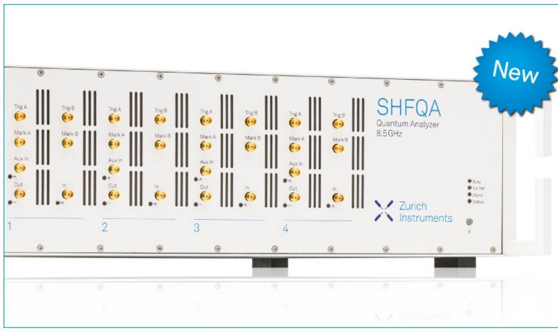

Research Processes of Oil and Paper Insulation of High-Voltage Equipment during Operation

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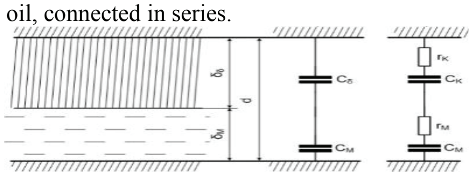
Abstract. The article analyzes the factors that accelerate the aging process of the oil-paper insulation of the condenser type and shorten its service life. Attention is drawn to the fact that the breakdown of flat insulation made of condenser paper occurs at the location of the inclusion, which approximately corresponds to the field of uniform field. An example of damage to the insulation of a current transformer due to its aging and moisture is given. This work was analysed the influence of thickness and density of paper, grade of mineral oil on short-term electrical strength. The characteristics of the insulating papers of the permeable composition largely determine the electrical strength of the paper-oil insulation.Since paper-oil insulation consists of a series of successive layers of paper and oil, it is advisable to present such insulation by the equivalent scheme shown in fig. 1, in which the thickness of the paper-oil dielectric is divided into two layers: paper (fiber) and mineral oil, connected in series.



a) b)

FIGURE 1. Equivalentpaper-oilinsulationscheme: a –tocalculatethevoltageontheoillayer;b – tocalculatethedielectriclossininsulation.

The increase in the dielectric constant of the paper is accompanied by an increase in the tension in the oil layers of paper and oil insulation, which promotes the development of discharges in these layers and facilitates the breakdown of the insulation. As a result, the effect of paper density has a different effect on the short-term and long-term strength of the insulation. In determining the short-term strength, the influence of the first factor prevails, which contributes to its increase with increasing paper density. For example, by increasing the density of paper from 0.7 to 1.3 g/cm^3, the electrical strength of sheet insulation (flat samples) increases by 60%.However, in determining the long-lasting strength, partial breakdowns in the oil layers lead to considerable destruction of the insulation. In this case, as the paper density increases, the breakdown strength is reduced and the insulation life is shortened.

INTRODUCTION

High-voltage equipment is often operated under difficult conditions that lead to a rapid reduction of residual resources, cause accidents and man-made disasters, damage to valuable equipment, and sometimes death of people (Fig. 2).

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FIGURE 2. Examples of man-made disasters

Difficult operating conditions of electrical networks cause accidents, which often cause not only economic losses but also human casualties.High-voltage electrical equipment is important and capital-intensive equipment for power systems. Damage or deviation from the normal mode of operation of the insulation material of power equipment can be caused by various reasons: defective design, hidden manufacturing defects, violations of the rules of transportation, technology of installation or rules of operation (Fig.3), poor repair. In most cases, the damage does not occur immediately, but after a less prolonged period of adverse effect.

FIGURE 3. Examples of damaged high-voltage equipment and paper insulation

Over the last decades, the development of electricity throughout the world has been characterized by the emergence of a number of factors that determine the need for radical transformations in the power industry: the increasing pace and scale of development of information and computer technologies; increasing level of equipment wear; the need for massive investment in the renovation of fixed assets; reduction of the general level of reliability of energy supply [1].

Therefore, nowadays, repair and diagnosis of power electro technical equipment, in particular paper and oil insulation in operating conditions is becoming a common technical measure to improve the reliability and quality of power supply. As paper and oil insulation of 330-750 kV equipment is one of the most widespread and responsible elements of electrical equipment of power systems [2, 3], special control systems have been created and developed to evaluate its technical condition [4]. In [5, 6, 7] various methods of operation and diagnosis on the example of power transformers are considered. However, for one diagnostic parameter, it is difficult to detect with certainty a defect of a certain kind. To effectively control the condition of the object as a whole, it is necessary to have rationally selected sets of diagnostic parameters. In order to identify defects in paper and oil insulation of 330-750 kV equipment under operational conditions, it is advisable to use even complex and costly control and diagnostic systems, for example, the system of automatic determination of the location of the damage and its causes [8]. The basic assessment of the paper and oil insulation of 330-750 kV equipment is often made during periodic inspections with the equipment switched off. Aging of solid insulation is determined by measuring the degree of polymerization of DP cellulose molecules (Degree of Polymerization) in samples taken at the dismantling of the transformer being repaired. The degree of DP polymerization is directly related to the mechanical strength of the paper [9].For the control of aging of insulation of inputs in Germany was the method of analysis of currents of charge and discharge (CDM - Charge Difference Method), which differs from the commonly used PDC method by operations with neither currents, but with charges moving in the process of polarization.Analysis of polarization phenomena in insulation, which contains a large proportion of paper, makes it promising to evaluate the moisture and aging of equipment such as high-voltage inputs, the method of analysis of polarization phenomena in isolation (for example, the analysis of the dependence of the capacity of paper-oil insulation and tangent angle dielectric lossestgδ or frequency[10, 11, 12].However, microprocessor-based continuous monitoring and diagnostics systems that use a complex of sensors are promising in the prevention of equipment crashes [5]. The purpose of such systems is to detect, at an early stage, development of equipment defects directly during operation, as well as to process, analyze and display the equipment status parameters (its isolation) in a form that is convenient for the operating personnel.

As we can see, despite the large number of methods and means, both periodic and permanent monitoring of the state of paper and oil insulation of the EEC, there are no rare cases of damage to high-voltage equipment of powerful power plants and substations.Nowadays, at many 110-750 kV power substations in Ukraine, a large number of high-voltage equipment (HVE) has been operating for more than 25 years in the conditions of high and low voltages, high electric field strength. Continuation of accident-free operation of paper-and-oil insulation of such equipment requires the introduction of modern methods, tools and technologies for determining its technical state [13, 14], which is one of the tasks of the SMART GRIDs concept, aimed at improving the information and automation support of production automation, transmission, distribution and consumption of electricity. As noted in [13], a low degree of monitoring of the condition of the equipment leads to the need for routine repairs of the equipment, rather than repairs to the actual condition, which leads to irrational costs. After all, the goal of intellectualization is to optimally use the reserve of equipment due to the ability to determine its current state and operating conditions. In [15, 16], a theoretical analysis of modern methods of continuous control of main insulation of measuring transformers and high-voltage inputs (MT and HVI) of 330-750 kV under operating voltage was carried out, and it was proved that high requirements for control of MT and HVI insulation can be achieved by controlling the insulation characteristics of $tg\delta_1$ and C_1 by the bridge and vector comparison methods.The goal of the research is to improve the reliability of operation of power equipment by improving the methods and means of detecting defects of paper and oil insulation of equipment 330-750 kV aimed at improving their information content.To achieve this goal, the following tasks are solved:

1. Investigate the factors that affect the condition of paper and oil insulation of condenser type high-voltage equipment, accelerate its aging process and shorten the life of the equipment.
2. To investigate the possibility of breakdown of flat insulation made of condenser paper occurs at the location of the inclusion, which approximately corresponds to the field of uniform field.
3. To analyze the results of wetting of paper-oil insulation of condenser type of high-voltage equipment.

Consider the isolation of high-voltage equipment such as, for example, cellulose-insulated equipment that has high electrical strength (short-term and long-term), which has a relatively low level of dielectric losses, whose insulation is similar to that of power transformers and shunt reactors of 110 to 750V. The results of the influence on the cellulose isolation of the operating conditions are shown in Fig. 4-5.

a b c

FIGURE 4. Cellulose insulation before and after exposure to operating conditions:a– strong fibers, b,c– short damaged fibers

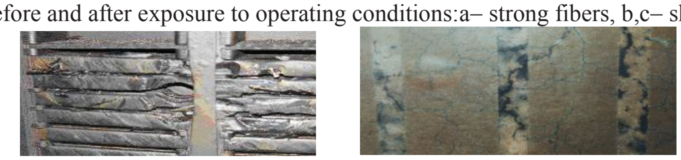

FIGURE 5. Examples of the aging results of insulation material

Operation of oil-filled high-voltage equipment is always associated with the potential risk of insulation breakdown [17-19]; and with the possibility of oil leakage. Therefore, studies are conducted on the effect of the electric field on insulation.Under operating conditions, insulation is subject to a variety of different effects: voltage, mechanical loads, high temperatures and electric arc.

MATERIALS AND METHODS OF RESEARCH

Insulation is one of the most important elements in the design of electrical equipment and largely determines the dimensions and reliability of its operation during operation.Factors related to insulation damage are shown in Fig. 6.The peculiarity of the work, for example, the internal insulation of HVE it is the ability to influence an electric arc, the temperature of which reaches several thousand degrees. The electrical strength of the insulation at an alternating voltage of the industrial frequency depends on the speed of voltage rise and the dwell time of the insulation at a given voltage [15].

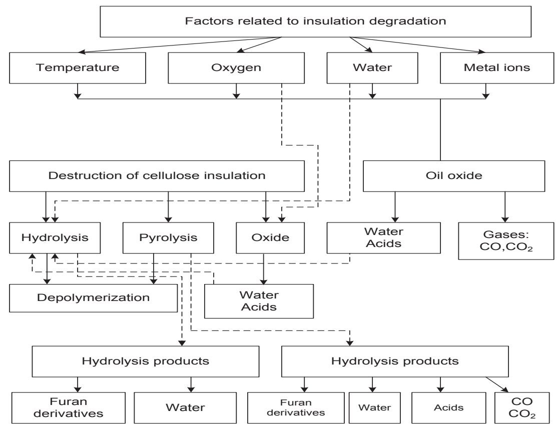

FIGURE 6. Factors related to damage to the insulation

ANALYSIS OF AGING PROCESSES OF SOLID INSULATION

Short-term electrical insulation strength is usually determined by the gradual rise of the industrial frequency voltage to the breakthrough, and in such tests for insulation samples with a breakthrough voltage up to 20 kV, the rate of rise of the voltage is usually equal to 1 kV·sec^{-1}. The duration of the voltage rise, in any case, should not be less than 10 seconds. At high values of breakdown voltage, the lifting speed is 2-3% of the expected breakdown voltage per second. In this method of determination, the electrical strength at a gentle rise in voltage approximately corresponds to the strength at 30-second exposure to the voltage applied to the shock insulation.It is known that the dependence of the breakdown voltage on the thickness is different for flat paper insulation made of capacitor and cable papers.The small thickness of each sheet of condenser paper (7-12 microns) causes a significant dependence of the breakdown voltage on the number of sheets. In one sheet of condenser paper there are always conductive inclusions consisting mainly of particles of coal dust, metals, their salts and oxides. The number of such inclusions depends on the thickness of the sheet and for paper with a thickness of 10-12 microns is 50-60 per square meter of its surface [12].

Similarly, the breakdown voltage U_{pr} of three sheets will be determined by the electrical strength of the two sheets; four sheets - the strength of three sheets, etc.

As follows

$$U_{bd} = E_{wi}(n-1)\delta_s \quad (1)$$

whereE_{wi} – electric field strength of breakdown of paper without inclusions;

δ_s – thickness of one sheet;

n – the number of sheets in the insulation layer.

Middle electric field strength of breakdownE_{bd} is defined:

$$E_{bd} = U_{bd}(\mathrm{n}\delta_s)^{-1} \quad (2)$$

As the number of sheets in the insulation layer increases, the average breaking strength will increase by law:

$$E_{bd} = E_{wi}\frac{n-1}{n} \quad (3)$$

The presence of conductive inclusions in the layer mainly results in a breakdown of the insulation in the region of the middle of the electrode. However, if the number of sheets is more than seven to eight, then the marginal effect on the edge of the electrode (cover) begins to be indicated. As soon as the thickness of the dielectric increases to such an extent that the conductive inclusions will practically cease to be affected (close to one), the breakdowns will occur at the place where the electric field strength is greatest.In a sharply heterogeneous field, the breakdown condition can be formulated in two ways. Assuming that the difference of potentials traversed by an avalanche of electrons must exceed a certain critical value, then the condition of the partial discharge transition through the breakdown is expressed by the following formula:

$$\int_0^{r_c} E_r dr \geq U_{bd} \quad (4)$$

Wherethe distance from the point of the electrode where the tension is greatest, counted along the path of discharge;

E_r–the electric field strengthon distance r,

U_{np}–the critical value of the difference in the potential that avalanche of electrons are passing.

Under another possible breakdown condition, the field strength E_r must exceed the strength E_0 sufficient to support ionization at a certain distance r_k, which is necessary for the creation of an avalanche of electrons of sufficient intensity. This condition is written as follows:

$$E_{r_k} \geq E_0. \tag{5}$$

The analysis of the field near the edge of the plate of a flat capacitor, taking into account its thickness [9, 17], leads, regardless of which of the two conditions of the breakdown development is taken as a criterion, to the following formula of the average breakdown strength as a function of the thickness of the dielectric d:

$$E_{bd} = kd^{-0.5}, \tag{6}$$

where coefficient k depends on value U_0 orE_0.

The characteristic dependence of the breakdown strength on the number of sheets is presented in Fig. 7 [16]. As can be seen from this figure, in this case, due to the imposition of the two mechanisms discussed above, a maximum breakdown of the tension occurs at a layer thickness of about 80 microns (number of sheets about 8). The number of sheets (the thickness of the insulation layer) corresponding to the maximum of the breakdown voltage depends on the area of the electrodes, shifting as the area increases in the direction of the larger number of sheets.

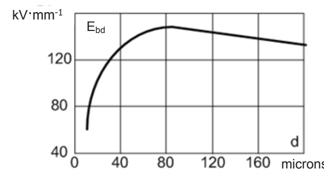

FIGURE 7. The dependence of the breakthrough strength on the thickness of the insulation for 10 µm capacitor paper.

In some cases it is desirable to choose a thickness of dielectric at which the breakdown voltage would be greatest. Therefore, the thickness of the insulation sections made of condenser paper is often taken to be equal to seven to eight sheets at a sheet thickness of 10-12 µm. In addition to short-term electrical strength, insulation is characterized by a variation in the breakdown voltages of individual samples. Increasing this variation in the process of mass production increases the likelihood of weakened insulation. In Fig. 8 show the breakdowns of the specimens by the breakthrough stress for the number of sheets equal to 3, 5, and 7. Comparison of the distribution curves shows that the scattering of specimens with five sheets is little different from the scattering of specimens with seven sheets. A significant increase in the breakdown in breakdown voltages occurs when the number of sheets is less than five. Reducing the electrical strength and increasing the breakdown of breakdown voltages by reducing the number of sheets in a layer of less than five leads to the necessity, in this case, there is a decrease in permissible tensions. The dependence of the punching strength on the thickness of the insulation of the cable paper has a slightly different appearance. Due to its large thickness, it is unlikely that such an inclusion would shunt the entire sheet.However, the gradual wetting (too much of the sheet or of the multilayer) insulation paper will eventually increase the temperature in the inner layers of insulation. The insulation in such layers is located far from the surface and is poorly cooled.However, during operation, there is a gradual dampening (many sheets of paper or many layers) of insulation paper [20]. Over time, such moisture will lead to an increase in temperature in the inner layers of insulation. The insulation in such layers is located far from the surface and poorly cooled (Fig. 8).In tape isolation, the presence of oil gaps between the layers of paper greatly facilitates the development of the breakdown.

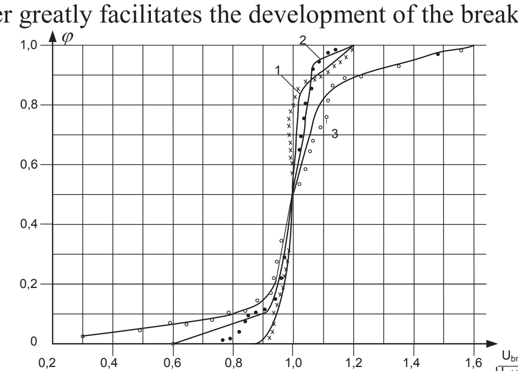

FIGURE 8. Probability curves for breakdown voltages for 12 µm capacitor paper - n = 7 sheets; 2 - n = 5 sheets, 3 - n = 3 sheets

CONCLUSION

1. Many high-voltage power transformers, measuring transformers, communication capacitors, high-voltage inputs and so on, are in operation today which have been working for over 25 years and have paper (cellulose) insulation. In order to reasonably extend the further operation of such insulation, it is necessary to know and predict its technical condition. Reducing the risk of damage to insulation material is possible only if the processes in it are understood while simultaneously affecting the condition of paper and oil insulation of condenser type high-voltage equipment of high or low temperature, moisture, prolonged and short-term normal and above normal (lightning and switching) (shocks, falls, bends, etc.), the effects of different types of radiation, which accelerate the aging process of insulation and shorten the lifetime value of high-voltage equipment.

2. Aging processes in the insulation of high-voltage equipment, such as high-voltage inputs, often occur in non-uniform and highly non-uniform electric fields. This complicates their modeling, research and analysis. Under certain conditions, the physical and mathematical model of such processes in some parts of the equipment and its insulation can be conditionally simplified, which allows to evaluate the qualitative and sometimes quantitative parameters of the aging process of the insulation material. The breakdown of flat insulation made of condenser paper, such as high-voltage coupling capacitors (330 kV) occurs at the location of inclusions of other (often poorly insulated) material that approximates the area of a uniform field.

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