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Effective Methods for Diagnostics of High Voltage Power Transformers of Large Power Plants

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I. Introduction

High voltage transformers are one of the responsible and expensive equipment of thermal and nuclear power plants. Unfortunately, their accidents are not rare. The causes of accidents are many, but the main one is the developing damage to solid insulation by partial discharges or other processes that can last several months or even years.

To prevent accidents, a large number of methods and devices have been developed and implemented, but, as you can see, they are still insufficient for the long and reliable operation of high voltage transformers. What difficulties are there to resolve this issue. First of all, partial discharge pulses have a very low intensity, that is, their electrical signals are weak against the background of powerful electrical noise present inside the high voltage transformer and penetrating into it from the network from the equipment of substations and high voltage lines.

Secondly, partial and other forms of discharges in a transformer not only manifest themselves with electrical signals, but are also accompanied by optical, sound, mechanical and other phenomena. Unfortunately, they are either not used at all, or due to their insufficient knowledge, they are applied at a primitive level.

Back in the 70s, in addition to the electrical signals of partial discharges, we studied electro-acoustic, optoelectronic, and other manifestations of such discharges in high voltage transformers, because of which instruments and devices for diagnosing oil-filled devices under operating voltage were developed. These devices were introduced in Krasnoyarskenergo, Sverdlovenergo, Uzbekenergo and other power systems to diagnose the status of the main power transformers 500-220 kV of the Krasnoyarsk hydroelectric station, 500 kV substations of the city of Krasnoyarsk, Surgut, Reftinskaya state district power plants. The complex, developed and created by us because of electro-acoustic and electric manifestations of partial discharges, has been successfully used for a long time during acceptance tests of 500 kV transformers after their repair at a specialized factory in Sverdlovenergo.

Over the next few years, taking into account the new designs of transformer assemblies and their inputs, studies of the processes of converting electric energy into other types of energy, work was carried out to improve the diagnostic system for transformers. These systems were used in accreditation testing of hundreds of oil-filled high voltage equipment.

II. A Brief Analysis of the Failures of High Voltage Transformers and the Dominant Processes Leading to Damage to their Components

The main parts and assemblies of high voltage transformers, in which damage most often occurs during their operation, are: windings, their coil insulation and screens; inputs; bends; butter; on-load tap-changer. In addition, oil circulation devices, magnetic circuit, expander, tank, radiators and others add a relatively small share in the occurrence of damage in the transformers.

Damage to the windings and the main insulation of the transformers leads to very serious consequences. Naturally, the insulation of the components and elements of the transformer, both solid and liquid - oil, ages over time and becomes more susceptible to the harmful effects of all factors affecting it. The analysis showed that failures associated with the main isolation of high voltage transformers account for up to 67% of all failures.

The dominant processes for damage and destruction of windings and solid insulation of transformers are: partial discharges; hydration; heat;

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high values of pulses of lightning and internal overvoltage's; through currents of short circuit (deformation and destruction of the design of the windings); aging solid insulation.

III. The Essential Role of Oil in the Failure of High Voltage Transformers in Operating Conditions

This is due to the fact that all internal damage to the transformer leaves traces in it, as if it draws in all the sores and diseases of all components of the equipment. Therefore, by checking the condition of the transformer oil, it is possible to determine local overheating, partial discharges, sparking in the contact joints, humidification, pollution, air ingress and natural aging of both the oil itself and solid insulation.

One of the main components of high-voltage transformers, which are most often destroyed under operating conditions and are the cause of accidents, are bushings.

In operation, there are leaky and sealed oil-filled bushings, as well as bushings with solid insulation. Recently, transformers have been delivered with hermetic and solid insulation bushings as more reliable. It should be noted that in countries with high ambient temperatures, in combination with intense solar radiation and with large differences in air temperature during the day and night, as in Uzbekistan, moisture from the ambient air is sucked into the equipment. This phenomenon is very relevant for inputs, as they do not have devices to maintain the temperature in them. Particular attention should be paid to the condition of transformer bushings, since the proportion of transformer failures associated with input failures remains very high.

An analysis of the damage to the bushings of high voltage transformers shows that the dominant processes leading to their destruction under operating conditions are: wetting and contamination of oil and solid insulation due to violation of their tightness; occurrence and development of partial discharges in oil and in solid insulation of inputs; the appearance of mechanical and other impurities in the oil inlets; general aging of oil and solid insulation.

IV. Transformer Voltage Regulators (On-Load Tap-Changers) Account for a Significant Part of Failures

Faults in the on-load tap-changer arise due to the unsatisfactory state of the contact system: violation of the pressing force, distortion and displacement of the contacts, damage to the components of the structure; moisture and dirt through non-density in his cabinets. For normal on-load tap-change operation, it is necessary first of all to check the quality of the oil from the on-load tap-changer tank, measure the resistance of the circuits to direct current, check the operation of the contactor, check the transformation coefficient at each position of the on-load tap-changer, and periodically scroll the on-load tap-changer.

V. The Magnetic Circuit, Oil Cooling System, Tank, Radiators, Expander and other Components also Contribute to the Transformer Failures

a) *Summary of Damage and Failure of High Voltage Transformers*

Of the recorded cases of damage to transformers with internal short circuits, explosions and fires accompanied 15%. These damages were mainly caused by damage to the windings, high voltage bushings and on-load tap-changers. In this case, the most severe consequences occur during the development of defects such as: a decrease in the electric strength of the oil channel of high-voltage sealed bushings due to deposition of sediment on the inner surface of porcelain and on the surface of internal insulation, as well as due to aging of the oil; humidification, pollution and wear of insulation of transformer windings; decrease in electric strength of paper-oil insulation of high-voltage leaking bushings due to moisture and pollution; burnout of coil insulation and turns of the windings due to prolonged non-shutdown of the through short-circuit current; installation, repair and maintenance errors.

VI. The Dominant Processes Leading to Damage to the Windings and Solid Insulation

As a whole are partial discharges; hydration; local overheating of solid insulation and oil; through currents of short circuit (deformation and destruction of the design of the windings); aging solid insulation.

Since damage to the coil and main insulation is associated with a variety of causes and serious consequences, the most attention is paid to the timely detection of this type of disturbance in the operation of transformers. In most cases, damage does not occur immediately, but over time. Timely identification of an emerging and developing defect allows you to take measures to prevent its development and maintain a healthy state of the transformer.

VII. The Applied Methods for Monitoring the Condition of Transformers and the Need to Expand them to Increase the Reliability of High Voltage Transformers

For a long time, a system has been used to periodically monitor the condition of high voltage transformers, made before putting the equipment into operation, after major repairs and, periodically, after a certain time, established by regulatory documents, with the transformer disconnected from the network. This system is useful in cases when the equipment is first put into operation, and after major repairs, when the transformer is not required for testing.

Over time, the accumulated experience has shown the low efficiency of such preventive tests, methods have appeared and developed that make it possible to assess the state of insulation and other components of high-voltage transformers without disconnecting it, directly under operating conditions, such as measuring partial discharges in insulation, chromatographic analysis of oil, and especially gases dissolved in oil, the attitude to disconnecting the transformer from the network for routine testing has changed dramatically.

Modern high-voltage transformers, especially very powerful and critical ones, are equipped with a set of diagnostic devices for continuous measurement of partial discharges in the insulation of bushings, windings and other transformer nodes, the capabilities of chromatographic analysis of gases dissolved in oil are actively used, along with standard transformer monitoring devices (temperature measurement and oil level; current, voltage and other electrical characteristics of the transformer; relay protection and automation system, including gas relay and others).

But, firstly, all these currently used methods and devices, although they provide significant assistance in detecting damage that has occurred and are developing in the transformer, do not cover all the partial and other forms of discharges present in it, as well as damage and defects that in principle, cannot be detected by currently used devices because of their insufficient sensitivity for some types of incipient damage. The fact is that, if we consider the methods for identifying the initial and subsequent stages of damage to a transformer by partial discharges, as the main ones, then, due to the attenuation of signals of partial discharges of low intensity along the length of the high voltage winding, and, due to the presence of large levels in the transformer interference, they cannot be detected.

Due to the great sensitivity, the integrity of the principle of operation and the simplicity of the analysis, the method of diagnosing the condition of equipment by analyzing gases dissolved in oil has become one of the important methods for monitoring its condition under operating voltage in operating conditions. At the same time, its shortcomings should be noted: it is difficult to assess the occurrence of damage in their initial stage, since the gas content of a normally working HV transformer varies widely; It is practically impossible to determine partial discharges of low intensity. It is also impossible to detect short and occasionally appearing discharges of high intensity and posing a danger to isolation. This stems from the large volume of oil and the integral essence of the method.

In connection with these shortcomings of the currently used methods for monitoring the state of high voltage transformers, their accidents continue, and even with its explosion. There are cases when during an accident of a responsible transformer entire city and regions were left without electricity.

Secondly, in diagnostics of the condition of transformers there are reserves that are not currently used. It should be noted that in partial discharges, in addition to electrical processes, significant non-electric disturbances also arise due to the conversion of electric energy stored on the equivalent capacitor *Cp* of the high-voltage insulation section where partial discharges occur to other types of energy, primarily electromagnetic radiation, in a shock wave, creating mechanical disturbances in isolation; gas is released, light emission and a temperature jump appear. These perturbations can be used to detect the arising of partial discharges, determine their location in isolation and measure their intensity.

The need to prevent accidents of critical high-voltage transformers and the impossibility of registering the initial, sometimes even developed stages of damage requires the development, creation and application of a continuous monitoring system for the condition of such equipment with the improvement of currently used methods and the addition of new, and primarily non-electric ones.

System of electrical registration, measurement of partial discharges of low intensity against a background of large interference. As noted above, partial discharges are one of the main processes leading to damage and failure of high voltage transformers. From the point of view of their timely detection, assessment of their real intensity, determination of their geometrical location, as well as from the point of view of actual danger, these processes present many more puzzles and difficulties.

A B

Figure 1: The processes for measuring partial

In this regard, based on the literature data and our own experiments, we thoroughly studied in laboratory conditions the processes of occurrence and development of partial discharges in oil, in paper-oil insulation samples in models of transformer tanks of various sizes in laboratory conditions and at the Chirchik Transformer Plant. In the photographs of figures, Figure 1.shows the processes for measuring partial discharges in transformer tanks in the test shop of this plant. In laboratory conditions, partial discharges in a purely oil medium and in a paper-oil medium were carried out in models of tanks of various sizes.

We studied such electrical parameters of partial discharges as the discharge voltage, the amplitude of the discharge current, the steepness of the current, and the duration of its flow. In this case, the shape of the electrodes, their surface size, and the length of the discharge gap were taken into account.

The objects of research were partial discharge models mounted in metal tanks with sizes of 840x530x640 and 240x140x100, wall thicknesses of 5 and 2 mm, respectively.

Partial discharge models were paper-oil insulation samples with various defects and spark gaps with typical electrode systems “needle-needle”, “needle-plane”, “ball-ball”. The parameters of partial discharges were selected on the basis of published data and preliminary experiments with various types of real partial discharges.

The energy of the channel of partial discharges was regulated by changing the value of the capacitance and the length of the spark gap. Vacuum capacitors of the KV and KM type of small capacity, to which partial discharge models were directly connected, were used as energy storage devices.

In Figure 2 shows the process of studying partial discharges in transformers under operating conditions.

Figure 2: The process of studying partial discharges in transformers under operating conditions

Figure 3: Test installation with a cascade of transformers for 1 million volts with a pilot span of an overhead line 500 kV 300 m long

To determine the value of the discharge voltage U_d, experiments were conducted with the measurement of the electrical characteristics of partial discharges. Based on them, the value of the charge of partial discharges (p.d.) was determined as $Q = I_{p.d.} * t_{p.d.}$ ($t_{p.d.}$ - pulse duration of the p.d.), which was compared with the experimental value $Q = C* U_a$ (U_a is the applied voltage) and, at a known value of the capacitance (C), the value of the discharge voltage was calculated. It was experimentally obtained that the discharge voltage U_d amounts to (60-80) % of the rectified voltage applied to the partial discharge electrodes.

To reduce the influence of the parasitic capacitance of the installation and high-voltage connections, partial discharge models were connected to the voltage source through a resistor with a resistance of 100 MΩ, the dimensions of the discharge circuit were reduced to a minimum. To obtain partial discharges of very low energies (up to 10-10 *J*), we used the capacitance of our own electrodes of partial discharge models and supply wires, the magnitude of which was 6.9-7.1 *pF*. In the electrical circuit of the measuring part of the installation, measures were taken to suppress interference coming from the network. They were suppressed by connecting in-line filters consisting of two capacitive and one inductive elements connected in a Π-shaped circuit to the network test leads.

To measure the magnitude of the partial discharge current and record the shape of its curve, a measuring resistor (50-200 *Ohms*) was connected in series with the discharge circuit, the signals from which were fed to measuring instruments and oscilloscopes via a delay line (t_{del} = 350 *ns*).

All these processes were investigated on these models, the parameters of partial discharges were determined upon their excitation in different sections of paper-oil insulation and in oil. Thousands of oscillograms were obtained characterizing the types of partial discharges occurring in the insulation and on the surface of paper and cardboard. Moreover, in addition to the electrical characteristics of partial discharges, their electromagnetic manifestations were also recorded: wave intensity, frequency characteristics and features of partial discharges arising in various characteristic sections of transformer isolation.

When studying partial discharges in models and recording their characteristics, experiments were also carried out with the measurement of the parameters of partial discharges when superimposed on the measured circuits, noise recorded from the inputs of high voltage transformers directly in operating conditions at substations. In addition, interference was also used from our pilot flight of a 500 kV overhead line 300 m long with power from three-phase regulated alternating current source (Figure 3.).

Moreover, in addition to those actually existing in this electric circuit: 10 kV supply network - voltage regulators - step-up transformers - voltage supply to the measuring cabins at high potential and from them to the pilot span of the 500 kV overhead line, artificially created interference was also created in this circuit in the form partial discharges in the air in separate sections of insulating structures; discharges on drafts; sparking loose contacts.

VIII. Study of Electro-Acoustic Characteristics of Partial Discharges in the Isolation of High Voltage Transformers

Interest in the electro-acoustic method for monitoring the state of insulation of high voltage transformers is increasing every year. Back in the 60s of the last century, we used the electro-acoustic method as the main method for flaw detection of insulation of high-voltage pulse capacitors as part of powerful batteries and in production conditions at the Serpukhov condenser plant. In the early 70s, we developed a 4-channel acoustic-high-frequency device for monitoring the status of high-voltage transformers and with its help examined all transformers 110 kV and above the power system of Uzbekistan, identifying bottlenecks in their insulation. The device was transferred for permanent operation to the isolation service of the Ministry of Energy of Uzbekistan.

Subsequently, taking into account the results of studies of partial discharges and their acoustic manifestations, many nodes of such a device were improved. This allowed us to monitor the insulation status of critical transformers of 500 kV at substations of Krasnoyarskenergo, Sverdlovenergo, including Surgut and Reftinskaya state district power plants, in Tajglovenergo, Yuzhkazenergo and other 500 kV substations. A flaw detector based on electro-acoustic and high-frequency electrical insulation control methods, specially developed for these purposes, was transferred by us to a specialized Sverdlovenergo enterprise for the repair of transformers 220-500 kV, which, judging by its reviews, was successfully used by it after repair, in t. hours capital, during acceptance tests. With its help, latent defects of transformers were discovered [1]. Acoustic-high-frequency devices have also been successfully used in testing head samples of products - high-voltage transformers developed and manufactured by the Chirchik Transformer Plant, during research and certification tests of transformers and other high-voltage equipment in the amount of more than 200 works.

IX. Reception of Weak Acoustic Signals of Partial Discharges when Monitoring the Status of High Voltage Transformers by the Electro-Acoustic Method

Acoustic waves emanating from partial discharges in the insulation of transformers are accompanied by a very high level of interference, consisting of low-frequency (at harmonics of the supply voltage), high-frequency (interference present in the transformer itself and coming from the high voltage

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network) electrical and acoustic (vibration of the magnetic circuit, operation of oil pumps, fans and other devices) interference.

An analysis of tens of thousands of waveforms obtained when monitoring the state of 220-500 kV transformers directly under operating conditions, confirming the literature that the spectral components of the acoustic waves of partial discharges of transformers extend from tens of hertz to hundreds of kilohertz, at the same time, revealed a number of new spectral features of these signals, depending on the type of partial discharges, their location and the stage of development of insulation failure.

Theoretical studies have shown that when partial discharge signals are detected, the interference of high-voltage transformers received with the help of piezoelectric sensors and passed through optimal filters that minimize the mean square error can be considered as a stationary random process. And partial discharges in high-voltage transformers can be detected and measured by the magnitude of the fluctuations of the current estimate of the mathematical expectation of the received process.

X. Determining the Intensity of Partial Discharges According to the Electro-Acoustic Control System

When electroacoustic monitoring the insulation state of high voltage transformers, it is important to establish a relationship between the output voltage of the monitoring device (U_{out}) and the energy of partial discharges ($W_{p.d.}$). The output voltage U_{out} depends on the transmission coefficient of the control device (K_{tran}), the sensitivity of the applied sensor and the fractions of the energy it receives, the total energy of the acoustic wave (*M*), the attenuation coefficient of the acoustic wave propagating from the source to the sensor (*S*), and the electrical conversion efficiency discharge energy into acoustic (Ψ) and from discharging energy ($W_{p.d.}$). Values (K_{tran}) and M are known, *S* is determined by the distance between the source and the sensor after finding the place of partial discharges, therefore, the electroacoustic efficiency of partial discharges remains the only unknown, as a result of which determination by the output voltage of the device it is possible to estimate the energy of partial discharges and judge their danger to isolation.

It is known that an acoustic wave during partial discharges appears as a result of a sharp jump in the temperature of the discharge channel, instantaneous decomposition of oil and the emergence of very high pressure — a shock wave, which then turns into a regular acoustic wave. The pressure at the front of the shock wave is directly proportional to the density of energy stored in the discharge channel (plasma), i.e. depends on the rate of energy input into the discharge channel, which is determined by the steepness of the current of partial discharges carrying energy into the discharge channel. Therefore, the steepness of the partial discharge current is an important factor in determining the electro-acoustic efficiency discharge and output voltage of the control device.

The studies were carried out in an oil-filled tank of a transformer model with dimensions of 840x530x640 mm and a wall thickness of 5 mm. For partial discharges in a purely oil medium, vacuum-coaxial capacitors with capacities from 6.5 to 100 pF are used. The discharge gaps (needle-needle; needle-plane and ball-ball) were directly connected to the terminals of the capacitor and, for the convenience of the experiments, they are mounted together on an insulating board, which is easily lowered into the tank with oil by means of a lever mechanism and lifted out of it.

The measuring circuit consists of electro-acoustic and high frequency channels. The acoustic sensor is a piezoelectric sensor (made of ceramic of lead titanate zirconate STS-13 grade), which converts the mechanical vibrations of the tank walls into electrical impulses. In the measurements, a broadband amplifier with a gain of up to 100000 was used. Using the spectrum analyzer, we studied the frequency response of noise and acoustic signals of partial discharges up to 200 kHz.

For partial discharges in oil, the equivalent circuit can be represented, as a circuit with a series connection of C, L, R elements, where C is the capacity of the discharge section, L, R are the inductance and resistance of the discharge circuit, respectively. At $R < 2\sqrt{\frac{\mathcal{L}}{C}}$ (for partial discharges in transformers), the current in the circuit is described by the equation

$$i = -\frac{U_C}{\omega_0 \mathcal{L}} e^{-bt} \cdot sin\omega_0 t, \qquad (1)$$

Where ω_0 is the circular frequency, ,$b = \frac{R}{2\mathcal{L}}$ is the attenuation coefficient).

Therefore, at the same voltage value, the steepness of the partial discharge current (Y) or the rate of energy input into the discharge channel is determined by the magnitude of the inductance. Therefore, when studying the effect of current steepness on the value of the signal of an electro-acoustic sensor, the value of the circuit inductance was mainly changed in the range from 1 to 50 *μGen.* To maintain energy constancy and determine the effect of capacitance on the signal value, the capacitance of the capacitor was changed in the range of 6.5-100 *pF*, and measures were taken to reduce the magnitude of stray capacitances and inductances of the plant elements.

Thus, the steepness of the partial discharge current in the region of its high values was managed to be regulated by more than an order of magnitude, and the duration of the pulse front was 25–27 nsec.

The dependence of the output voltage of the sensor on the current slope in the range of 107 - 109 A / s for different frequencies (f = 1.7 (1);6 (2); 10 (3); 20 (4); 40 *kHz* (5)) according to the amplitude-frequency characteristic of the sensor signals and at a constant discharging energy is shown in Figure 4. It is seen that with increasing steepness at all frequencies, the values of U_{out} significantly increase. So, for a frequency of 1.7 *kHz* with an increase in the value from 5*107 to 5*108 *A / s* (i.e., by an order of magnitude), U_{out} increased from 2.9*103 to 5.5*104, and for frequencies of 20 and 40 *kHz* with the same range of variation (Y), the value of U_{out} increased, respectively, from 40 and 5.5 to 480 and 50 μV.

From this it follows that the output voltage of the electro-acoustic monitoring device increases by about an order of magnitude with the same increase in the steepness of the discharge current, and, at the low frequencies, it increases faster than at high frequencies.

Studies conducted in the models of oil and paper-oil insulation of transformers showed that the electro-acoustic efficiency of their partial discharges is in the range of 10 - 35% for discharges in oil and 3 - 12% for partial discharges in paper-oil insulation.

When electro acoustic monitoring the state of high voltage transformers to determine the energy of partial discharges, it is important to evaluate the absorption of their acoustic signals by transformer oil, various barriers located between the source of partial discharges and sensors.

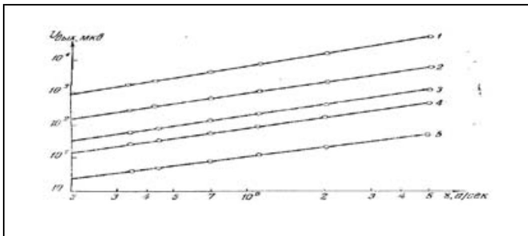

Figure 4: The dependence of the output voltage on the steepness of the current of partial discharges

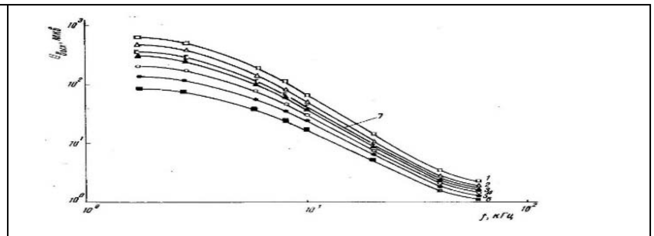

Figure 5: The dependence of the output voltage on the frequency for barriers of various thicknesses, mm.1-0; 2-0.5; 3 to 2; 4-3.5; 5-6; 6-8

In acoustics, the attenuation of waves in liquids and in solids is fairly well understood. The propagation of acoustic pulses in such a complex object as transformer tanks with limited dimensions and an extremely heterogeneous medium has not yet been studied quite strictly. For such an object, the attenuation coefficients of various materials due to wave diffraction can differ significantly from data determined by classical methods. In this regard, based on simplified models, the propagation of waves through a transformer medium was theoretically investigated, and the attenuation coefficients of acoustic pulses introduced by transformer elements were determined experimentally in transformer tanks with real sources of partial discharge waves.

It was revealed that the attenuation coefficient of acoustic waves in oil increases both with increasing frequency and with increasing distance. In contrast to oil, the damping coefficient in the barriers decreases with increasing frequency and the more significant the decrease, the thicker the wall of the barrier. This can be explained by the appearance, at wavelengths greater than the thickness of the barrier, of bending waves having a propagation velocity lower than the speed of sound in oil.

A study of the propagation of acoustic waves through the transformer windings showed that the oil channels in the windings of power transformers play a positive role in the penetration of waves through the windings. When the ratio of the channel area to the corresponding total surface of the winding is more than 10%, the influence of the attenuation coefficient of the winding can be neglected. At lower values of this ratio, the attenuation coefficient increases both with decreasing channel width and with frequency.

The walls of the transformer tank, standing in the way of the movement of waves from the source to the sensor, also contribute attenuation. The research results showed that the attenuation coefficient of the waves from the transformer tank increases both with increasing thickness of the tank, and with increasing wave frequency.

Based on the obtained experimental results on the dependence of the wave attenuation coefficient on the distance over the oil, the thickness of the insulating barriers, the wall of the tank, the type of windings and other elements of the transformer, a generalized formula is derived that allows one to determine the energy of partial discharges by the output voltage of an electro-acoustic monitoring device

$$W = \frac{4\pi S^2}{\eta \rho_{\text{ср}} C_{\text{ср}}} \cdot t_{\text{эф}} \cdot K_C^2 \cdot K_{\text{зат.Т.}} \cdot U_{\text{вых}}^2, \qquad (2)$$

where S is the distance between the source of partial discharges and the receiver, m; η - electro-acoustic efficiency of partial discharges $\rho_{\text{ср}} C_{cp}$- acoustic resistance of the medium, H *s / m^3; t_{eff} is the effective discharge time, s; K_c is the coupling coefficient between the pressure of the acoustic wave and the output

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voltage of the device; Kzat.t is the total attenuation coefficient of solid barriers.

The study of partial discharges and vibroacoustic interference of transformers under operating conditions showed that even after optimal linear filters, the signal and interference levels are of the same order. For reliable signal estimation, additional post-detector processing is required. An analysis of the structure of the signals and the interference after the filters shows that good results can be obtained by comparing the current average values of the signal plus interference and one interference.

To obtain an unbiased estimate of averaging, it is necessary to introduce a correction factor and use an integrator that implements the following operator:

$$M^*_{f1}(t) = \frac{M^*_f(t)}{\frac{1}{T}\int_0^T h(t')dt'} = \frac{\int_0^T h(t')f(t-t')dt'}{\int_0^T h(t')dt'}, \qquad (3)$$

where M^*_{f1} is the estimate of the current average value of the random process *f(t)*; *h(t)* is the weight function of the integrator.

When a single interference is applied to the integrator's input, the output voltage will change smoothly along the noise envelope, and if there is a signal of partial discharges and interference, it will have more sharp deviations.

To register them, after the optimal filter, two detectors are connected with integrators having different time parameters $h_1(t)$, $h_2(t)$ and transmission coefficients providing a zero response at the output of the subsequent subtract or when only interference is applied and a response *g (t)* proportional to energy partial discharges [3].

The optimal integrator parameters are found by examining the response of g (t) to a maximum depending on the ratio of $h_1(t)$ and $h_2(t)$.

Based on the results of the electro-acoustic properties of partial discharges, analysis of the acoustic signals of partial discharges and the impact of interference, a series of four-channel (DAV-4) and single-channel (DAV-1) electro-acoustic and high-frequency flaw detectors - devices for monitoring the state of high voltage transformers [2] were developed.

Figure 6: 4-channel acoustic-high-frequency device for monitoring the status of high voltage transformers

Figure 7: Single-channel acoustic-high-frequency device for monitoring the state of insulation high voltage transformers

DAV-4 devices, in addition to the high-frequency channel, have 4 electro-acoustic channels with 4 electro-acoustic channels and a signal comparison unit at the output. This allows a preliminary location of the area of partial discharges or mechanical damage to transformer units. Next, by installing electro-acoustic sensors closer to the sensor, which showed the maximum signal value, and comparing the readings of the high-frequency channel, we determine the location of the transformer malfunction.

Single-channel devices DAV-1 are fully assembled on integrated circuits and semiconductor elements, have autonomous power, small weight, small dimensions. Their power is supplied from 2 miniature dry batteries of the Krona type, which ensure their continuous operation for 30 hours. Their power is also provided by small-sized 9 Volt rechargeable batteries.

Small weight of the device, portability, autonomy of power with very low power consumption, ease of installation of a sensor with a magnetic cartridge on the wall of the transformer tank directly under operating voltage without any switching in its circuits greatly facilitates its use for periodic monitoring of transformers by both commissioning and operational personnel of substations.

Its portability and autonomy of power have helped us many times to detect partial discharges and other defects of transformers whose tanks are under very high voltage, including for monitoring the state of cascade transformers at 1 million volts (Figure 3) after major repairs and during preventive tests. Moreover, since the transformer tanks are under voltage of 167; 501 and 833 kV, respectively, the autonomy of the power supply of the device, its small size and high noise immunity were indispensable. The device, along with the sensor, was alternately attached to the walls of the tank transformers, and the observation of the reading of its output meter was carried out using a telescope.

According to the testimony ofDAV-1, in the tank of one of the transformers, after overhaul, partial discharges with an intensity of up to 10^{-9} *Cl* were detected and eliminated. Each time after opening the transformer tank and the work performed therein, the levels of partial discharges were measured with the help of DAV-1 and, when they were exceeded, measures were taken to eliminate them.

Devices assembled according to this principle, not only through electro-acoustic, but also through a high-frequency electric channel using PIN inputs, grounding transformer tanks, have shown high noise immunity and reliability when conducting hundreds of studies to monitor the condition of 220-500 kV transformers in Uzbekistan, Russia and in other CIS countries. It should be noted that in all these devices, except for the pulse mode, there is also a continuous mode of operation, with the help of which the state of fastening of the magnetic circuit, windings and other components of the transformer, which are weakened, deformed and destroyed by through short-circuit currents, especially multiple ones, is estimated.

Here are some examples. In studies, in addition to electro-acoustic channels for receiving and processing partial discharge signals, high-frequency electrical signals from PINs of inputs and grounding of the transformer tank were also used. At one of the 220 kV transformer ODTGA-40,000 / 220, with a capacity of 40 mVA (group power of 120 mVA), at the Kuylyuk substation of the Uzbek power system, partial discharges of 1.2 * 10-10 C were detected. It became known that this transformer was overhauled 3 months ago with the change of high voltage windings. Analysis of the oscillograms and other parameters of the pulses of partial discharges showed that they arise in the paper-oil insulation of the transformer.

In this transformer, partial discharges were regularly studied for 46 days with the recording of oscillograms and all their parameters on a photo and movie camera, as well as on a tape recorder. The dynamics of partial discharges by the 40th day from the beginning of our measurements indicated a steady increase in the intensity of partial discharges to 8.10^{-9}C and, consequently, further dangerous destruction of the insulation. In our opinion, the transformer could not be left in operation. This was reported in writing to the leadership of the Ministry. The transformer was disconnected from the network and type tests were carried out after major repairs.

However, no deviations from the norms were found for them. In this regard, the transformer was turned on under voltage, but according to our measurements made before it was turned off and after connection, and our instructions, the enterprise specified the reserves, developed a consumer unloading scheme and prepared the maintenance and repair personnel for possible consequences with the specified transformer.

Eight days after switching on, this transformer failed due to coil closures of the 220 kV winding near the 110 kV branch, confirming the correctness of our measurements and solutions. This transformer subsequently served as the basis for comprehensive research on the development of partial discharges in real paper-oil insulation of high voltage transformers.

Another typical case of transformer faults in the field. When measuring using the DAV-1 instrument developed by us, at one of the high-voltage transformers at a substation in Chirchik (Uzbekistan), a source of mechanical vibrations of a relatively low frequency but significant intensity was found in the lower part of the transformer tank a height of about 0.5 m from its bottom from the side of the low-voltage inputs of the structure. According to these results, the transformer was disconnected from the network. When it is opened in the zone of the tank volume, determined in advance using the DAV-1 device, a weakening of the winding fastening is revealed due to the falling out of the lower wedges.

According to the results of gas analysis in oil of single-phase transformers 4ATG of a group of 3 АОДЦТН 267000/500/220/20 Reftinskaya GRES district power stations of phase "A" (factory number 83315), the content of gases characterizing the appearance of a defect in it was found. During 3 months of observations, the intensity of these gases grew continuously and reached unacceptable limits. In this regard, the GRES chemical laboratory recommended disconnecting the transformers for overhaul with opening the phase *A* tank. Measurements made by the acoustic-high-frequency device DAV-1 in "pulse" and "continuous" modes, as well as electrical measurements with PIN-s and transformer grounding, showed that the main source of gas evolution are mechanical vibrations that appear when the yoke beams are loosened, pressing rings, tie rods of the magnetic circuit, as well as in unsatisfactory state of fastening of auxiliary nodes of the transformer.

Considering the great difficulties of disconnecting high-power transformers in the autumn-winter period, the possibility of wetting the insulation when opening the tank in an unsuitable room, prolonged lack of electricity and significant costs for incompletely justified opening and repair, we proposed to leave the transformer in operation, but under special control and with measurements of electro-acoustic, high-frequency characteristics of the transformer and gases dissolved in its oil. The proposal was accepted, the transformer worked for a long time before the repair.

When measuring at all substations of 500 and 220 kV, DAV-1 devices showed high noise immunity and stability of their parameters.

The results of studies of the electro-acoustic characteristics of partial discharges, attenuation introduced by transformer elements, and experience with the DAV-4 and DAV-1 flaw detectors made it possible to develop the following methodology for determining the energy of partial discharges according to the output voltage of the monitoring device:

- Registration of partial discharges with an electro-acoustic device, taking readings of the output voltage of the device;

- Preliminary determination of the location of the source of partial discharges inside the transformer tank;
- Determination of the type of partial discharges and their characteristics (slope of the current, the ratio of pulses at positive and negative polarities of the voltage, the phase of occurrence of partial discharges);
- Finding the location of the source of partial discharges relative to the electrical circuit of the transformer;
- Determination of preferred propagation paths of acoustic waves from the source to the sensors (oil distance, total thickness of the barriers, angles of incidence of the wave to the barriers and walls);
- Determination of the acoustic energy of the source from the output voltage of the device and the attenuation data of the wave in the oil and barriers;
- Assessment of electro-acoustic efficiency channel, determining the energy of the discharge channel;
- Estimation of the total energy of partial discharges based on the energy of the channel and the characteristics of the pulses of the partial discharges;
- Assessment of the danger of registered partial discharge pulses for isolation, taking measures to exclude an emergency transformer failure.

The studies we have described above show that to monitor the condition of transformers and other critical high voltage equipment under operating conditions, it is not sufficient to use one or more of the methods used discretely, i.e. occasionally 1 time over a period of time, since the main types of damage to such equipment generate signals in the electrical circuits and in the environment that are random in time and in intensity. These signals can appear and then disappear for many hours or even days, especially in the initial stages of damage development. Therefore, discrete (episodic) measurements (or state monitoring) of the characteristics of these signals may not fix them.

Based on the results of laboratory research and the experience of monitoring the status of critical transformers 500-220 kV in Uzbekistan, Russia, South Kazakhstan and Tajikistan, a concept was developed for continuous monitoring of the condition of the insulation and the entire transformer under operating conditions, in which, besides standard measuring and monitoring tools the state of the transformers includes noise-protected high-frequency channels from PIN inputs, from the tank ground and electro-acoustic channels for both partial discharges and for detecting mechanical damage, displacements of windings, magnetic barriers and other transformer nodes [4]. A simplified block diagram of the continuous monitoring of the status of transformers is shown in Figure 8.

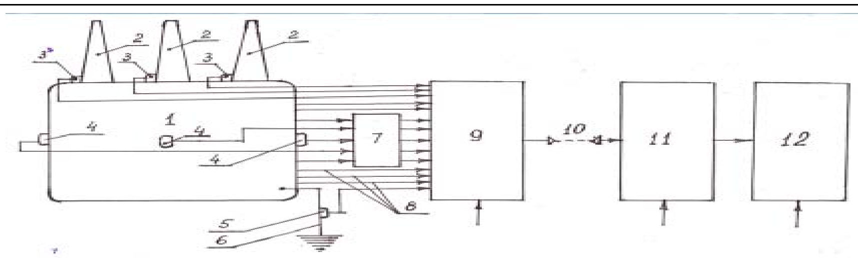

Figure 8: Simplified block diagram of a continuous monitoring system for critical high voltage transformers:1-diagnosed object (VN power transformer); 2-input VN; 3-PINs of inputs; 4-electroacoustic sensors; 5-current sensors; 6-grounding bus; 7-devices for the preliminary processing of acoustic and electrical signals; 8 - sensors for temperature, oil level, the appearance of gases), etc.; 9-a device for processing and converting signals; 10-fiber optic communication cable; 11-multi-channel signal conversion device;12-PC with special programs for signal processing.

XI. Conclusions

1. It is shown that the electro-acoustic method for monitoring the state of insulation and other components of high voltage transformers, along with the electric high-frequency method, is quite promising for a continuous monitoring system of its condition.
2. The results of studies of the processes occurring during partial discharges in oil and in the paper-oil medium of transformers showed the role of the steepness of the currents of these discharges on the shock wave and on the output voltage of the electro-acoustic channel of the control device.
3. The attenuation of acoustic waves during their propagation through the winding, through insulating barriers, through the oil and through the tank wall, studied in transformer models, showed that when the width of the oil channel is more than 10% of the total surface of the winding, the influence of the winding on the attenuation of the acoustic wave can be neglected , the attenuation coefficient of the acoustic (ultra-acoustic) signal when partial discharges occur in the oil increases both with the

removal of partial discharges from the sensor and with increasing frequency; attenuation coefficient increases when there are barriers between the wave source and the sensor.

4. A method has been developed for calculating the energy of partial discharges recorded by electro-acoustic control devices, which makes it possible to assess the danger of these discharges.
5. Electro-acoustic and high-frequency electrical methods, devices for recording and location of partial discharges and other transformer problems, developed by us, which use optimal filters and use the noise-immunity method of receiving weak acoustic and high-frequency signals against a background of high noise, have been successfully used for a long time to control condition of critical transformers 500-220 kV of the Ministry of Energy of Uzbekistan, Krasnoyarskenergo, Sverdlovenergo, including at 500 kV substations of Surgut and Reftinskaya GRES district power plants. With their help, sources of partial discharges and other transformer malfunctions that were not detected by other methods.
6. A system is proposed for continuous monitoring of the state of critical high-voltage transformers, based on in-depth studies of the processes of initiation and development of damage in insulation, in other components of transformers, for more than 40 years of experience in long-term measurements of the characteristics of partial discharges and other transformer malfunctions at substations 500 - 220 kV directly in operating conditions under operating voltage.

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