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MAJOR DEFECTS AND DIAGNOSTICS OF SOLID INSULATION OF POWER TRANSFORMERS

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The main defects and diagnostics methods of paper-, wood-, and polymer-based solid insulation used in power transformers are presented. Specific examples of pollution, sludging, moisturizing, and mechanical defects and their development during partial and arc discharges are discussed. The distribution of moisture content of cellulose insulation along the height of transformers with natural and forced oil circulation is analyzed. The danger of local wetting of solid insulation is noted. Examples of transformer failures as a result of moistening of wooden strips for attaching taps, as well as defects in epoxy insulation of low-voltage transposed conductor windings, are given.

Keywords: power transformer; solid insulation; pollution; sludging; moisture content; partial discharges; degree of polymerization.

INTRODUCTION

In recent years, the internal solid insulation of power oil transformers, traditionally made of cellulose or wood, has increasingly used polymer materials. However, during operation, installation, and maintenance, various defects can develop in such insulation, including contamination, sludging, humidification, mechanical damage, destruction, and partial discharges (PD), which can lead to breakdowns and failures of transformers.

The technical evaluation of the internal solid insulation in power transformers during operation involves monitoring the level and dynamics of the insulation characteristics of the windings (R_{60} and $\tan\delta$) [1, 2], which can deteriorate due to contamination, sludging, and moisturization of solid insulation.

In the event of damage to protective filters (mesh, plate, etc.), contamination in the active part of transformers may occur due to the carryover of silica gel from adsorption and dehydrating filter breathers. Although dry and uncontaminated silica gel is a good dielectric, the conductivity of silica gel increases significantly as moisture and oil degradation products are adsorbed. Therefore, the carryover of silica gel into the transformer tank can lead to the contamination of solid insulation and consequent failure of the transformer due to the breakdown of the insulation gap.

Furthermore, filling dehydrating and adsorption filters with humid or unwashed with dry oil silica gel, or silica gel characterized by significant granule destruction, can lead to the contamination of the active part (including solid insulation) with silica gel dust.

The thermographic inspection of adsorption and dehydrating filters represents the most effective control over the possible carryover of silica gel (Fig. 1). The underfilling of a filter may indicate the improper replacement of silica gel or its loss, followed by possible ingress into the active part of the transformer.

When short-circuits or other defects occurring in the magnetic system of transformers are accompanied by spark discharges, the decomposition of oil results in contamination of the active part with carbon (Fig. 2). Subsequently, the gradual accumulation of acetylene dissolved in oil can be observed, whose concentration often reaches or exceeds the limit value of 10 ppm or 0.001%. The level of contamination depends on the power of the spark discharge and the duration of the defect development. It is possible to identify the contamination of the active part with carbon by variations in the dissipation factor ($\tan\delta$) of the oil (at 90°C). For example, HC-grade hydrocracking oil obtained from the transformer tank (Fig. 2) exhibited $\tan\delta = 0.8\%$ on the day of sampling, with a subsequent decrease to 0.15% on the next day (following sedimentation).

Less commonly, the active part can be contaminated with peeling paint from the inner surface of the tank (Fig. 3) or oil pipes in some designs of foreign transformers [3]. Analyses have shown that the paint used for this purpose may contain

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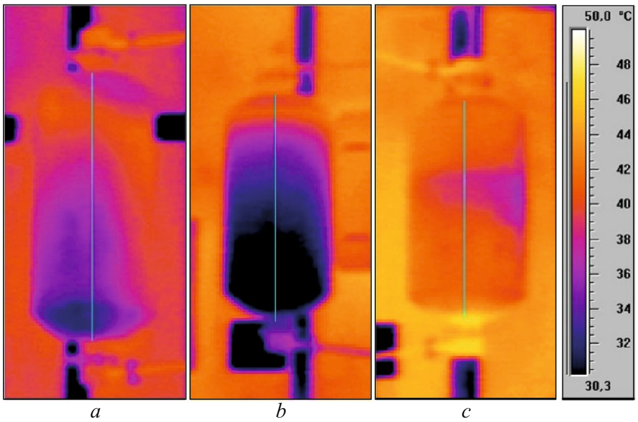

Fig. 1. Thermograms of adsorbers: *a*, fresh silica gel is filled; *b*, initial stage of sludging and contamination of silica gel; *c*, silica gel is underfilled.

materials based on metal salts (usually iron), whose accumulation in large quantities leads to a decrease in insulation characteristics, as well as transformer failures [3].

Severe damage to the insulation can be caused by contamination with metal shavings (Fig. 4) resulting from the failure of oil pump bearings in transformers with forced oil circulation, especially in the absence or destruction of the plate filter.

Timely detection of such defects is most effective through periodic vibration monitoring of oil pumps, using equipment and software based on analysis of spectral-amplitude characteristics measured at various sections (in the bearing area and “snail”).

It should be noted that when the insulation is contaminated with materials having high conductivity (especially metal shavings), the insulation resistance R_{60} significantly decreases, while the dissipation factor $\tan\delta$ increases to a lesser extent. For example, in a TRDTsN-80000/110 U1 transformer (Fig. 4), the resistance decreased by 5 – 6 times (Fig. 5), while $\tan\delta$ increased only by 1.5 – 2 times, being less or equal to 0.37% at 20°C for the measurement scheme HV-G+LVl+LV2. Here, the low moisture content (0.6 – 1.1%) in solid insulation affected the insulation characteristics insignificantly.

The removal of metal shavings, carbon, and fine silica gel from the insulating surfaces of transformers during overhaul repairs has proved difficult and inefficient. For instance, for a transformer shown in Fig. 4, following the removal of shavings using a directed flow of oil, the active part was washed and dried using the oil circulation and spraying under a vacuum. The resulting insulation resistance increased by 2 times at 20°C (up to values of 600 – 930 MΩ in different zones), while the dissipation factor was reduced by 0.05 – 0.19%.

Nevertheless, washing and drying of insulation by oil spraying, particularly, when using detergent additives and

Fig. 2. Carbon contamination of solid insulation of TDTs-250000/500 transformer at a developed defect of magnetic system.

Fig. 3. Bottom of TRDNS-40000/35-74U1 transformer tank having paint defects.

Fig. 4. Contamination with metal dust of lead-outs of TRDTsN-80000/110 U1 transformer windings.

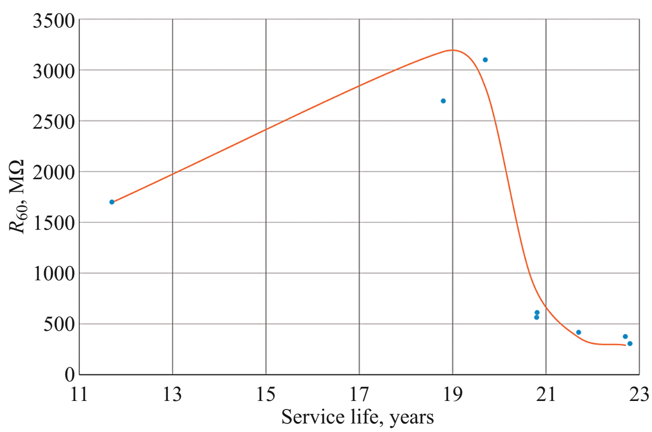

Fig. 5. Dynamics of R_{60} resistance (normalized to 20°S for HV-G+ LV1+LV2 measurement scheme of a transformer (Fig. 4).

Fig. 6. Characteristic areas of filter membranes contaminated with sludge samples at approximately 100× magnification.

advanced technologies [4], can be efficient for restoring humidity- and sludge-contaminated insulation [3].

The aging and consequent oxidation of oil leads to the formation of sludge, whose deposition on the surface of solid insulation results in increased electrical conductance and the deterioration of the insulation characteristics of windings (Fig. 6).

The most dangerous condition for transformers is the moisturization of the solid insulation. With a combination of moisturization and contamination (sludging) of insulation, the risk of transformer failure increases significantly. In general, moisturization of the active part leads to an increase in the moisture content of both solid (primarily cellulose) insulation and oil. In this case, diagnostic testing involves analyzing the moisture content of solid insulation, measuring the insulation characteristics of the windings, as well as monitoring the oil moisture content and associated breakdown voltage. In addition, it is possible to use a solid insulation model in order to directly determine the moisture content. The insulation models, however, are typically used to monitor moisture content during the commissioning phase following the installation of a transformer. In addition, their location in the upper part of the tank may impede the accurate determination of the maximum moisture content of cellulose insulation during operation.

The results of direct measurements of the moisture content of solid insulation (3 mm thick insulating cylinders and barriers, a 0.5 mm thick winding selected at the attachment points of the leads-out) (Fig. 7) were as follows. Transformers having a D cooling system (natural oil circulation) are always characterized by higher moisture content in the cellulose insulation at the bottom of the tank, while transformers having a DC cooling system (forced oil circulation) show only a slight difference in moisture content values between the top and bottom of the tank. Figure 8 depicts the diagrams of the highest recorded moisture content in the selected samples collected from the upper (*1*) and lower (*2*) parts of several 110, 150, and 220 kV transformers equipped with D and DC cooling systems. In these diagrams, the conditional numbers of transformers are indicated along the *x*-axis.

No significant difference in the moisture content of the cellulose insulation of the winding and barriers was observed. The variation of the moisture content of samples having different thicknesses reached 20 – 40% of the maximum,

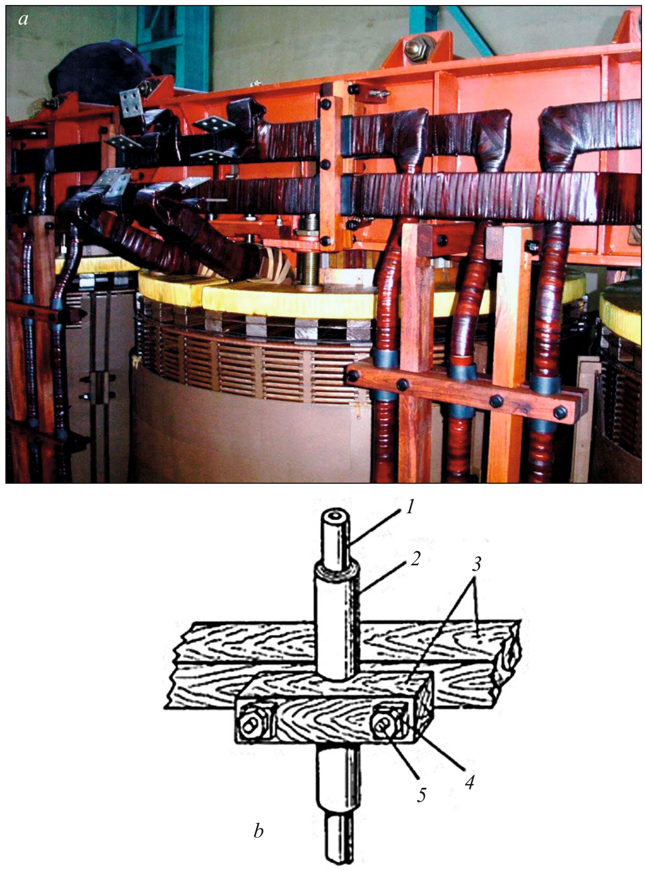

Fig. 7. Attachment points of lead-outs: *a*, sampling area at the top of transformer; *b*, mounting structure; *1*, insulating lead-out; *2*, electrical cardboard insulation; *3*, beech plates; *4*, *5*, textolite pin with nut.

while being within the statistical deviation for samples having the same thickness collected in the same zone of the active part.

Since the direct determination of the moisture content of cellulose insulation is only possible during overhaul repairs of transformers, this parameter is determined analytically during operation [1, 2]. In the Russian Federation, the method of determining moisture content by dielectric characteristics is most commonly used [5]. The highest moisture contents of cellulose insulation obtained by the method described in the work [5] were compared with those of direct measurements during overhaul repairs of 38 110 and 500 kV transformers having a service life ranging from 14 to 46 years. The characteristic values of the moisture content of the insulation are shown in Fig. 9 (*1*, highest measured value; *2*, calculated value).

In general, irrespective of the type of cooling system (D or DC), the calculated values for the moisture content of the solid insulation were in close agreement with the highest actual measurement results (deviations of calculated values were within ±12% of the measured result). In two cases, the calculated values exceeded the measured values by

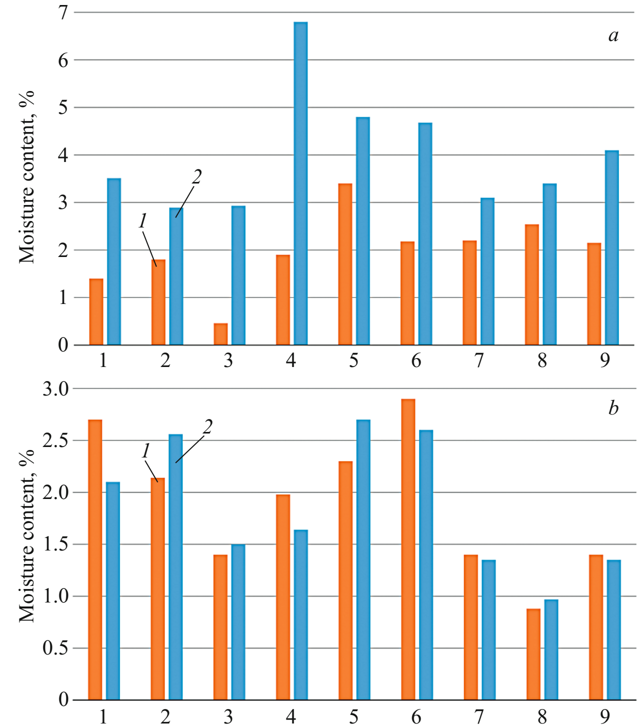

Fig. 8. Moisture content of insulation in the upper and lower parts of transformer tank equipped with cooling systems D (*a*) and DC (*b*).

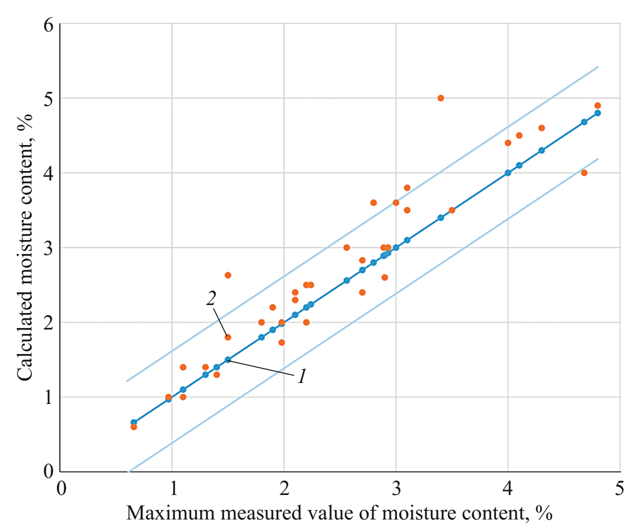

Fig. 9. Comparison of maximum measured and calculated values of moisture content.

30 – 40%. However, in these transformers, high values of the dissipation factor of oil (5.9 and 18.2%) were recorded.

The local moisturization of insulation can be rather dangerous. Transformer failures can occur when free water enters the active part through loose pins of 220 kV or higher voltage bushings under variable loads. This is particularly risky when transformers are operating under thermal cycling

Fig. 10. The active part of TRDN-25000/220 U 1transformer (*a*) and damage to mounting rails of leads-out in arc burn zone (*b*).

conditions, leading to oil level oscillations in the conservator and current-carrying inlet pipe.

Moisture accumulation in wooden spacers is another common cause of transformer failures. As an example, the results of an evaluation of the active part of the TRDN-25000/220 U1 transformer are shown in Fig. 10, where a flashover occurred along the horizontal and vertical wooden spacers from the attachment point of the high-voltage (HV) A-phase leading to the attachment point of the neutral lead. The moisturization of the wooden spacers might have been due to insufficient drying of the active part by the manufacturer or moisture ingress during the storage of the transformer. In addition, the failure of the transformer occurred due to exceeding the minimum permissible (calculated) distance along the horizontal spacer between the A-phase and neutral leads, as well as a defect in the lead attachment. Due to vibrations, the bolted connections of the leads in the wooden spacers were loosened, resulting in the displacement of the leads and unwinding of the additional insulation of HV leads of the A-phase, as well as the C-phase (Fig. 10*a*).

Although the results of dissolved gas analysis (DGA) in the transformer tank oil performed less than 6 months prior to failure, as well as physical and chemical analyses of oil (including breakdown voltage and moisture content), indicated no development of discharge processes and general moistening of the active part, it was necessary to dry the active part and the oil prior to commissioning the transformer a year before its failure.

Mechanical damage to the insulation of transformers, as well as sludging, contamination, and moisture, can induce the development of discharge processes. In the TDG-40500/110 transformer, for example, following the replacement of the 110 kV input in the fortieth year of operation, the hydrogen concentration in the oil increased (Fig. 11*a*), reaching 322 ppm in 5 years (at the limit value of 100 ppm). This indicated the development of partial discharges (PD) in the active part. The measurements of PD by an electrical method showed that the level of discharge activity is less than 12 – 15 nC.

When locating discharges on the tank wall, a zone of acoustic activity (marked in yellow in Fig. 11*b*) was detected. The signal occurred at intervals during each half-period of the industrial frequency. The maximum of the amplitude-frequency dependence of the signal reached approximately 80 – 100 kHz, which is characteristic of PD. Upon opening the transformer in the area of acoustic activity, mechanical and thermoelectric damage to the insulation of the B-phase HV lead were detected (Fig. 11*c*); these resulted from a technological disturbance during the installation of a new lead and the development of discharge processes in the damaged area.

An important parameter in determining the service life of cellulose insulation and the entire transformer involves the degree of polymerization of the paper in the hottest areas. Typically, such zones are located at the top of the active part. In order to determine this parameter, it is most convenient to select insulation winding from LV leads as control samples. Since determining the degree of polymerization of cellulose insulation is a laborious and time-consuming process, which can only be carried out in a few laboratories in the country, the degree of polymerization of insulation is very rarely determined during repairs. Nevertheless, according to the work [6], it is possible to promptly assess the level of insulation destruction as per the mechanical strength class during the repair process. According to the work [6], the mechanical strength of insulation can be classified into the following four categories:

— Class 1: elastic insulation, remains intact when bent in half;

— Class 2: hard insulation, cracks are formed when bent in half.

— Class 3: brittle insulation, breaks when bent in half.

— Class 4: old insulation, breaks when bent to a right angle.

TABLE 1. Degree of polymerization for different insulation strength classes

Mechanical strength class	Degree of polymerization, units	
	Minimum – maximum values	DP value determined by (1) ±Δ
1	1096 – 1730	1326 ± 354
1 – 2	480 – 1276	1002 ± 200
2	500 – 1170	757 ± 170
2 – 3	328 – 872	572 ± 161
3	326 – 793	433 ± 180
3 – 4	231 – 613	327 ± 113
4	148 – 301	247 ± 42

A correlation of the mechanical strength class (MSC) and the degree of polymerization of over 120 samples of cellulose insulation having a thickness of 0.3 – 3 mm, summarized in Table 1, can be described by the following equation

$$DP = e^{7.7 - 0.5\mathrm{MSC}}. \quad (1)$$

The values of DP at different insulation strength classes in accordance with Eq. (1) and the confidence interval Δ at the reliability level of 0.9 are shown in Table 1. Although the CPM values are rather approximate, they allow the level of insulation degradation to be assessed, taking into account Eq. (1) and the variations shown in Table 1, in order to develop the optimal recommendations for the further operation of the transformer.

In some instances, the use of new types of insulation and winding wires led to transformer failures as a result of violations of the winding manufacturing technology. The use of transposed wires coated with an epoxy resin allows a monolithic conductor to be obtained, along with improving the strength of the winding and reducing the risk of interconductor short circuits. However, procedural violations during the production of epoxy insulation for elementary conductors (Fig. 12*a*), as well as the curing (“baking”) technology of epoxy resin, can lead to negative consequences.

Here, a failure during the baking of the low-voltage (LV) winding led to a decrease in the electrodynamic resistance of the 220 kV transformer. As a result, a deformation of the A-phase LV winding that occurred during a close three-phase short-circuit led to the destruction of pressing elements and short-circuit of the LV winding of this phase to the upper yoke beam. Subsequently, the deformation and electrical breakdown occurred in the middle part of the three insulating cylinders between the HV and LV windings, as well as the deformation of the HV winding of the damaged phase.

In another case, in the LV winding of a 500 kV transformer, epoxy resin was applied to the elementary conductors in strips, while on some conductors the resin was applied only to a small area with uneven distribution along the length of the elementary conductor (Fig. 12). Along with other factors, this technological violation is identified as having led to internal short circuit and transformer failure. Here it should be noted that the diagnostic parameters — including DGA and the readings of the monitoring system — indicated no development of dangerous discharge processes or other de-

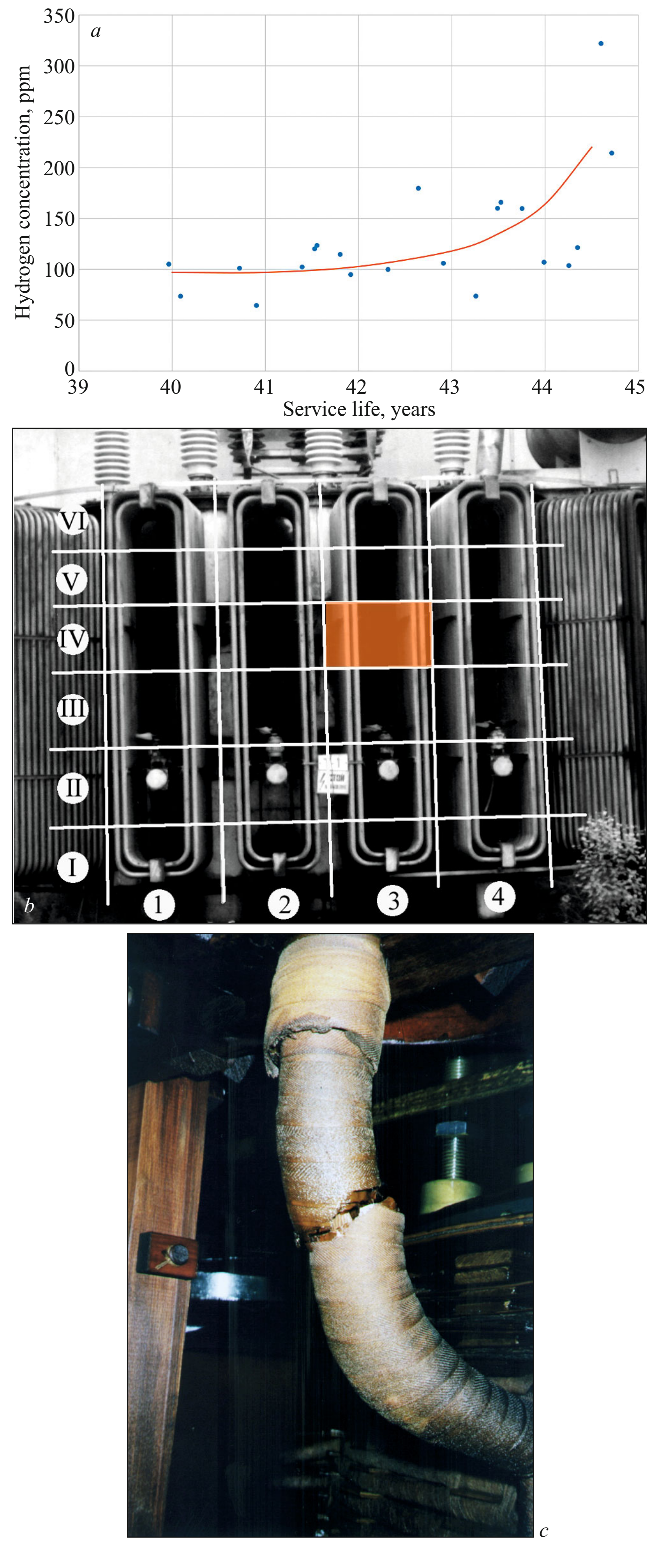

Fig. 11. Variations in hydrogen concentration (*a*), acoustic activity zone (*b*), and damage to insulation of HV output of phase B (*b*) of TDG-40500/110 transformer.

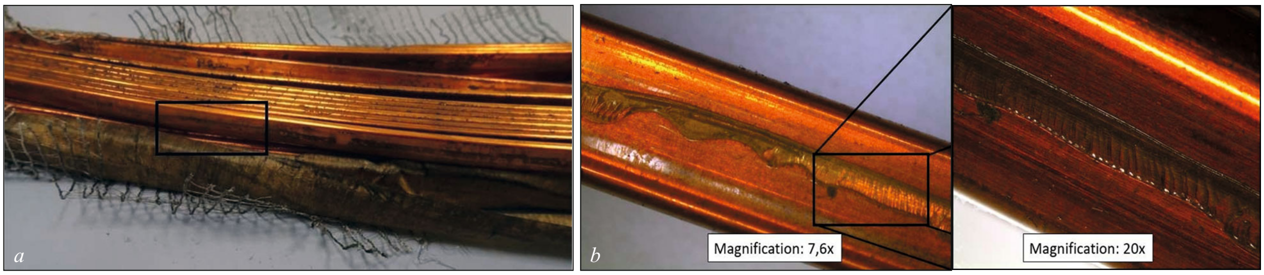

Fig. 12. A fragment of a 500 kV transformer LV winding wire (*a*) and zones of single conductors at 7.6× and 20× magnification (*b*).

fects. The concentration of hydrogen was less than 11 ppm while that of acetylene was less than 1 ppm (with limit values of 100 ppm and 10 ppm, respectively), with all other diagnostic parameters also remaining significantly lower than the permissible values [1, 2].

CONCLUSIONS

1. In order to improve the reliability of power transformers operation, it is necessary to control the insulation characteristics, DGA, PD, and other parameters of the active part systems, as well as to periodically inspect the attached equipment. In particular, in order to reduce the risk of insulation contamination, the thermal imaging control of dehydrating and adsorption filters, as well as vibration monitoring of oil pumps of transformers using forced oil circulation, should be carried out.

2. The maximum moisture content of cellulose insulation in transformers equipped with different cooling systems can be evaluated analytically by measuring the insulation characteristics [5]. In transformers using natural oil circulation, the moisture content of the insulation in the lower part of the tank typically exceeds the moisture content in the upper part by 1.5 to 6 times. In transformers having forced oil circulation, however, the moisture content of the cellulose insulation over the height of the tank remains approximately equivalent.

3. During overhauls, the degree of polymerization of cellulose insulation can be evaluated with sufficient accuracy by determining the mechanical strength class [6].

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