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THE REPAIR OF POWER TRANSFORMERS WITH A LONG SERVICE LIFE

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Summary. This paper is devoted to the description of the main technologies of washing and drying of the active part of the transformer. Repairs of transformers with a long service life according to the new technology, worked out by SPA Technoservice-Electro, improve the winding insulation characteristics and retain and enhance the mechanical strength of the paper insulation due to strengthening of hydrogen bonds in macro molecules of cellulose and improve the crystal grating.
Keywords: **Transformer – Repair – Solid Insulation – Mechanical Strength.**

1. At present in Russia most power transformers for 110 kV and higher have already worked out their standardized service life of 25 years. There are transformers which have been in operation for 40, 50 and even 60 years. Taking into consideration the real economic situation and the total number of transformers with a long service life, it is impossible in the nearest future to replace most of the transformers whose lifetime has been exceeded. Thus, in order to maintain the required operating security, it is very important to carry out comprehensive diagnostic inspections and to perform overhauling repairs if necessary.

However, an un-argumented decision on carrying out overhauls, its scope and the technologies employed may, on the one hand, lead to unjustified expenses and, on the other hand, may even result in a decreased safety margin, lower resources and failures and in the final analysis, it can lead to considerable material losses.

During the inspection of the active part of the transformer, the oil and the solid insulation come into contact with un-dried air. This can result in a decrease in the insulating characteristics. Besides, in case of a violation of the technology there is some danger of gas cavities appearing when the transformer is filled with oil, and, therefore, there is high probability of flashover of the insulation when connecting the transformer. During repairs, there is a possibility of an accidental breakdown of individual items (especially when lifting and installing the bell), contamination of the active part and filling the transformer tank with foreign objects. Drying of the active part of the transformer may subject the paper insulation to accelerated ageing.

That is why the decisions on the repair work and employed technologies should be carefully selected and thought out, especially for transformers with a long service life. At present, transformer repairs may or may not include changes of the windings. Repairs with changes of the windings are

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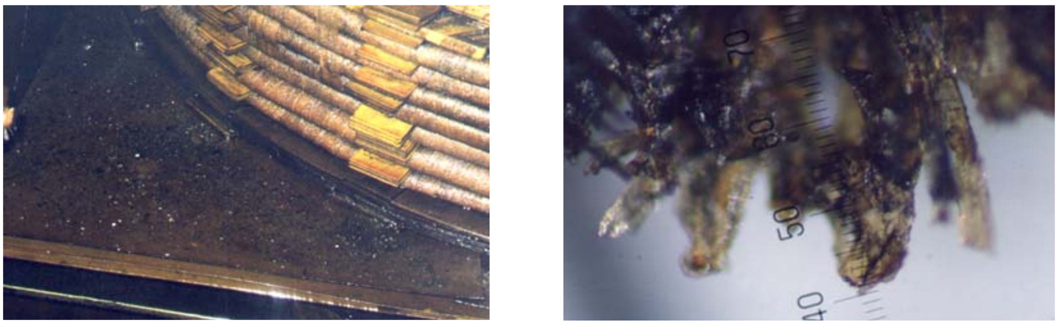
performed at specially equipped repair workshops or at plants of the manufacturer. The cost of these kinds of repairs can be equal to that of a new transformer. As a rule, these kinds of repairs are justified from the economic viewpoint for failed “young” transformers with a small total service life.

Repairs without changes of the windings are normally performed on the site of transformer operating organization or at the erection site. Four kinds of technologies are used for treatment of the solid insulation: without drying of the active part; with drying of the solid insulation using the method of thermodiffusion; with washing and drying of the insulation by oil spraying at a maximal allowable residual vacuum; with washing and drying of active part according to the technology worked out by SPA Technoservice-Electro.

2. When operating the transformers different kinds of defects are generated. The ageing of the paper-oil insulation can be aggravated by moistening, sliming (Fig. 1), and destruction. As a result of these negative factors, the insulation characteristics gradually deteriorate. In transformers with forced oil circulation, the active part can be contaminated with metal shavings, paint, appearing in the course of the cooling system faults (Fig. 2, 3) and other products. The most common defects are short circuits, appearing under the influence of leakage fluxes, or in some cases, under the influence of the main flux (caused by loss of insulation of separate elements of the magnetic system). These defects are accompanied by heating and in most cases by electric and arc discharges. In the case of arc discharges, the active part of the transformer experiences carbon sliming. Besides, the rubber seals become gradually destroyed and different defects are found in the cooling system equipment, voltage control devices, bushings and the like. The enumerated defects and their aftereffects can be eliminated in the course of transformer repairs without changing the windings.

If winding deformations (Fig. 5a), defects of the winding insulation, caused by short-circuit overheating (Fig. 5b), insulation damages in the result of arc and sometimes partial discharges are developing, transformer requires repair with magnetic circuit dismantling and changing of the windings. In case of grave deterioration transformer repair is not economically and technically justified



a) b)

Fig. 1 Slime in the active part of a 40500/110 transformer, which has been 44 years in service (a) and a fragment of the filter membrane after the deposition of slime, containing naphtenants of iron (b).

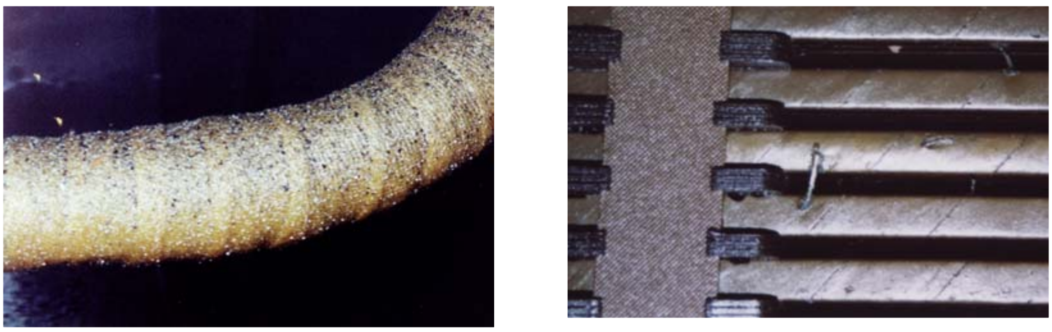


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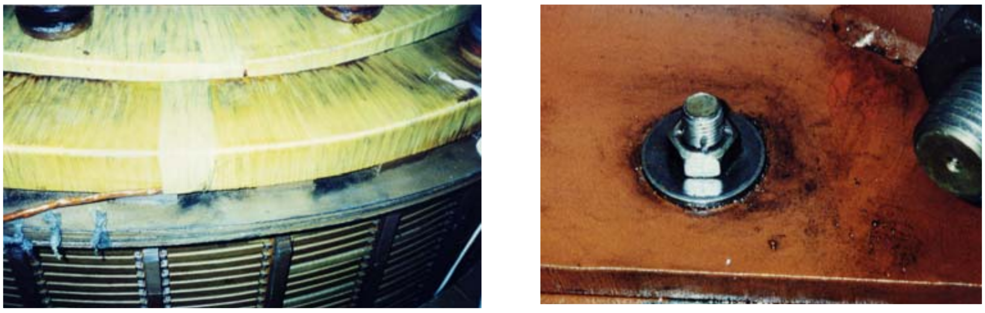
Fig. 2 Contamination of the active part of a transformer with metal shavings:

(a) – HV winding tap of a 80000/110 transformer, 23 years in service; (b) – HV winding of transformer 80000/110, 28 years in service.

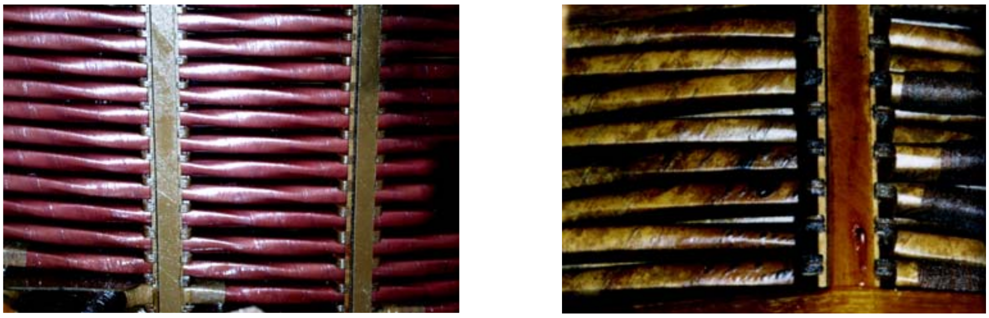
a) b)

Fig. 3 Fragment of the inner surface of an oil-pipe (a) and contamination of the tank of a ASEC 400/400/100 MWA, 400/220/31.5 kV transformer.



a) b)

Fig. 4. Contamination with carbon of the active part of 250000/500 transformers: a – winding, b – yoke beam.



a) b)

Fig. 5 Deformations of windings in an 167000/500/220 autotransformer (a) and thermal defects of the HV winding insulation in a 25000/10 furnace transformer (b), caused by short circuit currents.

If winding deformations (Fig. 5a), defects of the winding insulation, caused by short-circuit overheating (Fig. 5b), insulation damages in the result of arc and sometimes partial discharges are developing, transformer requires repair with magnetic circuit dismantling and changing of the windings. In case of grave deterioration transformer repair is not economically and technically justified.

3. Transformer repairs without changing of the windings consist of the following main stages:

1) A complex diagnostic inspection of the transformer [1 - 3]. On the basis of its data analysis, the objective assessment of the state of all the transformer units is given and technical grounds for transformer repairs, its scope and the employed technologies are confirmed.

2) The program for repairs is developed and the constructor documentation prepared for the reconstruction of separate units; the working plan and other documentation are worked out; sets of parts and materials are supplied.

3) Mobile physico-chemical and electrotechnical laboratories (if necessary) are installed on the repair site. The supply and installation of equipment for rigging work, oil and sorbent treatment, drying of the active part (the electric hoist, the hydraulic and rack-operated jack, the pushers, the sling ropes, the degassing device, the oil heater, filters and other items).

4) Pre-repair and after-repair electric tests of the transformer and a physico-chemical analysis of the oil (the insulation characteristics of the windings and bushings, the no-load losses at a reduced voltage, the short-circuit impedance, the dc impedance of the windings and the breakdown voltage, the power factor, the content of mechanical impurities and gas in the oil, the moisture content in insulation board and in the oil and other parameters).

5) Rigging work, including bell lifting and the taking out active part.

6) Visual inspection of the active part of the transformer, checking of the grounding circuit, measurement of tightening hairpins, bandages, yoke semi-bandages, pressing rings, yoke beams, active steel and other elements.

7) Elimination of the defects found in the active part; other work according to the established standards (including winding and magnetic circuit pressing, inspection of the cooling systems and voltage control system, adsorbents and thermosiphon filters; leakage elimination; the change of the damaged insulation in the taps and magnetic system and the rubber seals).

Note that the pressing force on the windings of the transformer with a long service life should be no more than 0,7 of the manufacturer's value. Higher pressing levels may lead to damage of the paper insulation (with a decreased mechanical strength and flexibility).

8) Reconstruction of the separate transformer units is performed, for example, in case of a change in the protection system against moistening of the oil and the installation of a protective film and bushings with different overall dimensions and in other cases.

9) The preparation of oil and sorbents is one of the most important components of quality of the repairs and future reliable operation of the equipment. This kind of work is very time consuming.

The oil treatment includes drying, cleaning, degassing, regeneration with the help of silica gel or other sorbents and the antioxidant additive 2,6-dytrebutil-4-metylphenol (IONOL, AGIDOL-1). Pre-repair laboratory tests of the state of the oil oxidation stability before and after regeneration and also after the addition of the antioxidant additives. The data obtained from these tests helps to evaluate the grounds for oil treatment from technical and economic viewpoints and to estimate the approximate residual oil resource.

Oil used for a long time requires great expenses for improvement of its insulation characteristics. That is why change of the oil may be more reasonable.

However, many transformers, manufactured in Russia at the end of the 1940s and in the early 1960s are filled with high-quality mineral oils extracted in the Baku region (for example Dossor oil). Tests show that this kind of oil maintains its dielectric properties even after 40-50 years of use. After oil treatment, including regeneration with the use of silica gel, the dielectric properties are not worse than the ones new oil has.

Table I shows the oil parameters from the tank of a 110 kV transformer which was in service for 49 years. After 44 years of transformer operation, the oil was considerably contaminated, slimed and moistened. After cleaning, drying, and regeneration using silica gel, the oil regained its parameters (for example, the value of tgδ at 90^{o}C was no more than 0.1%).

Note that the initially used oil was not stabilized with the help of an antioxidant additive. Before the transformer was filled with oil, the additive AGIDOL-1and the oil T-1500, made at present in Russia, were added to the used oil. After 5 years of further use, the oil parameters did not change. An insignificant increase in the moisture content was observed, however it was foreseen at the time the repair work on the transformer was done.

10) During the last stage of the repair work, the drying of the insulation in the active part usually takes place. For transformers with a long service life, experiencing moistening and sliming of the insulation, the method of spraying oil under vacuum is used. It should be mentioned that almost all the methods of solid insulation drying are connected with a high-temperature impact, and in the case of vacuum treatment - with macromechanical impact on cellulose when extracting moisture. As a result of this process, the accelerated ageing of paper insulation is observed, with a subsequent decrease in the degree of polymerization (by 50-250 points).

Table I

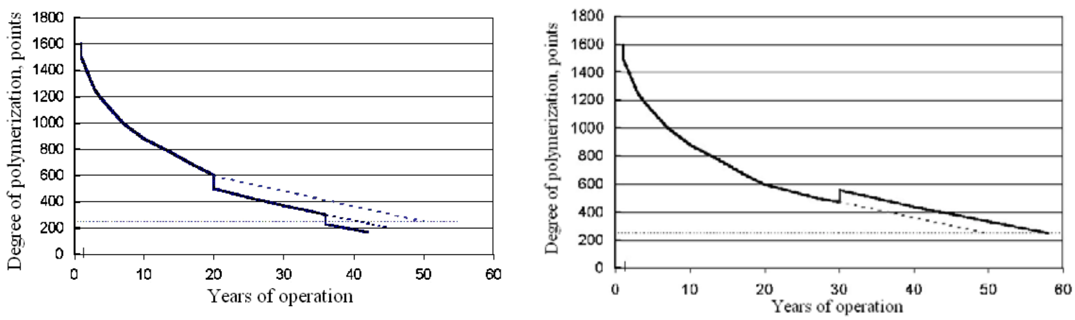
Physico-chemical parameters of oil in the transformer tank after 45 years of operation (before the repair), supposed for oil filling of the tank, after oil filling and after 5 years of operation (after the repair)

Parameters of oil quality	Values of oil quality							
	Oil		Mixture of oil ТК (85 %) и Т-1500 (15%)					
	Operational (before the repair)		Supposed for filling of the tank (after regeneration)		After oil filling		After 5 years of operation (after the repair)	
	Mea-sured	MAV	Mea-sured	MAV	Mea-sured	MAV	Mea-sured	MAV
Breakdown voltage, kV	52	≥35	72	≥60	63	≥55	62	≥35
Acid number, mg KOH/g	0,03	0.25	0,01	0.05	0.012	≤0.05	0.01	0.25
Flash temperature, °C	142	≥125	140	≥130	142	≥130	141	≥125
Moisture content, ppm	26.3	≤30	4,8	≤20	7.6	≤25	11.2	≤30
Commercial frequency class	9	≤13	8	≤11	8	≤12	8	≤13
tgδ, % at 90°C	1.21	15	0.1	5	0.1	6	0.14	15
Antioxidant additive content, %	0	≥0.1	0,3	-	0.3	-	0.3	≥0.1

Note: MAV – maximal allowable value according to the requirements of Russian standards [4].

4. Figure 7a shows the approximate nature of the change in the degree of polymerization of the paper insulation in the course of operation of the transformer. Basically, the process proceeds in accordance with an exponential law, whose damping time constant depends on the level of the transformer load, and more specifically, on the temperature mode. The typical abrupt decreases in the degree of polymerization are caused by drying of the insulation at the manufacturing plant, and also when doing repair work (in the given case, after 20 and 40 years of operation). As a result, after the last repairs, the degree of polymerization of the paper insulation of the transformer decreased to less than the critical value 250 points, and further operation of the transformer is involved with a great risk.

The new technology of washing and drying of the insulation helps to maintain and, in several cases, to improve the mechanical strength and the degree of polymerization of the paper insulation (Fig. 7b).



a) b)

Fig. 7 An example of the typical nature of the change in polymerization according to the traditional technology of insulation drying (a) and according to the technology of SPA Technoservice-Electro (b).

The technological scheme for washing and drying of the insulation is similar to the traditional one and contains at least two circuits: the circuit for washing of the active part and the vacuum treatment circuit. The washing circuit operates in a closed cycle and includes sprayers installed in the active part of the transformer, oil heater, which performs heating and final cleaning of the oil, circulation pump, filters, valves and also the connecting tubes. The vacuum treatment is done with the use of initial rough exhaust. The vacuum treatment circuit may include vacuum installation. The washing scheme may additionally contain regeneration circuits, additional drying and cleaning of the oil, which are often used in the technological process.

Russian transformer oils with a high content of aromatic substances are used as the technological oil. For the intensifying of oil dissolving capability, a Midel 7131 additive (based on non-halogen esters of pentaerythritol acid) and several other components are added at a certain stage. Whether or not to continue exposures of periodic washing (warming) and vacuum treatment is decided upon individually for every transformer, depending on the state of the paper insulation (its strength, moisture content, composition sliming and contamination degree). In the course of operation the moisture content, the level and character of the mechanical impurities, the power factor and other parameters of the washing oil are continuously monitored; solid insulation polarization indexes R_{15} and R_{60} are also under control. Depending on the value of the controlled parameters, some changes are made in the washing oil temperature, the vacuum level in the transformer tank, and the duration of separate stages washing scheme (washing without vacuum, washing under vacuum, vacuum treatment without washing), additive concentration and other parameters. This helps to solve successfully three main tasks: 1) to intensify the process of moisture extraction from the solid insulation; 2) to remove effectively the products of ageing of the oil, the naphtenats of iron and copper, and mechanical impurities; 3) to prevent the decrease of the strength of the paper insulation and the accelerated destruction of paper while drying.

This technology was used for the repairs of 110-500 kV transformers with a service life from 20 to 54 years. The polarization index R_{60} was greatly increased and tgδ was decreased by 1,5-5 times. In a number of cases, the degree of polymerization of paper was increased by 100-200 points.

The IR-spectrometry and X-ray diffraction analyses of the insulation carried out prior to and after their washing, based on the new technology, have proven the strengthening of hydrogen bonds in cellulose macro molecules and the improvement of the crystal grating. Sometimes, after repairs, the cellulose crystal structure of solid insulation samples was increased by more than 20%. Laboratory tests have proven the effectiveness of this technology, especially for transformers having a long service life with the polymerization degree of the paper insulation of 250-500 points.

The performed repairs have proven that the new technology is efficient. For example, a TDG 40500/110 transformer, after 44 years of service, had a considerable moisture content, sliming and contamination of its solid insulation (including contamination by oxides and naphtenats of iron, Fig. 1). The results of its repairs showed that the power factor of the winding insulation decreased by 1.5 – 2 times, the polarization index R_{60} increased by 2.5 – 7 times. Moreover, polarization indexes of the insulation exceeded the pre-repair parameters of manufacturer by 2 times (Table II). The mechanical strength of the paper insulation was enhanced, and the degree of polymerization was increased by 200 points.

Table II

The insulation characteristics of transformer windings

(44 years of service)

Measurements	**t, °C**	**Insulation characteristics, at 20°C with measurement scheme**				**Mechanical strength, class**	**Degree of polymerization, points**
		HV-LV+F		LV-HV+F			
		tgδ, %	R_{60}, MOhm	tgδ, %	R_{60}, MOhm		
Manufacturer	53	0.24	1810	0.24	1335	-	-
Before the repair	20	5,60	600	4,70	1000	3-4	340-400
After the repair	27	1,20	3985	0,88	2650	2-3	530-620

Notes.

1. t – temperature of the winding during measurements.

2. According to Russian normative documents [5] the best class of mechanical strength (at which paper insulation is not broken at sharp bending 180^0) is equal to 1, while the worst one (at which paper insulation is broken at right-angle bend 90^0) is equal to 4.

It should be noted that violation of the technological mode parameters, the percentage of the additive content, the absence of control over moistening, the nature of sliming, and the contamination of the solid insulation reduce the effectiveness of insulation rehabilitation. It leads to prolonged washing and drying processes and, in some cases, to a decrease in the insulation characteristics and strength. For example, in the case of the active part contamination with hydrogen (Fig. 4) filters of 5 microns in a closed washing circuit do not absorb the finely dispersed hydrogen in washing oil. Hydrogen is redistributed from the deposition site in the magnetic system to the other elements, including the solid insulation. It leads to an increase in the power factor of the winding insulation.

Table III

The insulation characteristics of transformer windings

Rated power and voltage, service life	**Measurement scheme**	**Insulation characteristics, at 20°C**				**Notes**
		R_{60}, MOhm		tgδ, %		
		Before the repair	After the repair	Before the repair	After the repair	
40.5 MVA 110/10 kV 45 years	HV-LV+F	2860	>>3000	1,104	0,40	Moistening and sliming with naphtenats of iron
	LV-HV+F	989	>3000	1,026	0,37	
250 MVA 330/150/10kV 30 years	HV+MV-LV+F	295	1623	0,451	0,194	Sliming with naphtenats of iron and contamination with metal shavings
	LV-HV+MV+F	190	882	0,421	0,192	
	HV+MV+LV-F	187	1006	0,445	0,191	
80 MVA 110/10 kV 23 years	HV-LV_1+LV_2+F	306	607	0,371	0,368	Contamination with metal shavings, sliming with naphtenats of iron (Fig. 2a)
	LV_1-HV+LV_2+F	383	798	0,496	0,336	
	LV_2-HV+LV_1+F	584	929	0,367	0,308	

Table IV

The parameters of transformer paper insulation

Rated power and voltage, service life	**Parameters of paper insulation**				
	Thickness, mm	**Mechanical strength, class**		**Degree of polymerization, points**	
		Before the repair	**After the repair**	**Before the repair**	**After the repair**
40.5 MVA 110/10 kV 45 years	2	**4**	3	**240**	322
	2	3	3	403	474
	0.5	**4**	3	**208**	377
	0.5	3	2-3	341	355
250 MVA 330/150/10kV 30 years	0.5	2	1-2	480	620
800 MVA 110/10 kV 23 years	0.5	3	2	697	966
	0.5	3	1-2	817	868
	0.5	2-3	2	627	820
Maximal allowable value [4,5]		**4**	**4**	**250**	**250**

5. The individual approach to the repairs of every transformer, strict observation of technological requirements, continuous control over the washing oil parameters and the winding insulation characteristics, and rich experience in repair work according to the new technology helped to achieve steady positive results for a number of different transformers. Table III, IV gives examples of the winding insulation characteristics and the paper insulation parameters for three transformers before and after repairs. The transformers had a different nature and degree of sliming and contamination. That is why in some cases an open insulation washing scheme was used. The insulation characteristics were evidently improved, even for transformers with considerable contamination of their active part with metal shavings. Besides, the mechanical strength of the paper has increased. The results shown in Table IV include an analysis of samples with a maximal and a minimal increase in the degree of polymerization.

An analysis of more than 30 cases of repairs has shown that insulation with a higher level of destruction has a maximal increase in the strength and degree of polymerization at equal conditions of treatment. Insulation with a high initial strength and degree of polymerization does not considerably improve these parameters.

X-ray diffraction and other analyses of insulation samples before and after repairs confirmed that two contradictory processes take place when drying: destruction and strengthening of cellulose. Activation of either of these processes is mainly determined by the technological parameters, and to a lesser extent by the continuity of washing. It should be mentioned that repairs according to the new technology last not more than 30-45 days, and it does not differ much from the time for repairs according to the traditional technology.

Conclusions

1. The new technology of repairs with washing of the insulation by oil containing special additives under vacuum treatment lets effectively perform drying of the solid insulation, remove the products of oil ageing, the naphtenats of iron and copper and the mechanic fines. Besides, this technology decreases the negative impact of temperature and vacuum on the paper insulation and prevents the mechanical strength to decrease when drying the insulation.

2. Repairs of transformers with a long service life according to the new technology improve the winding insulation characteristics and retain and enhance the mechanical strength of the paper insulation due to strengthening of hydrogen bonds in macro molecules of cellulose and improve the crystal grating.

3. Most effective results of transformer repairs are achieved as a result of individual choice of the washing and drying mode parameters, taking into consideration the degree of sliming, moistening and destruction of the paper insulation and the nature of the contamination of the active part.

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