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Condition assessment and life time extension of power transformers

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Summary. Above 40% of transformers of 110 kV and higher voltage level installed in Russia are in operation for a time longer than 25 years. Their replacement by the new ones is technically and economically impossible and unreasonable. Considerable part of such transformer may be used for further operation. Thus the problem of their service life time prolongation is of importance. The paper is devoted to the main aspects of this problem: assessment of long time used transformer condition and measures to secure their future reliable operation.

Key words. Transformer – Condition – Analysis – Failure – Inspection – Diagnostics – Repair technology.

1. Introduction.

At present the power industry of Russia includes about 20000 units of operating power transformers, auto-type transformers and shunt reactors (herein after referred to as transformers) of 110 kV and higher voltage level. The service duration of more than 40% of these transformers exceeds 25 years. The replacement of all of them is unreasonable economically and technically. The actual service life of many transformers essentially exceeds 25 years and it is possible to extend their service the required operational reliability being ensured.

The problems of old transformer codition estimation and measures to prolong their service life are considered below in this paper.

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2. Results of the transformer failure analysis.

The results of the analysis are carried out by the authors on the base of available statements of 110 kV and higher level and 63 MVA and higher capacity as well as the data extracted from [1] ahd [2] show that the most vulnerable to failures transformer components are bushings, windings and tap changers. The transformers practically don't fail due to the defects in magnetic cores. Based on the data provided in [2] a rather high percent of failures (about 25%) is related to the improper actions of the operating service and repair personnel. The repair works of "old" transformers by traditional methods without the proper diagnostics and specialized technology to restore their characteristics sometimes lead to economically inefficient costs, decreased transformer reliability and even to their failures.

3. Transformer complex inspection.

One of the most important components of the transformer future operational safety improvement is an impartial assessment of their state and a real transfer from the system of periodically carried out repairs depending on the specified calendar time interval of transformer service to the repairs depending on their actual state. In Russia the later concept is reflected the normative documents [3, 4].

It is universally recognized that such a system can be realized only if there is a possibility of a trustworthy definition of the equipment technical state, including the definitions made in the course of such equipment complex inspection.

A complex diagnostic inspection allows to evaluated the state of transformer as a whole and its components:

1) Hard insulation (moistening, dirtying, destruction).
2) Magnetic system (core compressing, component to tank insulation demage, etc.).
3) Windings (buckling and other deformations).
4) Transformer oil.
5) Systems of oil cooling, treatment and protection.
6) Bushings.
7) Voltage regulators and contact system.

A typical inspection program specified in Table 1 includes a rather wide set of both traditional and non-traditional diagnostics procedures.

Table 1

Transformer complex inspection program

Procedures of inspection, testing and measurements	State evaluation						
	1	2	3	4	5	6	7
1. Evaluation of the most probable damage points based on the similar type transformer defects analysis	+	+	+	+	+	+	+
2. Analysis of transformed modes of operation, operational and maintenance documentation, the results of measurements and tests	+	+	+	+	+	+	+
3. Visual inspection.					+	+	+
4. Oil chromatographic analysis	+	+			+	+	+
5. Oil chemical analysis	+	+		+	+	+	+
6. Definition of oil humidity at various temperatures and modes of transformer operation	+			+	+	+	+
7. Definition of availability and fractional composition of mechanical impurities in oil	+	+		+	+	+	+
8. Definition of antioxidizing additive content in oil				+	+	+	
9. Definition of oil residual stability				+	+	+	
10. Oil infra-red spectroscopy	+	+		+	+	+	
11. Definition of furan derivatives content in oil	+					+	
12. tgδ and oil conductivity measurement at various temperatures	+			+	+	+	+
13. Analysis of silica gel from thermosyphon filters	+			+	+		
14. Measurement of insulation characteristics of windings and bushings at various temperatures and voltage levels, for various zones inclusive	+				+	+	
15. Definition of hard insulation humidity based on a "paper-oil" equilibrium and on the measured values of insulation characteristics	+				+	+	
16. Measurement of partial discharges (PD)*	+	+				+	+
17. Transformer infra-red imaging*		+			+	+	+
18. Transformer acoustic inspection*	+	+	+				+
19. Vibration control of transformer tank*, oil pumps and cooling system fans		+	+		+		
20. Oscillograph record of low voltage pulses			+				
21. Short circuit impedance measurement			+				
22. Measurement of no-load current and losses (at nominal voltage inclusive)		+					
23. Measurement of oil volume in the extension tank at various temperatures					+		
24. Measurement of oil pressure in the bushings at various temperatures						+	
25. Calculation of bushings insulation electric strength						+	
26. Measurement of direct current resistance of windings and contact resistance at various positions of tap changers							+
27. Making a circle diagram and oscillogram of on-load tap changer operation							+
28. Measurements of phase currents of oil pump and fan motors					+		
29. Complex analysis of the results obtained	+	+	+	+	+	+	+

Note. 1. Inspections marked with * are performed for two modes of operation: maximum load and no-load run.
2. Sign «+» means that corresponding measurement is used to transformer element state evalation.
3. The numbers 1-7 correspond to the list of components given above.

The authors have in their possession the inspection results of more than two hundred fifty transformers of capacity range from 6.3 to 1000 MVA manufactured in Russia, Ukraine, Sweden and Belgium and installed in various climatic regions of Russia, Belarus and Yugo slavia. The total service of almost 70% of the inspected transformers exceeds 25 years. About a half of them refer to large transformers (> 100 MVA). The summarized results of complex diagnostic inspections have shown that it is possible to continue operation of 30% of the inspected transformers without any serious repears and restrictions; only 2% of them require substitution; the remaining transformers require either an overhaul (15%) or rather inconsiderable and not expensive reconditioning (23%), or simply more frequent control rates (30%).

It is worth mentioning some general comments based on the inspection results.

1. Transformers with a long service life, as a rule, experience serious humidification which can be caused by air ingress through some leakages missing the drying system as well as by a destruction of a rigid insulation, etc.

2. Rather often the old transformers have slime deposits on insulation (fig.1) caused by the products of oil ageing, rigid insulation destruction, metal fines from faulty oil pumps and fine silica gel fractions from thermosiphon filters.

Old transformers installed in the vicinity to chemical, metallurgical and some other production plants may have slime deposits caused by the emissions from such plants.

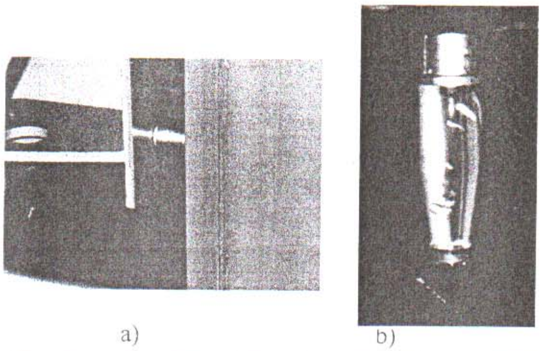
a) b)

Fig.1. Slime in the transformer
(a – inside the tank, b – on windings)

3. The majority of transformer bushings used over 25 years require substitution or repair with opening up. Nongermetic bushings are offer humidifield. Their insulation characteristics deteriorate gradually.Due to that it is easier to make the diagnose. A destruction of rubber elements of both nongermetic and germetic bushings takes place. In air-light bushings oil ageing is possible because of air inflow absence. It makes good conditions for colloid compounds formation and residue appearance on porcelain and insulation surfaces. If a transformer mode of operation is changed a process of moisture adsorption by a residue may be initiated resulted in the appearance of conductive areas with possible insulation flash-over. The recidue formation process is a spontaneous one and it is rather difficult to forecast it. The diagnostics of such defects is possible only by indirect indications (increase of oil tgδ, appearance of gases in oil, decrease of tgδ of bushiing main insulation). It makes their timely revealing rather difficult.

4. Faulted loops which are often found in magnetic system structural elements lead to overheating, increased gas emission and formation of carbon at spark and arc discharges. Carbon spreading beyond the arc burning area can result in semiconducting deposit formation on the insulation of both windings and bushings (Fig.2) and in creation of conditions for flash-overs.

5. No-load losses of old transformers, as a rule, increase due to the magnetic core pressing-out and the insulation breach between the laminations.



a) b)

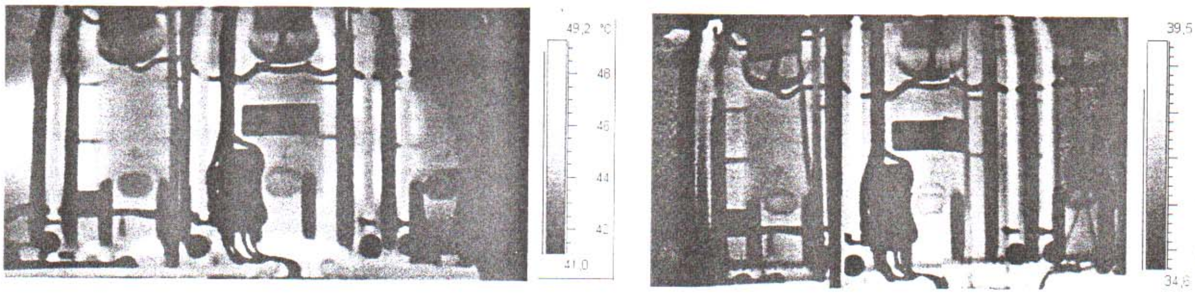
Fig. 2. Carbon deposit formation on bushing surface a - spark discharges point in the area of the transportation bolt; b - carbon covered porcelain cap of the bushing located above the discharge area.

6. Old LTC, oil cooling and protection systems usually require rather simple measures to restore them.

7. Paper insulation of the transformers operated 25-30 years, as a rule, still have a safety margin with respect for its mechanical strength and polymerization degree. Such paper insulation can be partially restored. The transformers with a natural ageing of paper insulation, practically, are not subject to rejection.

A number of inspections listed in table 2 are performed for two modes of transformer operation: no load and maximum load. The defects related to the formation of faulted loops in magnetic system can be diagnosed best of all namely by comparison of the results obtained for the various modes of transformer operation. Efficiency of such a comparison can be illustrated on an example of infra-red imaging of autotransformer ATDCT- 250000/330/150 of 250 MVA capacity and 330/150 kV voltages (see fig. 3).

It is seen in the fig.3 that registered by infra-red (IR) imager temperatures of the lower parts of the tank were essentially higher in the case of on-loaded transformer than in the case of no-load operation mode. After the transformer opening up yoke beam contact to frame was reveiled. The chomatographic analysis of this transformer showed only inconsiderable (52-67 ppm) increase of ethane (C_2H_6) concentration in comparison with its allowable level (50 ppm). The above mentioned defect could not be revealed by the other means: e.g. acoustic, partial discharges, vibration, etc.



a) b)

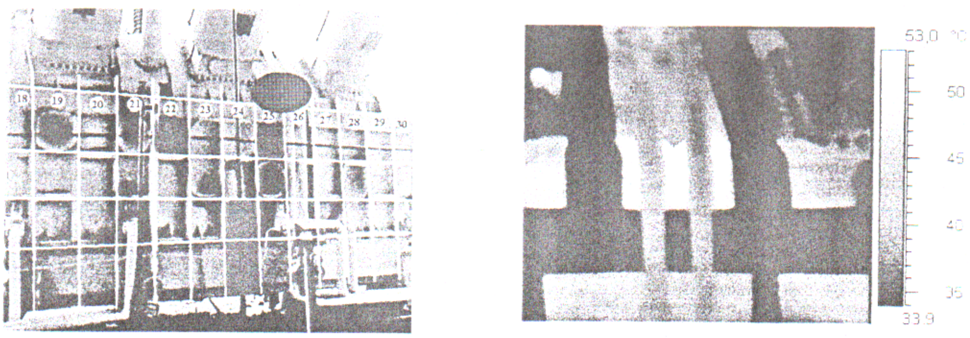
Fig. 3. Infra-red imager examination results of autotransformer ATDCT- 250000/330/150 under load (a) and under no-load (b) modes of operation

But in some other cases these and some other inspection methods were adequate enough. It may be demonstrate by the example of inspection of power plant step-up unit 360 MVA 220 kV transformer (TDC-360000/220 type). An increased gas concentration was fixed in this transformer and it was assumed that a high temperature overheating affecting the rigid insulation took place there. The PD measurements revealed some pulses which were identified as discharges in the magnetic system. Acoustic examination showed the availability of areas of an increased acoustic activity, including ones created by the sources with signal frequency of 30-40 kHz (marked with yellow colour in fig. 4, a). The overheated areas were revealed by IR-imager inspection (fig. 4, b).

Diagnosis: loss of tie studs insulation. After the transformer opening up it was found out that 5 tie studs had zero insulation relatively to the magnetic core.

4. Features at old transformer repair technology.

Prior to the discussion of the matters regarding the old transformer repair it is expedient to clarify the authors' position in respect to their thesis stating that the use of the traditional technologies for the repair of old transformers can be unfavourable for their condition:



a) b)

Fig. 4. Results of acoustic (a) and infra-red imager (b) inspections of transformer TDC-360000/220

- Firstly, the effect of high temperatures and high vacuum results in paper partial loss of its polymerization degree. This leads to a decrease in paper mechanical strength as well as to a decrease of its remaining service life.
- Secondly, drying of old insulation in order to reach moisture content levels of less than 0.5%, (the level specified for new transformers) results in the increase of paper brittleness. Under the dynamic effects in the process of the transformer further operation this can lead to paper falling off with subsequent break-down or flash-over.
- Thirdly, pressing of winding up to the manufacturer levels can result in long operated paper insulation damage as well.
- Fourthly, drying of old insulation without its preliminary cleaning may results in worsening of insulation characteristics due to dirt "baking" on the insulation surface. Such transformers often fail just after they are repaired.
- Fifthly, if a transformer is contaminated by carbon formed in the course of arc burning in the short circuited electric loops, the use of a closed-loop washing system with filters of 5 μm min does not allow to remove finely dispersed carbon which spreads from the point of its formation along the whole tank and contaminates the insulation. This results in a deterioration of the insulation characteristics.

In accordance with the authors' opinion, the repair procedures should be individual for each transformer and should include several stages:

1. A complex diagnostic examination shall precede the transformer repair works. Based on the results of such examination a technically substantiated scope of repair works and the required technology shall be developed.

2. On the eve of the repair works beginning a mobile physical & chemical laboratory and, if required, electrical laboratory shall be provided in the production plant. The following equipment shall be installed at the repair site: process equipment for rigging, drying, regeneration and degassing of oil, oil heaters, units of sorbent drying and preparation, devices for the transformer active part washing.

3. Rigging works, transformer opening up and repair works performance shall be in accordance with typical nomenclature documentation requirements but taking into account with the revised process parameters mentioned above. Pressing of windings and magnetic core only up to 50-60% of their factory levels is assumed in particular.

4. Reconstruction of transformer individual units. In particular, the replacement of an exhaust pipe for a safety valve, transformer provision with a film system of oil protection, especially in the areas where the emissions of chemical and metallurgical production plants take place, replacement of old type bushings by the new ones, etc. had place.

5. Preparation of oils and sorbents. This work requires considerable time period.

Not only spent oils require treatment but also fresh oils from oil storages. As a rule, this treatment means drying, cleaning, degassing but in a number of cases also oil regeneration using silica gel.

If oil was used for a long time its regeneration can be ineffective from the economic viewpoint or technically difficult . However, as the experience shows, oil of TK grade produced out of high quality oils of Baku origin (e.g. dossor oil) maintains its high dielectric properties even after 40-50 years of operation. After treatment the dielectric parameters of such oils are as good as the best parameters of new oil grades.

In the course of the repair works it is obligatory to control the moisture content in silica gel prepared for thermosiphon and air drying filters. Usually it should be dried a little. Besides, it requires oil flushing.

6. Washing and drying of insulation is one of the main repair component of the transformers with a considerable service life as well as of the transformers which experience humidification and slime deposit formation. In such cases both traditional and new solutions are recommended.

The specific features of washing and drying process are as follows: the duration of exposures of periodic heating (washing) and treating under vacuum is defined based on paper insulation mechanical strength, its moisture and slime content. Vacuum level in the transformer is defined based on the state of rigid insulation and design peculiarities of the extension tank. Heating temperature shall be the optimum one in order to obtain the best final result. In the course of washing at various stages the temperature and pressure of oil in the tank vary depending on the values of the controlled parameters.

At a certain stage of washing the ordinary transformer oil is substituted for a transformer oil solution containing detergent additive Midel 7131 and other components. The optimum additive content in oil, defined as a result of laboratory and on on-site analyses, allows, from the one hand, to increase considerably the mechanical strength, and, from the other hand, to provide an active washing-out of slimes and good insulation drying.

It is worth saying that a violation of the technological conditions and content (%) of the additive sufficiently decreases the efficiency of paper insulation mechanical strength improvement and drying. These works foresee a permanent control of moisture content, class of the industrial cleanness, insulation and the other characteristics of washing oil, as well as, (if possible) of winding insulation resistance values R_{15} and R_{60}.

Additive Midel 7131 is an electrical insulation liquid produced based on halogen-free esters of pentaerythritol acid. In accordance with IEC classification it belongs to type T1.

Moisture absorbing capability of Liquid Midel 7131 by 200 times increases the moisture absorbing capability of oil. Besides, it demonstrates a considerably higher dissolving capability.

The results of the repair works performed have shown a significant efficiency of a new washing technology. For example, it was possible to increase winding insulation resistance R_{60} by 2.5-5.5 times and to decrease tgδ by 5 times (Table 2) of the transformer of TDG-40500/110 type (40 MVA/ 110 kV) the service life of which was 44 years and which had demonstrated a high degree of humidification and contamination of rigid insulation (including contamination by iron oxides and naphthenes). The moisture content of hard insulation control specimen was reduced by more than 2 times.

It should be noted that the developed and commercially proven technology of hard insulation washing and drying allows to improve not insulation electrical characteristics only, but in a number of cases, the mechanical ones as well.

The IR-spectrometry and X-ray diffraction analysis of insulation specimens carried out prior and after their washing based on a new technology have proven the strenthening of hydrogen bonds in cellulose macro molecules and the improvement of crystal grating.

The data of Table 3 are related to the mechanical condition classes and polymerization degrees of TDG-40500/110 type transformer hard insulation specimen being under operation about 45 years.

Table 2

Transformer TDG-40500/110 insulation characteristics

Measurements	$t_{meas.}$ °C	Insulation characteristics reduced to 20°C at the following measurement scheme				Hard insulation moisture content, %
		HV-(LV+F)		LV-(HV+F)		
		tgδ, %	R_{60}, MOhm	tgδ, %	R_{60}, MOhm	
Prior to repair	20	5.57	600	4.7	1000	3,5-4,2
After repair	27	1.2	3980	0.88	2650	1,5-1,7

Designations: HV- high voltage; LV – low voltage; F – frame.

Table 3

Mechanical condition classes and polymerization degrees of transformer TDG-40500/110 hard insulation specimen

Insulation type	Thickness, mm	Specimen taking point		Mechanical condition, Class		Polymerization degree, units	
		Side	Phase	Prior to repair	After repair	Prior to repair	After repair
Barrier	2	HV, above	B & C	3-4	3	273	327
	2	HV, below	B & C	3	3	403	474
	2	HV, above	A & B	**4**	3	**240**	322
Additional insulation of winding top leads under beech fixation laths	0.5	LV	A	**4**	3	**208**	377
	0.5	LV	B	**4**	3	**238**	309
	0.5	HV	A	3	2-3	341	355
	0.5	HV	B	3	2-3	326	335

Insulation mechanical condition class numbers indicated in table 3 are given in accordance with the following arbitrary specification:

Class number	Insulation mechanical condition
1	Elastic; has no damage at 180 degree bending.
2	Hard; does not crack at 180 degree bending.
3	Brittle; breaks at 180 degree bending.
4	Decrepit; breaks at 180 degree bending.

No doubt, the technology described above does not guarantee a complete renovation of old insulation. Nevertheless, in a number of cases it helps to improve by 15–20% the mechanical strength of insulation showing signs of considerable destruction as well as to improve rather effectively the insulation indices.

Thus the obtained results confirm the possibility to extend the service life of paper insulation and, as a result, in many cases the service life of the transformers.

Summing up it is worth saying that the complex inspection cost is less than 1% and the cost of the most complicated repair is less than 10% of the transformer cost.

Conclusions

1. Taking into account the objective necessity to operate the transformers with a long service time and to improve the reliability of their operation, it is reasonable to perform complex diagnostic inspections which allow to obtain the true data on the transformer state.

2. A new repair technology of insulation washing with oil containing special additives allows to improve considerably the insulation characteristics of transformer windings as well as to improve cellulose crystal structure and increase the insulation mechanical strength in case of paper significant destruction.

Optimum selection of repair conditions (concentration of additives, vacuum level, intervals between washing operations, vacuum processing and heating) allows to restore the transformers with 35-45-year service time. Such rapoirs ensure the possibility of transformer service life extension. The 50-year service life seems to be regarded as a limiting one for the transformers; after this term the transformer operation may be unjustified and hazardous.

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