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Technology and evaluation procedures of integrated diagnostic survey of large power transformers

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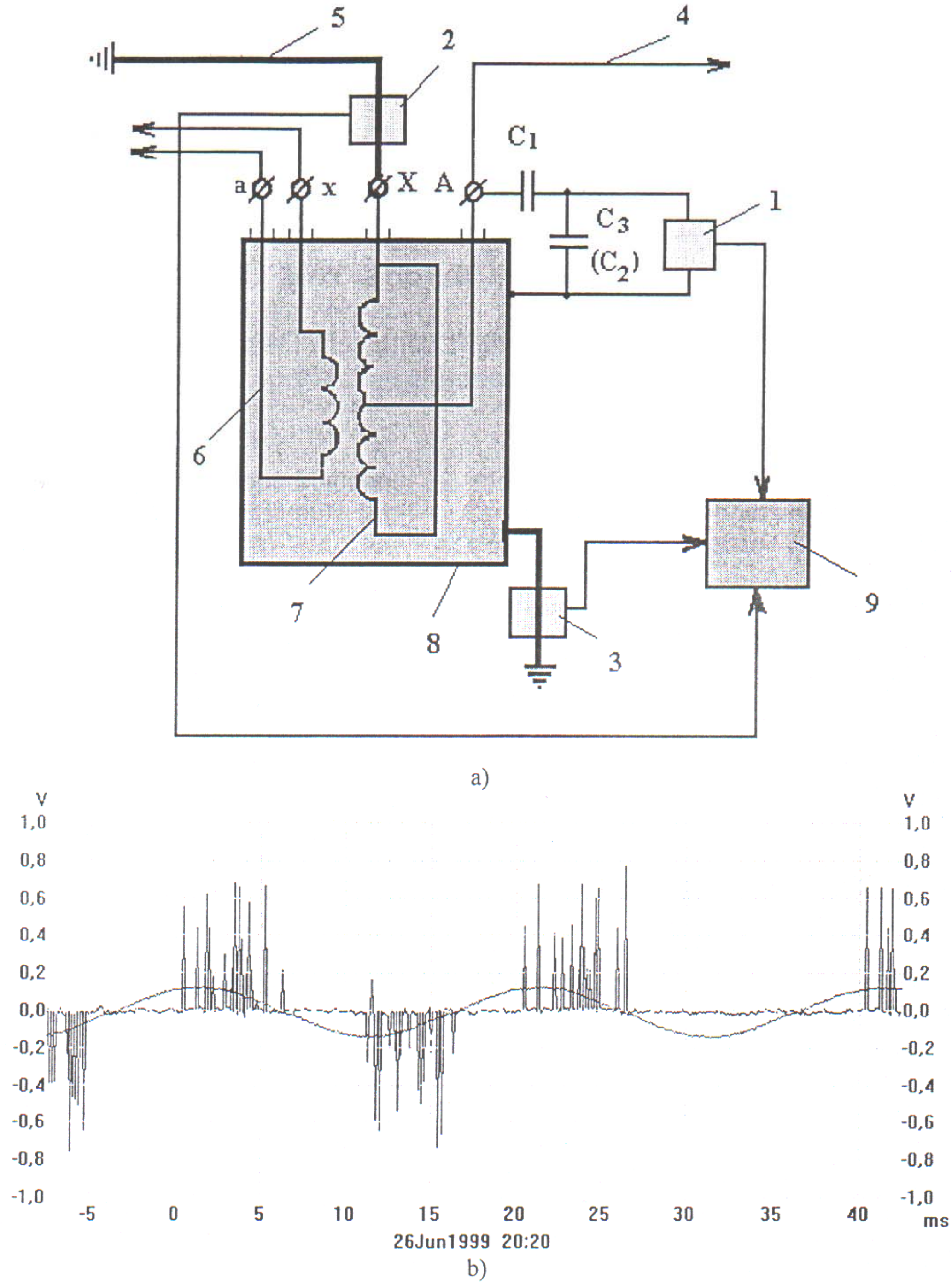
Summary. Integrated diagnostic survey permits reliable detection off transformer faults and evaluation of the degree of these faults. Basing on these results, recommendations can be issued to continue safe operation of transformers or to point up the necessity of repair.
The results of survey of about 250 transformers, as well as faults discovered during repair of 14 transformers, bear evidence of high efficiency of the technology.

Introduction. Integrated diagnostic survey permits to assess objectively the condition and to detect faults in every transformer systems, including its active part (windings and transformer core), bushings, cooling system, voltage regulating system, etc.
During 6 years "Technoservice – Elektro" has inspected about 250 transformers of 110-500 kV and 6,3-1000 MVA. Transformer survey has been made on : hydro, thermal, nuclear power plpants and substations and within every climatic region of Russia. Lifetime of transformers was from 15 to 54 years. Almost 90% of transformers had lifetime of 25 years and more. All transformers were made in former USSR (Russia and Ukraine now) and 4 of them made in Sweden (ASEA and Stromberg).
Transformer technical condition and danger of propagation of faults were assessed basing on Russian and international regulations [1-4], scientific investigations of Russian and foreign authors [5-7] and experience accumulated by "Technoservice – Elektro" [8].

Procedure of integrated diagnostic survey.
Integrated diagnostic survey of transformer consists of: analysis of relevant faults of given type of transformers; analysis of engineering data and routine measurement results; on-line measurements at load duty and idling, off-line measurements; oil sampling from transformer tank, oil-filled bushings, OLTC -oilr and physico-chemical analysis of these oil samples in laboratory.
All measurements and analyses for transformer diagnostics can be divided conventionally into five groups.
First group includes traditional off-line measurements: tgδ and R of insulation of windings and bushings, dc copper resistance, standby losses and short circuit resistance. These measurements are carried out regularly by operating personnel.
Second group of measurements is carried out on transformers at operating voltage at maximum load duty and/or idling. The following works can be mentioned: Measurement of partial and other electrical discharges, as a rule by inductive sensor (fig.1).
Acoustic survey of transformer tank in order to determine sources of electrical discharges. For this two types of devices are used: 1) system of registration of acoustic signals with piezoelectric sensors, oscillograph and computer; 2) location of acoustic signals with Ultraprobe-2000 sound converter, which permits to determine acoustic frequency of mechanical sources, spark or arc discharges, partial discharges.
Vibration survey of transformer in order to determine pressing ratio of winding and transformer core, general stability of construction, as well as condition of oil pumps of cooling system. The technology is based on analysis of oscillation spectrum of tank surface.
Thermographic survey of transformer tank, bushings of conservator of heat exchanger, thermosiphon filters, electric motors and oil pumps of cooling system, contact connections.



1,2,3 – bushing sensors, neutrals, earth buses, 4 – HV bus, 5 – neutral earth bus, 6 – LV winding, 7 – HV winding, 8 – object of control (transformer), 9 – measuring device.

C_1 – basic insulation capacity; $C_3(C_2)$ – capacity of final coverings (of measuring terminal condenser); A – line bushing of HV winding; X – neutral bushing; a and x – LV winding bushings.

Fig.1. Structural arrangement of measurement of partial and other electrical discharges (a) and example of partial discharge findings (b).

Third group of measurements – physical and chemical oil analysis of tank, oil-filled bushings and OLTC oil.

Among them there is a big group of traditional measurements widely applicable during operation (measurement of disruptive voltage, acidity index, etc.).

Besides, chromatographic analysis of 11 typical gases is carried out, destruction of solid insulation of transformer windings is determined by liquid chromatography, different slime and residual dissolved in transformer oil is determined by infra-red spectroscopy. Analysis of fractional composition of foreign particles in oil can be made with automatic particle counter or by membrane filtering. Measurements of dielectric oil losses of high-voltage bushing and alteration of their temperature give information about existence of polar products in oil.

Fourth group includes measurements of monitoring system of bushing insulation and daily measurements of basic indices of transformer performance.

Fifth group of analyses is carried out for transformers that basing on results of the first four groups of analyses are scheduled to a major overhaul. This group includes also determination of degree of polymerization of paper insulation, direct measurements of its specific humidity and strength.

While analysing diagnostic data the following items should be considered:

1. Probability of development of several faults (particularly for service aged transformers), which manifestation may be similar in some diagnostic factors.
2. Probability of instrument error or error of method of measurements.
3. Existence of latent defects that were not revealed during direct measurements or that could be detected only in specific modes (for example at short circuit).
4. Faults that were self-liquidated but could be detected, for instance, by physico-chemical analyses of oil.

Wide range of diagnostic methods permits to master mentioned difficulties and give impartial data about the condition of all transformer systems, even without performing continuous monitoring.

Principal results

Reliability of results of diagnostic survey is confirmed by faults revealed during repair of 14 transformers, as well as by successful and long run of other transformers.

As an example in Table 1 are given basic parameters of two transformers that were under survey and repair and measurement results.

With bold characters and italics in Table 1 are shown parameters that exceed rated values [1,2] and give indication of incipient faults.

After analysis of data (Table 1) of 120 MVA 220/110/10 kV autotransformer the following faults were established and confirmed during repair:

1. Ageing and destruction of solid insulation. Degree of polimerization of paper samples within the hottest zone was 540 units.
2. Sludging-up of insulation with products of oil deterioration.
3. Deep thermal oxidative ageing of oil, its renewal is needed.
4. There is a source of electrical discharges within a zone of C phase. A thin burr has been detected sticking out of the lower transformer yoke and traces of discharges in this spot over tank bottom.
5. Source of acoustic activity within a zone of A phase of non-electrical nature. Cylinder of bushing of 220 kV A phase exhibits longitudinal crack and spallings.

Experience lead us to conclude that individual diagnostic parameters do not transcend limiting values [3], equipment cannot be rejected, neither repair recommended. But integral analysis of diagnostic factors may give an objective pattern of equipment condition and reveal timely incipient faults. Thus, in 200 MVA 220 kV transformer the following has been revealed:

1. Good condition of paper and oil insulation.
2. Relatively low pressing ratio of winding of C and B phase.
3. Decrease of pressing ratio of transformer core that is most probable in A phase core and in upper transformer yoke between A and B phases.
4. Fault of electric nature in lower part of the tank from the end of C phase originates short circuit currents from belt leakage.

Decrease of pressing ratio of windings and transformer core was predicted basing on vibration survey results (Fig.2, a, b). Numerals on Fig.2 show pressing ratio, which maximum value is equal to 1. The lower is this value, the lower is the pressing ratio. Condition of pressing ratio of windings and transformer core is considered faulty with coefficient close to 0.7.

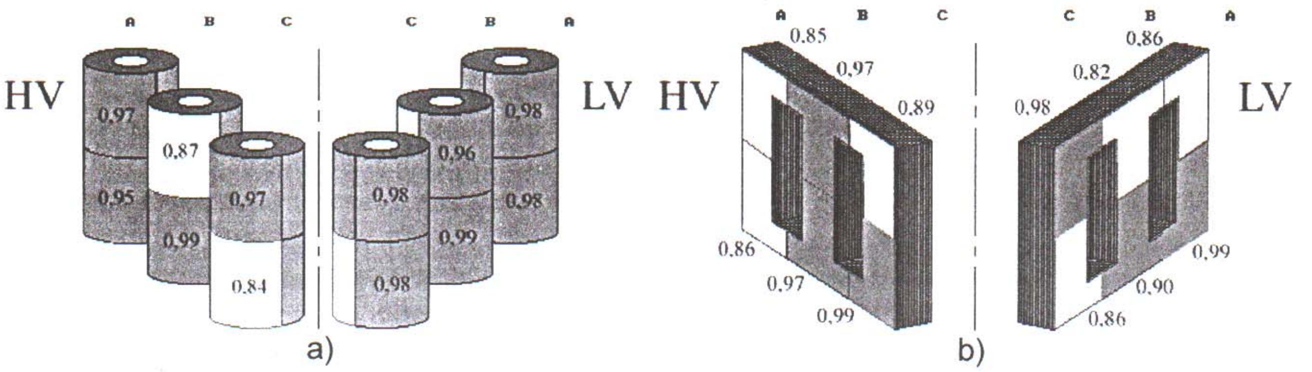


Fig. 2. Pressing ratio of windings (a) and transformer core (b) of 200 MVA 220 kV transformer

Results of diagnostic survey were completely confirmed by opening of transformer. Fouling of active part is insignificant. In inferior part of the tank three non-removed shipping bolts were discovered. In a place of contact of bolts with support core plates severe carbonization was detected.

There are cases when a cause and a place of fault prove to be detected very precisely. For example a 360 MVA 220 kV transformer has been in reserve for some years. After a year of putting it into operation increased concentration of H_2, CH_4, CO, C_2H_4, C_2H_6 and C_2H_2 was detected in transformer tank oil. Rate of increase of these gases during the last half-year before the survey was high (Table 2).

Measurements revealed sources of spark and arc discharges within magnetic system with apparent discharge of 15-22 nC. Acoustic survey revealed four sources with 35-45 kHz frequency in upper and lower transformer yoke.

Near both sources over the tank surface hot zones were detected (Fig.3).

After opening of active part of transformer loss of insulation of four tie rods of transformer core was detected right in zones of acoustic activity.

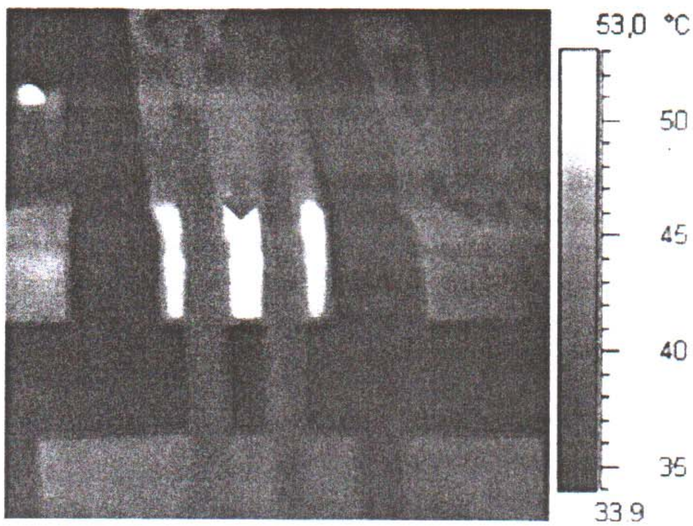


Fig.3. Thermogram of upper part of tank surface within fault zone.

Table 1

	Transformer	AT 120 MVA	200 MVA
Basic parameters of transformer	Rated capacity, MVA	120	200
	Rated voltage, kV	220/110/10	220/15.75
	Lifetime, year	29	15
Insulation characteristics of windings	R_{60}, MOhm	**92…110**	2900…4200
	tgδ, %	**1.1…1.2**	0.16…0.28
Physico-chemical parameters of tank oil	Concentration of dissolved gases, that give indication of fault propagation, ppm	CO – **640** C_3H_x – **113**	CH_4 – **131** CO – **270** CO_2 – **5590**
	tgδ, %	*13.5*	0.6
	Content of water-soluble acids, mg KOH	**0.52** – before regeneration **0.23** – after regeneration	-
	Acidity index, mg/g	**0.23**	0.024
	Percentage of oxidation inhibitors	**traces**	0.14
	Moisture content, g/t	*15.2*	7.1
	Contamination class	8	8
	Furane compounds, mg/kg: 5HMF	2.75	traces
	Furane compounds, mg/kg: 2FAL	*11.3*	absent
	Furane compounds, mg/kg: 2ACF	1.45	absent
	Furane compounds, mg/kg: 5MEF	*13.43*	absent
	Furane compounds, mg/kg: Σ	*28.9*	traces
Measurements at load duty and idle run	Measurement of partial discharges	There is a source of electric and may be partial discharges in C phase	Stable electrical discharges of $8x10^{-8}$ C in B and C phases
	Acoustic survey	In an area of A phase a source of acoustic signal of non-electric nature is detected; in an area of C phase near tank bottom there is a source of probably electric nature	Several zones of acoustic activity were detected at load duty and idle run including in lower part of the tank within A phase zone and in upper part of the tank within B and C phase zone
	Infrared survey	Noticeable abnormal temperatures were not observed	Zone of abnormal heating was detected in lower and middle part of tank end from A phase side
	Vibration survey	-	See Fig.2

Concentration and rate of increase of concentration of gases dissolved in oil of 360 MVA transformer

Table 2

Gas	H_2	O_2	N_2	CH_4	CO	CO_2	C_2H_4	C_2H_6	C_2H_2
A, ppm	144	22016	86556	395	995	6670	809	168	13
V, ppm/month	16.2	-	-	13.5	115	933	31	8.2	1.6

Conclusions

1. Integrated diagnostic survey permits to obtain true pattern of transformer technical condition.
2. Survey of more than 200 transformers with lifetime of 25 years and more proves that less than 2% of transformers need to be put out of operation immediately, about 23% require rush overall of active part, about 35% of transformers require minor repair (including replacement of bushings) or more frequent checking of several diagnostic parameters (I chromatographic analysis of dissolved gas in oil, etc.)

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