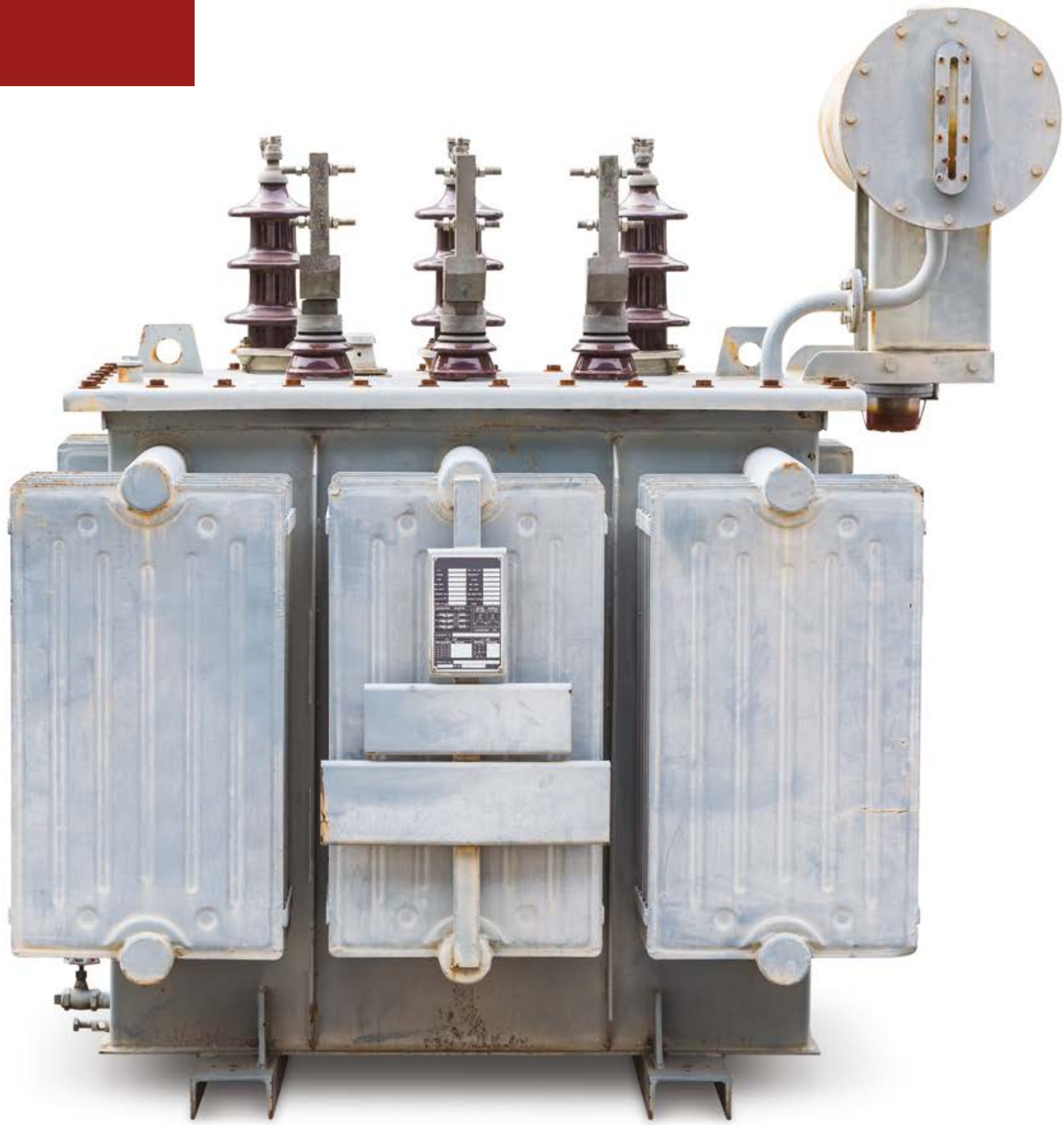

Written in the aid of technicians involved in the maintenance of electric equipment

Absorption index of insulation at end of service life – Part II

Old-aged transformers equipped with silica gel air breather

ABSTRACT

Absorption Index (AI) remains valid for old-aged unsealed transformers as a simple and effective method of non-destructive control insulation. The reasons for AI decrease within transformer operation are insulation moistening and contamination. Seven gradation levels of the insulation condition and algorithm of the operating procedures are proposed depending on the value of the measured AI and its variation in time. Along with AI, it is recommended to measure the polarisation index (PI) and the PI-2 (R_{600}/R_{15} ratio).

KEYWORDS

absorption index, cellulose insulation, contamination, distribution transformer, GOST, IEEE, insulation resistance, maintenance, moisture, oil, operation, polarization index, power transformer

5. Oil and AI

It is well known that oil quality has a significant effect on the insulation resistance and on AI and PI values. The better the quality of the oil, the higher the insulation resistance, and more reliable the transformer. But modern transformer oils with low conductivity (including Russian GK oil) have AI and PI close to 1 (see the last paragraph of Annex 3). This means that for insulation of the transformer as a whole, the AI and PI values will be lower when filling with a higher quality oil than when filling with a lower quality oil. To quantify this reduction in the AI, the following experiment was performed at ZTZ. The Russian old TKp oil (obtained from the oil by acid-base treatment) and GK oil (obtained by the hydrocracking method) were alternately poured into a three-phase three-winding transformer. The comparison of the AI at a voltage of 2.5 kV is shown in Table 4. As follows from this table, GK oil increases the insulation resistance by approximately an order of magnitude, and on average halves the AI value.

It is noteworthy that when oil is filled with TKp, the AIs in the schemes LV - (HV + MV + GND) (1.96 and 2.06 at different temperatures) are less than in the MV – (HV + LV + GND) schemes (3.52 and 3.95). And on the contrary, when pouring the GK oil, AI in the LV - (HV + MV + GND) scheme is larger than in the MV – (HV + LV + GND) scheme (1.43 and 1.24, respectively). This can be explained as follows. It is known that when changing the oil in a solid insulation of a transformer, up to 10 % of the old oil remains. The solid insulation near the LV winding of our transformer has fewer oil channels, and TKp oil remaining in it is older than in the oil in the solid insulation near the MV winding, where there are fewer oil channels.

The quality of the oil affects the insulation resistance and the AI and PI values - the more stable these values, the more reliable the transformer

6. AI dependence on the temperature

The author's data indicate that old-aged transformers with a high moisture content have the AI value significantly dependent on the temperature. This is valid for both the European climate conditions (Fig. 3) and tropical climate (Fig. 5).

In an operating transformer, the water migrates from the solid insulation to the oil and vice versa, depending on the transformer temperature. Therefore, AI values should be compared with earlier measured data at the same or at close temperature values of the transformer. According to the USSR practice, the temperature of HV winding phase B is assumed as the transformer insulation temperature, which is determined by DC resistance. For "cold" transformers, the temperature can be determined by sensors installed at the top oil layers. The difference between these methods can exceed 5 °C. It is suggested to use both methods, and for comparison, to apply the method used during the previous testing.

Various correcting formulas and tables are available for reducing the measurement results to the same temperature for IR [15, 16]. According to the author, there is no point in compiling such tables for AI values. It is preferable to take measurements during the transformer cooling after decommissioning, when the temperature approaches the level from previous measurements. Temperature difference should not exceed 5 °C.

Measured data indicate that old-aged transformers with a high moisture content have the AI value significantly dependent on the temperature

Table 4. Transformer 160 MVA 220 / 121 / 35 kV in the testing lab of ZTZ, February 1988

Type of oil, temperature T	Test	R_{15}, MΩ	R_{60}, MΩ	AI
TKp, 38 °C	HV - (LV + MV +GND)	250	480	1.92
	MV – (HV + LV + GND)	270	950	3.52
	LV - (HV + MV + GND)	260	510	1.96
TKp, 33 °C	HV - (LV + MV + GND)	330	650	1.97
	MV – (HV + LV + GND)	380	1150	3.95
	LV - (HV + MV + GND)	340	700	2.06
GK, 35 °C	HV - (LV + MV + GND)	4900	5800	1.18
	MV – (HV + LV + GND)	4500	5600	1.24
	LV - (HV + MV + GND)	2800	4000	1.43

During diagnostics, it is important to correctly evaluate the remaining "time to death", which depends, on the degree of insulation moisture content

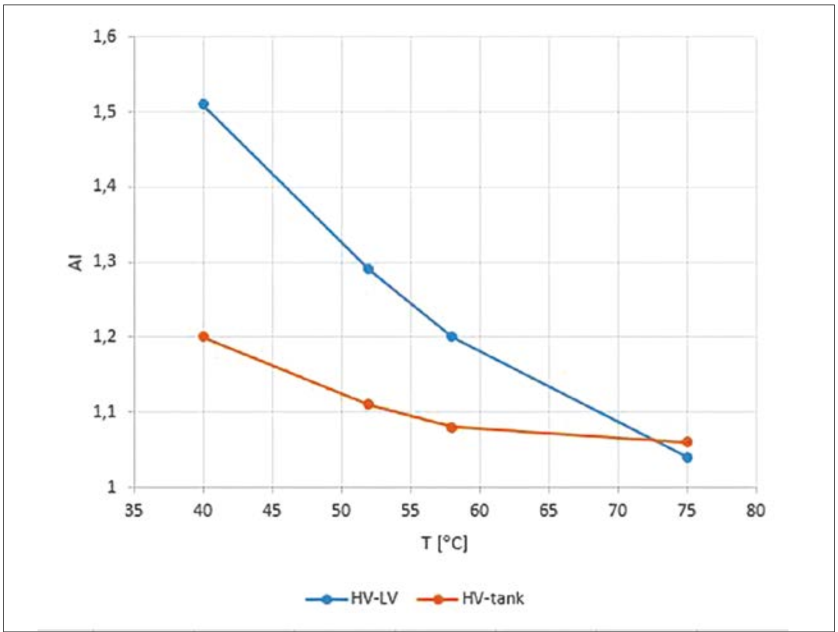

Figure 5. Temperature-dependence of insulation AI of autotransformer 4T (125 MVA 242 / 121 / 36 kV) TPP Neyveli at 5 kV. The test was carried out in February 1989. Before the shutdown of the AT, the moisture content in the oil was 40 ppm at 75 % load. The moisture content in the solid insulation was 4 % (calculated). The AT was manufactured by ZTZ in 1965.

7. Insulation condition evaluation using AI value and recommended measures

The problem related to insulation moisturizing of both old and new transformers remains relevant [10]. During diagnostics, it is important to correctly evaluate the remaining "time to death" of a transformer, which depends, among other things, on the degree of insulation moisture content. Over the decades of work in the field of transformers, the author occasionally returned in his thoughts on how to reanimate the criterion of AI value. The situation is as follows. Operating staff typically have the annual data of R_{15} and R_{60}. This set of data is maintained throughout the whole service life of the transformer. However, this data is not used efficiently enough, and the isolation condition remains underestimated. Therefore, the relevance of evaluating the permissible decrease of AI value and the permissible absolute AI value (previously equal to ≥ 1.3) was also practically assured. The author has repeatedly thought about improving the evaluation of the transformer insulation condition based on the AI criteria. In the afternoon of his life, the author has formulated and suggested the following simple algorithm of measures based on AI test results.

First, let us consider a marginal case when the transformer's measured AI value was 1.0. In 2001, at S/S "Varna TPP", Bulgaria, the bushing 220 kV was replaced by a company unqualified for the 200 MVA 230 / 121 / 38.5 kV autotransformer (AT) (manufactured by ZTZ in 1977) after 23 years of successful operation. In this AT, three single-phase OLTCs type RNOA 110 / 1000 are located on the 110 kV-side. Typically, over 20 years of transformer operation, rubber seals become brittle and must be changed. However, this has not been done. The rainwater has entered the phase C diverter switch reservoir through a poor seal between the transformer cover and the diverter switch and moistened the insulating parts of diverter switches. The measured AI in configuration HV - (LV + GND) was 1.0. Despite this, the AT was commissioned. After two months, the AT exploded, resulting in significant damage: a rupture of the diverter compartment and OLTC diverter switch of phase C, displacement of the AT out of the rails, damage of three HV bushings (the framework of damaged 110 kV bushing of phase c1 is shown in the foreground of Fig. 6), AT tank deformation, failure of the tank welded joints at many places, complete failure of two coolers, etc. During the investigation, water was also found at the bottom of diverter switch reservoirs of phases A and B. An emergency overhaul was carried out by Trafoservice company to upgrade and modernise the AT at the substation site. The AT was sealed (tank welding and installation of an air bag) and filled with new Bulgarian oil "Priesta Trafo A". During testing after the overhaul, AI was 1.30 at 35 °C and 1.26 at 55 °C. The AT has been commissioned and operated without any problems for almost 5 years. Then the AT was decommissioned. The annual preventive testing of the AT performed from that moment has confirmed the AT's operating capability until today (April 2020).

This fact indicates the unaccepted value of AI = 1.0. An assessment of higher AI values tolerability and the algorithm of proposed measures are provided in Table 5.

Initially, the lowest measured AI value is brought in correlation with the four gradations listed in column 2 of Table 5. Then ΔAI variation is calculated using the equation:

$\Delta AI = (AI_1 - AI_2) / AI_2 \times 100$ (%), where:
AI_1 – test performed a year before,
AI_2 – current test.

In the equation, the denominator contains the smaller AI value (AI_2 instead of

Water and moisture in the transformer insulation can cause a fatal damage, as in the case of the 200 MVA 230 / 121 / 38.5 kV transformer in "Varna TPP"

AI_1) for the purpose of a more accurate consideration of the decrease rate of AI for a significantly moistened and contaminated insulation (when AI is less than 1.1). For this purpose, different AI values (10, 5, and 2 %) are also indicated for different absolute values of AI. Δ values are the most controversial part of the proposal and require the most extensive clarification. It should be emphasized that the AI decrease revealed in the moistened and contaminated transformer encourages some degree of optimism because it ensures a degree of margin for a timely decision on the transformer decommissioning in order to prevent an accident.

The algorithm is related to old-aged unsealed transformers according to GOST, without reference to their power and voltage rating.

An example of effectiveness of the measures according to Table 5 is shown in Fig. 4. Another example is presented in Table 6.

There is an algorithm based on AI and ΔAI for evaluating the insulation condition of aged transformers according to GOST, without reference to their power and voltage rating

Transformer 4T (250 MVA 242 / 15.75 kV) AEC Kozloduy, Bulgaria, manufactured by ZTZ in 1974. The moisture content in the oil before repair – 26 ppm, after repair – 6 ppm. Oil spray drying was carried out in April–May 1994 by Research Center "ZTZ-Service".

The author feels the reliance upon effectiveness of his proposal for diagnostics of the transformer condition. Improvement of Table 5 is possible and necessary by analysis of AI data accumulated over many years for unsealed transformers by different manufacturers. Priority should be paid to the nature of change in AI of the HV – LV section over a long period of the transformer operation. It is also necessary to accumulate and analyse new data, especially for those transformers filled with new oil during an overhaul. By virtue of his age, the author himself can no longer do this in practice. He relies on consideration of other younger specialists.

8. Comparison of criteria for AI, PI, DAR and R_{600}/R_{15} ratio

The typical time-dependence of IR of the old-aged transformer in the range of up to 10 minutes is shown in Fig. 7. Table 7 rep-

Figures 6. Damage of the 200 MVA autotransformer at S/S "Varna TPP", Bulgaria

Table 5. Evaluation of insulation condition of the old-aged unsealed transformer and recommended measures

No.	AI	ΔAI*	Insulation condition	What to do (recommended action)
1	> 1.2	< 10 %	Excellent	No cause for concern. Continue to operate normally.
		> 10 %	Good	Continue to work, but the condition should be checked upon the first shutdown of T.
2	1.1 < AI ≤ 1.2	< 5%	Fair	Carry out additional measurements.** Continue to operate but check the decrease trend.
		> 5 %	Questionable	Continue to operate with excessive control.*** Check the decrease trend.
3	1.01 < AI ≤ 1.1	< 2%	Poor	Continue to operate with excessive control.**** Filtration or drying of oil, or replacement of oil within the next 6-12 months.
		> 2 %	Very poor	Continuation of operation is risky. Drying or replacement of oil or insulation drying within the next 1-2 months.
4	≤ 1.01	-	Dangerous	It is unacceptable to start up the transformer for operation. Insulation drying.

*Variation of AI value (see the equation in the text) at temperature difference between the tests not exceeding 5 °C.
**Make measurement of insulation IR, AI, PI, tan delta and their dependence on the temperature and voltage testing for all accessible sections of the transformer insulation. Make measurement of the oil characteristics (moisture content, tan delta, breakdown voltage). Plot graphs of variation with available data for the complete period of the transformer operation. Contact experts for advice onr evaluation of the transformer condition.
***Excessive control includes taking measurements** at least once per six months to clarify the trends.
****Excessive control includes taking measurements** at least once per quarter. If it is impractical to carry out the testing too frequently, it is possible to cut to estimation of the transformer condition as "very poor".

resents the comparison of AI, PI, DAR, and R_{60}/R_{15} calculated based on data in Fig. 7.

Let us compare conditions of transformer 2GT according to PI and AI criteria. If PI = 1.6, in line with IEEE (Annex 3 to this paper), the condition of transformer 2GT should be evaluated as "fair". For a complete evaluation of the condition using the AI criterion, there is no data for the year before 1988. According to the absolute value of AI = 1.18, the transformer condition should be evaluated in the rough between "fair" and "questionable".

DAR assumes only a very small-time domain in the absorption curve and a priori provides less information about the insulation moisture content if compared with other criteria. Considering also that a smaller error occurs when comparing large digital values, DAR should be considered unpromising for implementation of field tests in practice. R_{600}/R_{15} ratio (let us call this ratio "Polarization Index 2" **PI-2**) may be more informative.

The author's experience shows that a wider point of view that PI is temperature-independent may not be observed for old-aged highly moistened transformers. So, Fig. 8 shows a temperature dependence of AI, PI, and R_{600}/R_{15} (PI-2) for the distance from major solid insulation of the transformer 4T at TPP Neyveli (mentioned in Fig. 5). As can be seen from Fig. 8, PI noticeably decreases at the temperature increase, although to a lesser extent if compared to AI, and especially PI-2.

9. On the possible life span of old power transformers

By the start of the 1990s, it was found that power transformers and shunt reactors of up to 750 kV inclusive are able to operate reliably beyond the 25-year service life established by GOST [17, 18, 19].

The subsequent experience of the author suggests that transformers can successfully work for much longer. Many of the transformers discussed in this article are still in operation. Some

Table 6. Effect of insulation drying on AI

	Before repair	After repair
Transformer temperature	38 °C	43 °C
HV – LV	1.30	1.67
HV – tank	1.05	1.41

of them are over 50 years old. In addition, more than 100 transformers of up to and including 400 kV were renovated in Bulgaria by modernization. The vast majority of them continue to work successfully (as on April 2020). An analysis of this experience is beyond the scope of this article.

The author considers it incorrect and economically unreasonable to replace transformers that have successfully worked for 25 years with new ones. Just as during the time of Bratsk HPP (replacing 220 kV block transformers). Over the past five years, this vicious practice has been carried out in Ukraine (replacement of transformers of 750 and 330 kV).

Conclusion

The absorption index has kept its importance as the most straightforward method for evaluation of moisture content and contamination of the transformer insulation. A practical approach is proposed to improve this method (Table 5 algorithm, taking into account AI value and its variation over time). The approach requires verification in practice. This is just one of the methods for evaluation of the insulation condition; it does not substitute the need for additional testing and detailed expert analysis of the transformer condition as a whole. However, according to the author, it would assist in focusing on priorities of those transformers, which need to be considered the most.

Performance of AI test once a year is reasonable and sufficient. Along with the measurement of AI, it is recommended to measure PI (in order to use the American experience). DAR does not make sense to perform. The PI-2 could be more informative. It is also suggested to gain practical experience of comparison of AI test results and DFRT data.

The author expects that after clarification, Table 5 can also be applied to old-aged,

The absorption index has kept its importance as the most straightforward method for evaluation of moisture content and contamination of the transformer insulation

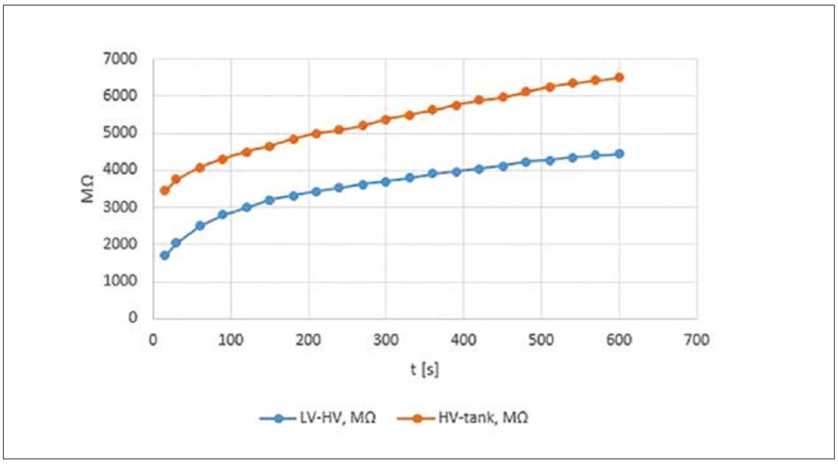

Figure 7. An insulation absorption curve of transformer 2GT at TPP Neyveli. Measurements at 5 kV were performed on 2/8/1989. The transformer's temperature was 28 °C.

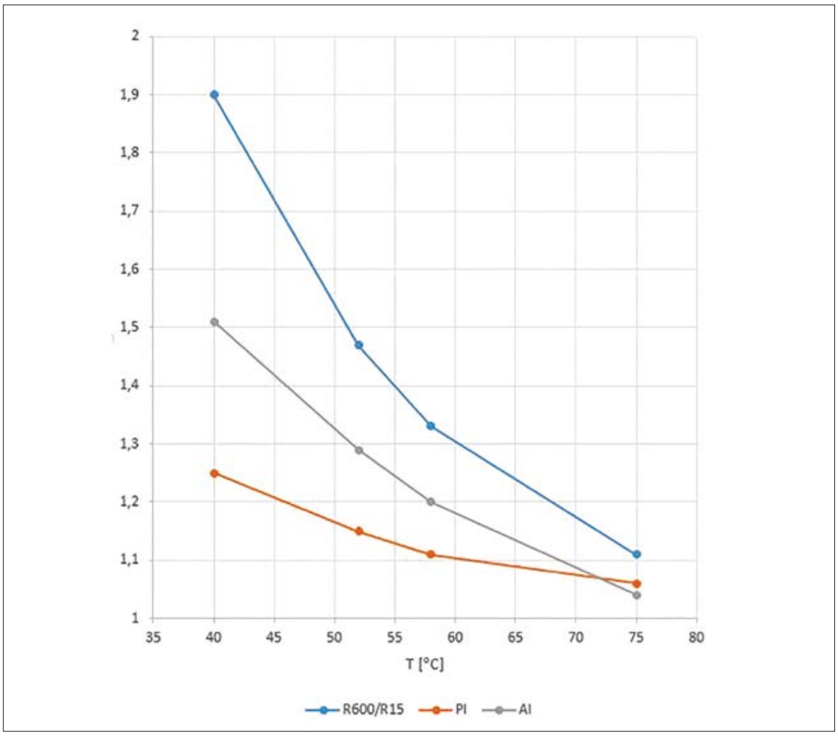

Figure 8. Temperature dependence of insulation AI, PI, and R_{600}/R_{15} (PI-2) of LV - HV for transformer 4T TPP Neyveli

Table 7. The values of AI, PI, DAR, and PI-2 according to Fig. 7

Time, s	15	30	60	600	AI	DAR	PI	R_{600}/R_{15}
IR_{LV-HV}, MΩ	1700	2050	2500	4450	1.47	1.22	1.78	2.62
$IR_{HV-tank}$, MΩ	3450	3750	4075	6500	1.18	1.09	1.60	1.88

Considering also that a smaller error occurs when comparing large digital values, DAR should be considered unpromising for implementation of field tests in practice

unsealed transformers from other manufacturers. The wider application of AI may be advantageous for oil-filled bushings, CTs, and VTs.

The author's experience shows that the safety margins of insulation of old-aged USSR oil-filled, free silica gel breathing power transformers are such that, subject to proper maintenance, they can be in service for the period up to 40–50 years, and with their modernization with tank sealing maybe even more.

Bibliography

[15] *Guide to the adjustment of electrical equipment of power plants and substations*, edited by E. S. Musaelyan, Energoatomizdat, Moscow, 1984 (in Russian)

[16] ANSI / NETA MTS-2011 Standard for maintenance testing specifications for electrical power equipment and system

[17] V. V. Gurin, S. D. Lizunov, A. K. Lokhanin, et al., *Service experience and requirements for insulation high-voltage tests of EHV power transformers and shunt reactors*, CIGRE, 1992, No. 12-202

[18] V. V. Gurin, A. K. Lokhanin, L. L. Glazunova, et al. *Requirements for testing the dielectric strength of insulation of power transformers 330 kV and higher in the norms of the USSR, USA, Canada and IEC*, Electrotechnika, No. 12, 1992 (in Russian)

[19] S. D. Lizunov, A. K. Lokhanin, V. V. Gurin, et al. *Experience of fault detecting, repairing and testing of EHV transformers and shunt reactors on site*, CIGRE, 1994, No. 12-201

Annex 1. Summary of the factory tests of new transformers.

Measurements of AI carried on for 484 transformers manufactured by ZTZ rated for voltage 35-750 kV and capacity from 11 to 630 MVA, filled with new oil type GK or Nynas have been analyzed. Circuits HV – (LV + GND), LV – (HV + GND), and (HV + LV) – GND have been considered. It turned out that AI values are in the range 1.17–2.75, and statistically, these values dependent in a minor way on the transformer parameters (power and voltage class).

The average values AI for LV – (HV + GND) are higher than for HV – (LV + GND) (1.79 versus 1.45), which is to be explained by the lump of solid insulation adjacent LV windings if compared to HV windings. At the dispatch from the factory, more than the third part of the transformers have an AI value less than 1.3.

With temperature increase, the AI value of new transformers is practically the same. But if the transformer is filled with old TKp oil, then AI value decreases significantly depending on the temperature, and this is much obviously for the distance HV-tank. This once again confirms the fact that at a distance of HV-tank, the main role is played by oil and that TKp oil gives higher AI values than GK and Nynas.

Annex 2. Other possible test connections of transformers for AI test

Two winding transformers:

1. LV – tank
2. HV – (LV + GND)
3. LV – (HV + GND)
4. (HV + LV) – GND

Three winding transformers:

1. LV – tank
2. TV – tank
3. HV – TV
4. LV – TV
5. HV – (LV + TV + GND)
6. LV – (HV + TV + GND)
7. TV – (HV + LV + GND)
8. (HV + LV) – (TV + GND)
9. (HV + TV) – (LV + GND)
10. (LV + TV) – (HV + GND)
11. (HV + LV + TV) – tank

Annex 3. Evaluation of T insulation by PI value (cited from clause 7.2.13.4 of the standard [1]).

The following are guidelines for evaluating transformer insulation using polarization index values:

Less than 1.0 = Dangerous
1.0 to 1.1 = Poor
1.1 to 1.25 = Questionable
1.25 to 2.0 = Fair
Above 2.0 = Good

The polarization index method should not be used to assess insulation condition in new power transformers.

The polarization index for insulation liquid is always close to 1. Therefore, the polarization index for transformers with low conductivity liquids (e.g., new mineral oil) may be low in spite of good insulation condition.

Author's note: What is PI, see Table 1 in the article. According to [1] *"Test voltages are typically 500 V, 1000 V, 2500 V, or 5000 V DC"*.

Author

Vitaly Gurin graduated from Kharkov Polytechnic Institute in (1962) and the Leningrad Polytechnic Institute. He was a candidate of technical sciences in the Soviet scientific system (1970). For 30 years he tested transformers up to 1.150 kV at ZTZ, including the largest one of that time in Europe, and statistically analysed the test results. For over 25 years he was the Executive Director of Trafoservis Joint-Stock Company in Sofia (the diagnosis, repair, and modernisation in the operating conditions of transformers 20 – 750 kV). He has authored about 150 publications in Russian and Bulgarian and is the main co-author of GOST 21023.