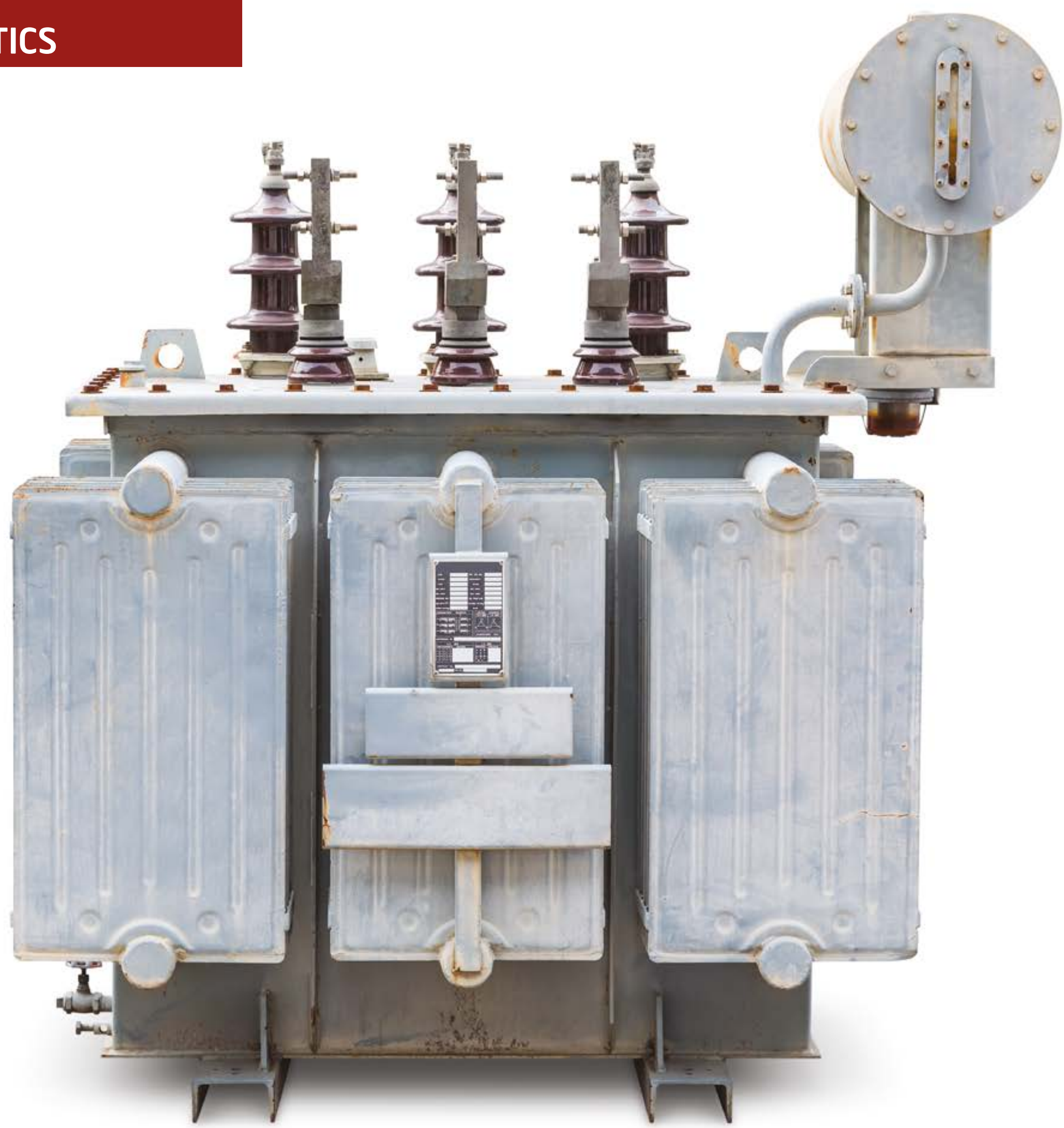

*Written in aid of technicians involved in the maintenance of electric equipment*

# Absorption index of insulation at end of service life – Part I

## 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, insulation resistance, moisture, polarization index


### Introduction

Transformers are the most important and most expensive equipment at a substation, and their failure leads to severe problems in the power supply. The purpose of preventive testing is to determine a runaway for the condition of the complex system of the transformer insulation from the initial state (at the factory and installation site), and upfront detection of the defects occurred. Preventive measures are based on the systematic inspections, and they allow to keep the equipment in operation state by means of cost-effective way, reducing the risk of permanent damage and potential failure, assisting the companies in avoiding major and costly repairs, and extending the service life of old-aged transformers.

Transformer fleets in all countries are ageing. With insufficient maintenance, a transformer older than 40 years can accelerate failure due to deterioration of the insulation condition (primarily due to its moisture and pollution). A middle-aged transformer may fail earlier, because its safety margin is substantially less, due to the fact that its design has been optimised for the limited service life of 25 years, according to GOST [1], Russian technical standard.

A significant number of old-aged unsealed USSR-made power and distribution transformers (in accordance with GOST) are in operation in the power systems and electric networks of Eastern Europe and a number of countries in Asia, Africa, and South America. Excessive moistening and contamination of these transformers are their main problems, since moisture and dirt at operating voltage, and even more so in case of the voltage increase, accelerate the insulation ageing. The combination of electrical voltage and insulation deterioration over time leads to the fatality of the transformer.

Measurement of insulation resistance (IR) at 15 and 60 seconds ($IR_{15}$ and $IR_{60}$) is the routine factory test, according to GOST. These values are specified in the certificate of each transformer. The operating manuals require regular (once per year) measurements of these values. During establishing these requirements, it was believed that using the trend of $IR_{15}$ and $IR_{60}$ decrease, it is possible to evaluate the degree of insulation moisture content of the transformer in operation. In addition to moistening, the experience has shown that these values are also affected by insulation contamination.

The article provides consideration of some real-life examples of old transformers manufactured by Zaporozhye Transformer Plant ZTZ and Moscow Electrozavod MEZ. The numerous measurements of $IR_{15}$ and $IR_{60}$ at the site in post-Soviet countries, in Bulgaria, Czech Republic, Slovakia, Macedonia, Serbia, and India, were conducted by the author personally, or under his guidance.

**With insufficient maintenance, a transformer can deteriorate rapidly due to worsening of the insulation condition, which occurs primarily due to the moisture and pollution**

The article goal is to describe the absorption index as the criterion for evaluation of insulation condition and for the provision of simple, practical recommendations for maintenance staff of old-aged transformers based on the test results.

## 1. Determination of absorption index AI

For more than 100 years, insulation resistance measurement using the Megger is the simplest and the most reasonable method for evaluation of a transformer and other electrical equipment insulation condition. At applying DC voltage to the transformer insulation, the transient phenomena consist of three main components:

- Charging current of the geometric capacitance of the measured section of transformer insulation; this current drops from maximum to zero within a few seconds.
- Absorption current due to the displacement of the molecular charges in the insulation. This transient current decays much slower (up to about 30 minutes).
- Insulation conduction current.

Absorption and conduction currents depend up on insulation moisture content and its contamination. They also change with a number of defects in the bushings and / or tap changers. Net current consists of the sum of these three components. Ohm's law calculated insulation resistance is used for diagnostics. The absolute value of $IR_{60}$ (IR test) and the resistance ratios measured at 15, 30, 60, and 600 seconds are used to assess the insulation state, shown in Table 1.

**For more than 100 years, insulation resistance measurement using Megger test is the simplest and the most reasonable method for evaluation of a transformer and other electrical equipment insulation condition**

Table 1. Criteria for assessing the status of insulation of transformers

| Ratio | Name | Abbreviation | Practice |
|---|---|---|---|
| $IR_{60}$ / $IR_{15}$ | Absorption index | AI, AI test | GOST |
| $IR_{60}$ / $IR_{30}$ | Dielectric absorption ratio | DAR | Testing of the electrical machines |
| $IR_{600}$ / $IR_{60}$ | Polarisation index | PI, PI test | IEEE [2] |

**In the late 1940s and early 1950s, Soviet specialists in the transformer field were discussing the suitable criterion for evaluation of the transformer insulation moisture content which led to the definition of the AI**

## 2. From the history of the application of AI

In the late 1940s and early 1950s, Soviet specialists in the transformer field (A. K. Ashryatov, S. A. Gorodetsky, A. I. Sapozhniyov, N. P. Fufurin, and others) held a comprehensive discussion regarding which criterion is more suitable and sufficient for evaluation of the transformer insulation moisture content during installation and operation. The following methods were considered: the capacitance ratio at 2 and 50 Hz ($C_2$ / $C_{50}$), t he dielectric loss tangent (tan delta), AI, $IR_{60}$, the capacitance ratio in the hot and cold state. As a result, the criteria $C_2$ / $C_{50}$ and AI were selected and included in the manuals. Gorodetsky [3] has proposed the permissible AI value of at least 1.3 at a temperature of 20 °C. Criteria $C_2$ / $C_{50}$ and AI ≥ 1.3 over the next two decades have been successfully applied in practice. Then $C_2$ / $C_{50}$ went into oblivion.

The requirement to measure AI remained unchanged, but the fate and fortunes of AI have proved to be challenging. The standard AI = 1.3 was later transferred to SEV 5266 standard (developed by the former German Democratic Republic) [4]. However, in the mid 1960s, due to a supply of 220 – 500 kV transformers to India and Egypt, ZTZ introduced more advanced drying methods and initiated the transformer filling with new high-quality oils (T-750, T-1150, obtained by hydrocracking GK [5, 6]). At the same time, it turned out that on frequent occasions, AI value became less than 1.3 just upon dispatch from the factory. In particular, this led to formal problems during the commissioning of 500 kV transformers at Aswan Hydroelectric Power Plant. To overcome the problem, ZTZ removed the standard value of AI ≥ 1.3 from installation instruction of the power transformers [7], so that AI was devaluated.

At the same time, the experience of servicing Soviet transformers in different countries and the personal experience of the author showed that this was a wrong decision, and it is very useful to know the acceptable AI values for practice.

In Russia and Ukraine, AI standard value = 1.3 is still maintained at 10 – 30 °C temperature as the criterion for the permissible start-up of the transformers up to 35 kV inclusive, rated for power less than 10 MVA [8]. This requirement is outdated (see Annex 1), and it needs to be revised.

Since 1995, the new method for evaluation of transformer insulation moisture content by means of measurement of insulation capacitance and tan δ depending on the frequency ranged from a few millihertz (0.1 – 10 mHz) up to 1 kHz (dielectric frequency response test (DFRT) [9]), has been introduced. Maintenance practice of the transformers does not always need such a complex method. As applied to old-aged transformers, DFRT method cannot replace AI method, also due to the fact that, as a rule, there is no basis for comparison of DFR, because such measurements have not been previously performed. DFRT is still not widespread in the distribution networks, especially because another new and relatively expensive device is required to carry out the measurements, and interpretation of DFRT results is much more complicated compared to AI.

**It is recommended to measure AI immediately after the transformer shut down, while its temperature does not differ by more than 5 °C from the previous measurements**

## 3. Preparation and measurement of AI

It is recommended to measure AI immediately after the transformer shutdown (but after the measurement of no-load losses at the reduced voltage for the transformer manufactured in USSR, or after the excitation current test for the transformer manufactured by others, with recording the transformer temperature). If transformer temperature during measurements differs by more than 5 °C from the previous measurements (usually a year back), repeat the measurements on the transformer during its cooling at temperature differing by no more than 5 °C.

All bushings, including neutral, should be disconnected from the network, including disconnection of the copper bus bars from the HV neutral and / or LV bushings.

### Example of the impact of support insulation of a piece of copper busbar connected to HV neutral

Unit transformer 01BAT10 (410 MVA 420 / 20 kV manufactured by AREVA, Turkey, 2007) in the Thermal Power Plant (TPP) AES Galabovo [10], Bulgaria, November 2012, transformer temperature was 17 °C. Initially, AI in the scheme HV - (LV + GND) was measured as 1.09. After the disconnection of a piece of the busbar, AI = 1.38.

Each winding should be short-circuited directly on the bushings' studs. The jumpers for short-circuiting should be made using short bare conductors and maximally distanced from the tank and other grounded transformer elements.

The weather conditions should be without precipitation and fog, and the bushings should be dry and clean.

Measurements carried out on the transformers rated for 110 kV, and higher may be affected by electromagnetic and electrostatic interferences. It is important to be sure in the safety of the transformer tank grounding and to ensure the grounding of adjacent de-energised substation equipment to prevent the floating potential.

Measurements should be carried out with unconditional observance of the instructions for devices and safety precautions. In order to remove the residual charge of the transformer windings (caused by the disconnection of the transformer or by previous tests) before starting the measurement, the winding should be short-circuited to ground for 2 - 5 minutes, and after measurement, it is to be grounded for a time period not less than the measurement interval.

One example of a principal scheme of the measurement circuit AI test is shown in Fig. 1. In the article, the author considers the AI values in these schemes precisely, since the insulating distance between the windings (HV - LV) contains the most solid insulation, and the distance (HV - tank) is mainly filled with oil. Therefore, these distances are the most informative for assessing the condition of a transformer. Other schemes are shown in Annex 2.

The minimum scope of the measurements, their sequence, measurement circuits, and test voltage should be similar to previous measurements. Based on the measurement results, it is proposed to create a graph of the dependence of AI on time, starting from factory tests, in order to better understand the trends in insulation, as shown in Fig. 2.

If there is a significant decrease in AI (read more about in the second part of the article), it is necessary to perform more measurements and to change the value of the test voltage (0.5, 1, 2.5, 5 kV, but not exceeding the rated voltage of the winding). New devices allow testing at 10 kV. For good insulation, AI will not be affected by the voltage test. And for poor insulation, this dependence will serve as additional information about the condition of the transformer. It is important to consider the effect of temperature on the measurement results (that will be shown in Chapter 6).

AI measurements are carried out periodically as part of the transformer diagnostics, in case of unsatisfactory results of oil analysis and / or dissolved gas analysis (DGA), and after those events that could cause the transformer insulation deterioration. By comparing the test data obtained after the failure with the results of the previous tests, it is possible to assume the nature of the transformer failure.

**If there is a significant decrease in AI, it is necessary to perform more measurements and to change the value of the test voltage**

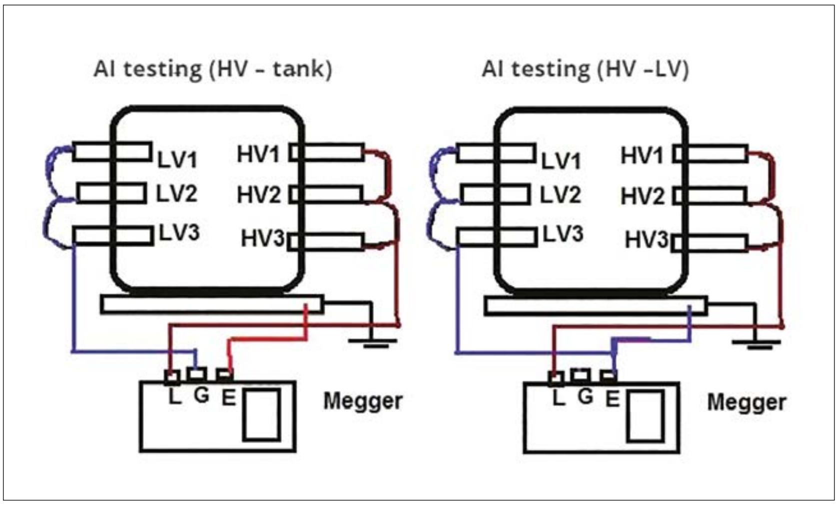


Figure 1. Connection diagram for AI in a double winding transformer (HV - tank and HV – LV)

## 4. Moisture content, contamination, and AI

The transformer insulation is a combination of transformer oil and oil-impregnated solid cellulose insulation (insulation paper, cylinders between windings and other barriers, angle rings, clamping plate and spacer blocks). The moisture content of dry solid insulation upon dispatch from the transformer factory manufactured in accordance with GOST, does not exceed 0.2 - 0.5 % [9]. Typical AI values for dry and clean insulation of new transformer are specified in Annex 1.

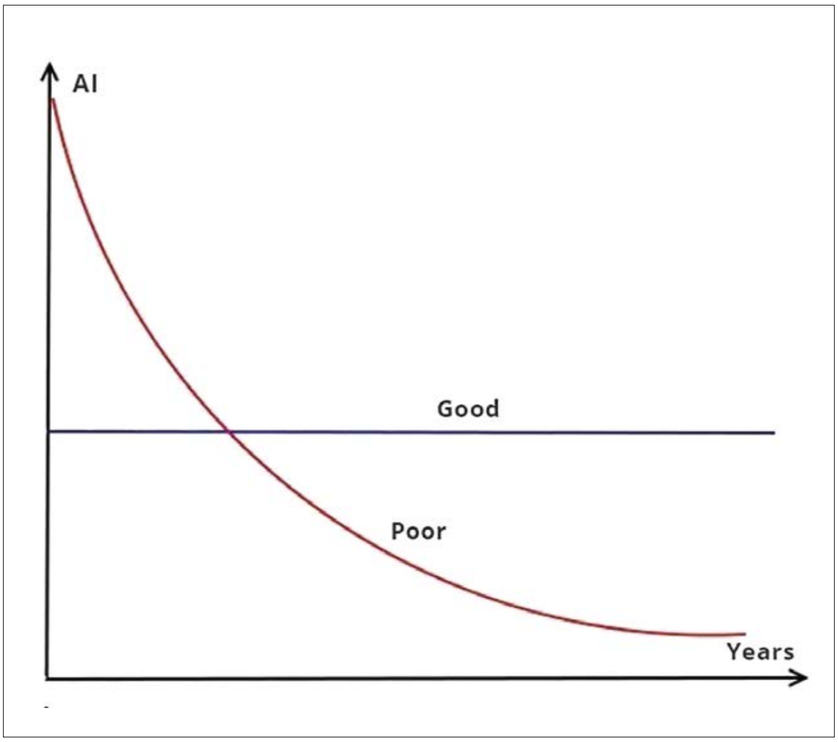


Figure 2. Change in AI over time (schematically)

**By comparing the test data obtained after the failure with the results of the previous tests, it is possible to assume the nature of the transformer failure**

Within long-term operation, the insulation condition is deteriorated inevitably. The transformer solid insulation is moistened up to 1.5–4.5 % [11] due to breathing and water absorption from wet air entering via air breather, or water ingress due to improper tank sealing. Water in the tank is also generated due to paper ageing. Solid cellulose insulation and wooden structural elements accumulate the bulk of the water. Oil is only a means of water transfer, in the case of oil ageing, its ability to dissolve water increases [12]. The insulation of old-aged transformers is also deteriorating due to inevitable contamination by polar oil ageing products and mechanical impurities, including the conductive ones. Therefore, for the LV - HV circuit, lower AI values are often observed compared to AI in the HV - LV circuit. The example is shown in Fig. 3. This can be explained by the fact that the total surface of the lower part of the LV bushings and wires from the bushings to the winding is several times larger than the similar surface on the HV side. More contaminants accumulate on a larger surface, and when a voltage test is applied to LV bushings, the absorption processes are stronger, and the measured value off AI is correspondingly less than when voltage is applied to the HV. This hypothesis needs additional verification. In practice, for comparison, it is required to use the scheme (HV - LV or LV - HV) that was in the previous test.

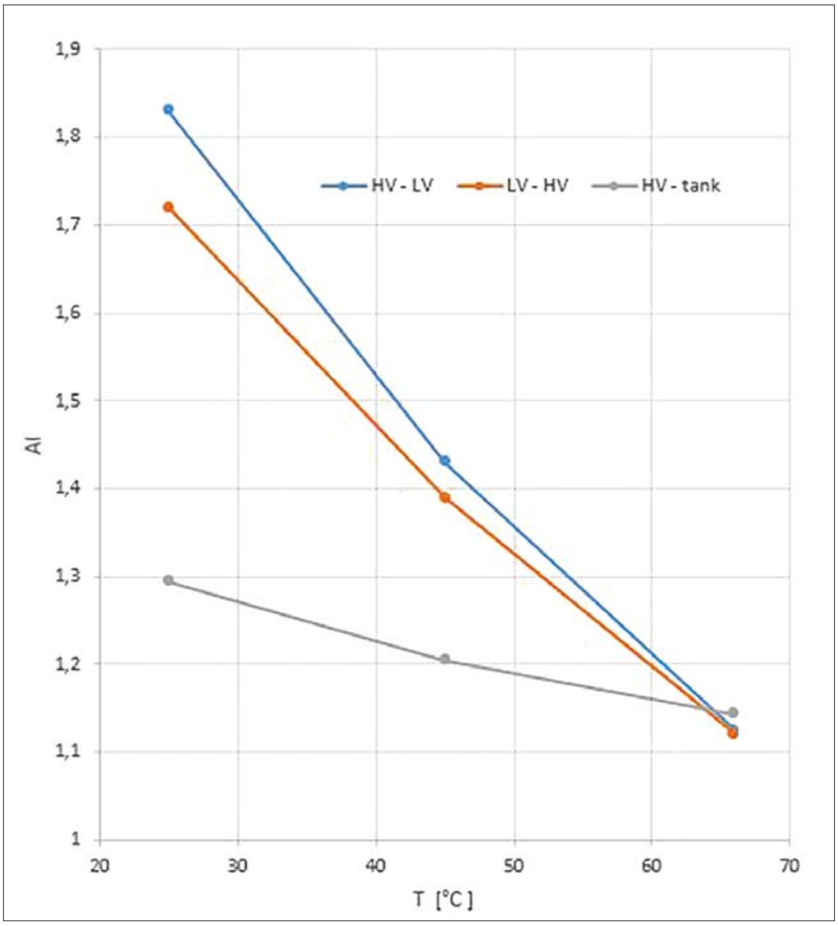


Figure 3. AI (HV - tank and HV – LV) difference of AI in the circuits HV – LV and LV – HV and temperature-dependence of AI. Autotransformer AT201 (200 MVA 220 / 121 / 36 kV) Dobrudja Substation, Bulgaria, manufactured by ZTZ in 1974. AT diagnostics was carried out in September 1996. Insulation resistance was measured at 2.5 kV. Before the shutdown of AT, the moisture content in oil was 36 ppm at 40 % load. The moisture content of solid insulation was 2.5 % (calculated)

Since 1992, under the supervision of the author, more than half of the 110 – 750 kV power transformers in Bulgaria have been surveyed. On 156 transformers equipped with silica gel air breather, a complete diagnosis was performed (under load and after decommissioning). It emerged that 80 % of the transformers that have operated for 20 years had the moistened solid insulation (2 % or more). 70 % of the transformers there had contaminated oil (often number 5 - dark colour) and required oil regeneration or replacement. Half of the transformers equipped with an on-load tap changer (OLTC) had moistened the insulating parts of the diverter switches. The rubber gaskets in major transformers lost their elasticity and did not provide oil sealing of the transformer tank, including the gaskets at the upper part of the bushings, in dehydrating filter breathers in the conservators. Ingress of water into the transformer was through the gaskets damaged. There were transformers with the poor condition of air breathers and dehydrating filter breathers; in some cases, silica gel was not processed before its filling into the air breathers and the dehydrating filter breathers [13, 14].

The moisture content of the insulation of an unsealed transformer depends on the mode of its load and the transformer service period. According to old Soviet rules, it was required to carry out the first overhaul of a power transformer with opening the active part, with the replacement of rubber seals and insulation drying to remove moisture at the first 6 years after the transformer installation. Then the interval to repair was increased in a consistent manner up to 8, 10 and 12 years [15]. This was justified by operating experience, each time confirming the transformer reliability. The next following major repairs (overhauls) are carried out when necessitated, depending on the transformer condition which is evaluated by the results of the diagnostics. The methods used in the past for drying transformers in the field are described in [7, 11]. Then varieties of the oil spray method were developed, one of which was used by the author in Bulgaria [16].

The author's data is the confirmation of the correctness of the previously established time period until the first overhaul. As shown in Fig. 4, even for almost 100 % round-the-clock and year-round loaded transformers, the value of AI is gradually decreased with deceleration during the periods between the repairs. In the example considered, in 1980, AI values at measurements of HV - (LV + GND) and LV - (HV + GND) were 1.33 and 1.25 respectively, and over 7 years they decreased to 1.13 and 1.12, respectively. Between the end of 1982 and the end of 1988, no AI measurements were made. In 1988, the overhaul was carried out with the transformer drying, after which AI value increased to 1.38 and 1.48.

During operation, AI value is significantly decreased for inter-winding distances due to the accumulation of moisture in the solid insulation. Table 2 contains AI measurement results at 2.5 kV for the transformer with doubled concentric HV winding (LV wining is located between HV winding concentres). The transformer was commissioned in 1965. It is shown in Table 2 that within 22 years of operation, the significant decrease of AI value is in LV-HV distance (from 2.27 up to 1.11), despite the two performed repairs of the transformer with insulation drying within this period of time.

**The transformer solid insulation can be moistened up to 1.5 – 4.5 % due to breathing and water absorption from wet air entering via air breather, or water ingress due to improper tank sealing**

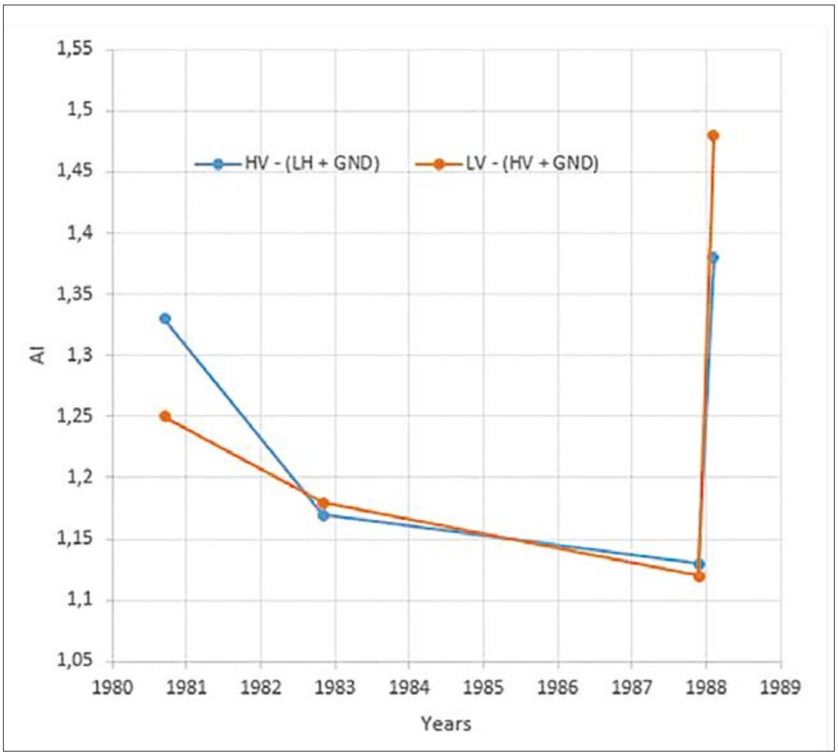


Figure 4. Variation of insulation AI of unit transformer 2GT (60 MVA 121 / 10.5 kV) TPP Neyveli, India, within 1980 – 1988, manufactured by MEZ in 1962

Table 2. Unit transformer T-8 (200 MVA 342 / 15.75 kV) Nevinnomysskaya TPP, Russia, manufactured by ZTZ in 1964

| Year | 1972 | | | 1994 | | |
|---|---|---|---|---|---|---|
| Transformer temperature | 35 °C | | | 45 °C | | |
| Test | $R_{15}$, MΩ | $R_{60}$, MΩ | AI | $R_{15}$, MΩ | $R_{60}$, MΩ | AI |
| HV - (LV + GND) | 460 | 900 | 1,96 | 220 | 250 | 1,14 |
| LV - (HV + GND) | 550 | 950 | 1,73 | 260 | 290 | 1,12 |
| (HV + LV) - GND | 720 | 980 | 1,36 | 350 | 400 | 1,14 |
| LV - tank | 1700 | 2080 | 1,22 | 1100 | 1300 | 1,18 |
| LV - HV | 770 | 1750 | 2,27 | 350 | 390 | 1,11 |
| HV - tank | 1150 | 1850 | 1,61 | 540 | 610 | 1,13 |

## During operation, AI value is significantly decreased for inter-winding distances due to the accumulation of moisture in the solid insulation

Another example of AI value at 2.5 kV decrease within the operating period is shown in Table 3.

It contains the comparison of AI values measured at the transformer dispatch from the factory and after 30 years of operation of another unit transformer of the same state district power plant. In both cases, the measurements were carried out at 2.5 kV. Within 30 years, AI value at HV - tank distance has been almost the same because AI in this distance is determined by oil, which was replaced during the transformer repair in 1989. But AI value of HV - LV distance has sharply decreased over 30 years (from 3.51 to 1.22), which is to be explained by moistening of solid insulation, and this indicates the low efficiency of the field repairs.

As follows from Tables 2 and 3, after approximately 30 years of operation of both transformers, AI value in the distance LV - HV of the transformer T-7, was higher (AI = 1.22) than the value of the transformer T-8 (AI = 1.11). This is due to the presence of solid insulation in this distance of the transformer T-7 (rated for 110 kV), and therefore, the amount of moisture is much less than in T-8 (330 kV): in T-7 there are only 2 cylindrical barriers against 6 cylinders in the T-8.

In case of inadequate maintenance of air breathers (untimely replacement of silica gel when its colour changes, insufficient oil level) and of dehydrating filter breathers, moisture content of insulation is accelerated. If AI tests are carried out rarely and irregularly (it is related to distribution transformers), then evaluation of the hazard rate of insulation moisturising will be constrained.

In the case of sealed transformers, the insulation moisturising from the atmosphere is excluded, and during normal operation, moisture is generated only due to paper ageing. The moisture content, in that case, should not reach 0.5-0.75 %, even after many years of operation [11]. In such transformers, the AI test will be useful in case inappropriate sealing is suspected.

### 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 10 to 630 MVA, filled with new oil type GK or Nynas have been analysed. 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 are 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 one third of the transformers have 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 evidently for the distance HV-tank. Once again this 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 transformer:
1. LV - tank
2. HV – (LV + GND)
3. LV – (HV + GND)
4. (HV + LV) – GND

Three-winding transformer:
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

Table 3. Unit transformer T-7 (200 MVA121/15.75 kV) Nevinnomysskaya TPP, Russia. T manufactured by ZTZ in 1965

| Year | 1965 | 1994 |
|---|---|---|
| Transformer temperature | 46 °C | 34 °C |
| Test site | Plant | TPP |
| LV - HV | 3,51 | 1,22 |
| HV - tank | 1,33 | 1,35 |

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**In case of inadequate maintenance of air breathers and of dehydrating filter breathers, moisture content of insulation is accelerated**

## 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.