Power oil transformers - Gas generation defects

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Abstract: - The article analyzes scientific research in the field of power transformer gas generation defects detecting by methods of Gas Dissolved Analysis (DGA) of transformer oil (chromatographic analysis) and measurement of short-circuit impedance differences. Power transformer defects that cause gas generation and are identified by the results of DGA should be divided conditionally into several groups: defects with circulating currents in windings and short-circuited contours, induced by scattering flux created by wind-ups, defects with an increase in the transient resistances of the grounding nodes of the structural elements, defects with partial discharges of oil gaps and on the surface of solid insulation, defects with a violation of the contact connections of the conductive circuits, defects with overheating and aging of solid insulation and transformer oil. The difference in short-circuit impedance, measured from the sides of the higher and lower voltages, brought to one side of the transformer, is directly dependent on the magnitude of the circulating currents created by the scattering fields, expressed as a percentage, that is, the percentage of the number of uncompensated turns of the windings with current.

Key-Words: – Power transformer, gas generation, Gas Dissolved Analysis (DGA), chromatographic analysis, short-circuit impedance, scattering flux.
Received: August 8, 2022. Revised: July 21, 2023. Accepted: August 25, 2023. Published: October 2, 2023.

1 Introduction

There are various anomalous phenomena, such as gas generation, the difference of phase currents in windings connected to the triangle, the inconsistency of the position of the tap-changer (voltage regulator) for a level of nominal voltage, partial discharges, overheating of individual parts of the tank connector, etc. during the operation of power oil transformers and autotransformers.

Possible causes of such anomalous phenomena may be design and operational features, as well as defects that have arisen during operation, under the influence of which is the decomposition of transformer oil and paper oil insulation with the release of hydrocarbon gases, oxide, and carbon dioxide.

2 Power transformer defects detecting method

The most common and reliable method of detecting a power transformer defect is Gas Dissolved Analysis (DGA) of transformer oil (chromatographic analysis), while exceeding or increasing the concentration of individual gases in most cases does not allow for localizing and establishing the cause of the defect, as well as to establish the impact of this defect on the operational reliability [1-6].

The gas chromatograph "Crystal 5000" is presented in the fig. 1.

Fig. 1. Gas chromatograph "Crystal 5000"

The transformer oil of the GK type for processing refers to naphthenic oils with positive gas resistance. To increase stability against oxidation, the transformer oil is subjected to intensive processing (hydro-cleaning) of hydrogen at high pressure and high temperature with the use of catalysts. All chemical reactions in the process of hydro-cleaning are in a state of equilibrium and it is possible that they can theoretically go in the opposite direction under conditions other than those under which the process of hydro-cleaning took place.

The new equilibrium is established in practice when new transformer oil is commissioned and the environment in which the oil exists changes. Balance can change due to changes in temperature, pressure, vibration, and pollution, causing a slight gas formation. In the absence of any external factors leading to gas generation, gas production in the transformer for 6-8 months, and sometimes more, months, stops. The main gas of this gas generation is hydrogen.

The decomposition of transformer oil and solid insulation with the release of hydrocarbon gases, oxide, and carbon dioxide occurs under the influence of electrical defects (electric arc in oil, partial discharges and arc in the oil barrier isolation, etc.) and thermal defects (heat decomposition of oil and oil barrier insulation, solid insulation overheating, aging of solid insulation and oil, etc.) [7].

3 Power transformer defects

Defects that cause gas generation and are identified by the results of DGA should be divided conditionally into several groups, namely:

Defects of the first group - defects that cause gas generation, are associated with structural and operational features, namely, defects with circulating currents in windings and short-circuited contours, induced by scattering flux created by wind-ups during operation and testing.

Windings with an asymmetrical and uneven distribution of linear load relative to the middle of windings and other windings (input coils from the end of windings, adjustment coils, etc.), asymmetrical location of windings relative to the magnetic window systems, asymmetrical location of shunts relative to the ends of windings, etc. refer to the design features of such transformers.

Uneven load of split windings (more than 20%) of transformers with split windings short-circuit of parallel conductors, multi-height windings, deformation of windings, turn-to-turn short-circuit, i.e. modes and defects leading to the uneven and asymmetrical distribution of loads by the height of the windings are the operational features of transformers.

Electromagnetic scattering is an incomplete electromagnetic connection in a transformer caused by the presence of magnetic flux that is not common to both windings, i.e. closed outside the magnetic system, and called the scattering flux. The degree of incomplete electromagnetic connection has a great impact on many technical parameters, including short circuit parameters.

It is known that the magnetic field (stream) of scattering, in a real transformer can be represented in the form of three fields: a longitudinal field, created by a full number of winding turns with current; a cross-field caused by the final height-width ratio of windings and the second cross field caused by the uneven distribution of linear load by the height of windings.

Defects that cause gas generation are associated with the presence of magnetic scattering flux in the closed circuits of the magnetic scattering space of windings.

The induced voltage from the scattering fields is applied precisely to the insulation gaps of the joints in the presence of butt connectors in the circuits; therefore, a section is formed with a high inhomogeneous electric field, causing discharge phenomena in the oil gap of the joint.

The prolonged exposure (months and years) of this insignificant electric field to the transformer oil in the joint area leads to the gradual accumulation of gases in the oil.

This process can be called partial discharges at the joints of closed loops.

Here, a typical example can be for distribution transformers a violation of the insulation of the tie rods, and yoke pressing beams, when as a result short circuits are formed with butt gaps in the openings of the channels of the yoke beams with studs.

Discharge phenomena can occur between the parallels themselves, which are separate electrodes, between which in the insulation gap (butt connector) an electromagnetic force (EMF) is applied in the case of parallel branches. The relatively small value of this EMF during prolonged (for months) exposure leads to the decomposition of oil and gas formation.

The scattering field of the transformer induces EMF in the wires and circuits located in the field zone, under the influence of which currents flow. These currents are closed inside the wires and between the parallel branches of the windings and short-circuited circuits, including in the magnetic system, and, unlike the load currents, do not go beyond the windings and circuits, and can occur during testing. In turn, the circulating currents in the windings create additional fluxes, which, combined with the main scattering fluxes, increase the magnetic fluxes in the yokes of the magnetic system and the tank, causing them to heat up. And the circulating currents in the butt connectors of short-circuited circuits, including at the joints of the plates of the magnetic system, create discharge phenomena. The maximum magnetic flux in the core of a single-phase transformer is shown in fig. 2.

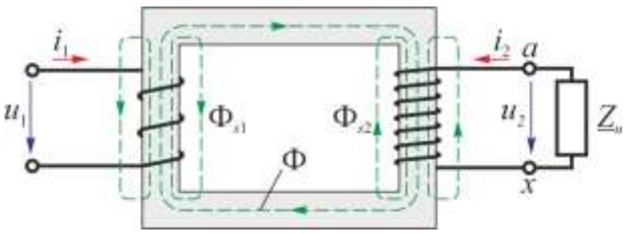

Fig. 2. Maximum magnetic flux in the core of a single-phase transformer.

The results of DGA of oil, and the results of transformer inspection prone to gas generation, confirm the presence of oil decomposition products (soot) at the joints of the plates of the magnetic system and the joints of the short-circuited contours of structural elements caused by electrical discharges and thermal effects on these areas [7].

Thus, the defects of the first group that cause gas generation are accompanied by the release of gases associated with defects of an electrical and thermal nature, and the source of gas generation is the magnetic system and structural elements, as well as windings with short circuits of parallel conductors and turn-to-turn short-circuits.

Defects of the second group - defects that cause gas generation, are associated with an increase in the transient resistances of the grounding nodes of the structural elements, the presence of structural elements under floating potential, and increased potentials in the structural elements and taps of the high-voltage bushings of transformers.

Currents arise in them under the influence of inductive EMF, scattering fields in short-circuited circuits located in the zone of an electromagnetic field.

Circulating currents cause heating and discharge phenomena at the joints of contact connections of grounding elements. In addition, discharge phenomena occur between structural elements under floating potential and grounded structural elements.

Defects with violation of the contact resistance of the grounding elements and the presence of elements under a floating potential are accompanied by gas generation associated with defects of an electrical nature. In this case, the defects of the first group enhance the discharge phenomena in the grounding elements.

Defects of the third group - defects that cause gas generation, are associated with partial discharges of oil gaps and on the surface of solid insulation under the influence of applied voltage, test voltage, lightning, and switching overvoltages, as well as gaps with increased electric field strengths.

Defects of the third group are accompanied by the gas generation associated with defects of an electrical nature. In this case, the defects of the first group enhance the discharge phenomena.

Defects of the fourth group - defects that cause gas generation are associated with a violation of the contact connections of the conductive circuits.

The most common defects with violation of the contact connections of conductive circuits are bolted and soldered joints, i.e. contact connections of bushings, on-load tap-changer, without-load tap-changer, and taps of the high-voltage bushings of transformers.

Defects in conductive circuits are accompanied by the gas generation associated with defects of a thermal nature. In this case, defects of the first, second, and third groups do not affect the defects of the fourth group.

Defects of the fifth group - defects that cause gas generation are associated with overheating and aging of solid insulation and transformer oil.

It is known that thermocatalytic degradation of solid insulation is usually accompanied by degradation (water yield) with an increase in the concentration of carbon dioxide (CO_2) and oxide (CO), as well as their increased ratio and increased moisture content of transformer oil [1, 2, 14, 16].

Defects of aging of solid insulation are accompanied by a decrease in the degree of polymerization, an increase in the moisture content of the oil, and an increase in carbon monoxide and dioxide. Moreover, defects of the first and third groups enhance the aging processes of insulation and transformer oil [8-14].

The analysis of transformer defect groups and their interconnections show that the defects leading to gas generation, in addition to the defect of the conductive circuits, are associated with the condition state of the windings, i.e. with a change and increase in scattering fields.

The short-circuit impedance is one of the parameters influenced by the scattering fluxes. It is also known that with the same geometrical dimensions and the same arrangements of the coils, their inductances and inductive resistances are proportional to the squares of the number of turns, that is, there is a relation between inductive impedances of higher and lower voltage:

$$Z_{s-c.HV} = К_{Т}^{2} \cdot Z_{s-c.LV}, \quad (1)$$

where $Z_{s-c.HV}$ – short-circuit impedance, measured from the side of higher voltage, Ohm; $Z_{s-c.LV}$ - short-circuit impedance measured from the low voltage side, Ohm; KT - the ratio of transformation, the degree of regulation.

Short-circuit impedance, measured from the side of the higher and lower voltages brought to one of the sides of the transformer, are not equal to each other in a real transformer in the presence of any defects. The measurement scheme of the short-circuit impedance Zk of the transformer in HV-LV mode is presented in the following fig. 3

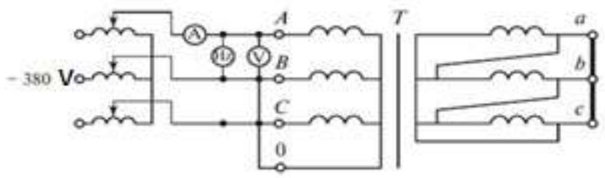

Fig. 3 Measurement scheme of the short-circuit impedance Zk of a transformer in HV-LV mode (HV-LV windings (phase A measurement).

Thus, the difference in short-circuit impedance measured from the sides of the higher and lower voltages arises when the geometric dimensions (deformation, different heights, shorting of parallels, etc.) differ and the arrangement of the coils or the presence of other defects [15].

The difference of short-circuit impedance reduced to the side of the higher voltage is determined from the expression:

$$\Delta Z_{s-c.} = \frac{Z_{s-c.HV} - К_{Т}^{2} \cdot Z_{s-c.LV}}{Z_{s-c.HV}} \cdot 100\% \quad (2)$$

The transformer must be taken out for repair if the value of $Z_{s-c.}$ deviates from the base by 3% or from the calculated by the passport by 5% in the HV-LV mode according to [12, 13, 16, 18].

However, from [15] it is known that the difference in short-circuit impedance, measured from the HV side and the LV side, more than 2.0% indicates a defect in the windings, and less than 2.0% is associated with defects in the contact connections of conductive circuits and ground circuits structural elements, as well as partial discharges under the influence of operating voltage and lightning switching overvoltages [16-22].

The relationship between the causes of gas generation that occurred during operation due to a structural defect (asymmetric and uneven distribution of the linear load relative to the middle of the windings and windings of different heights) is shown in the example of the 4 MVA/35 kV transformer.

4 Example 1.

4 MVA/35 kV transformer is operated in the system of Kolymagaz and it has been in operation for five years, the load was not more than 50%, and there was a strong gas generation (triggering of gas protection to the signal). Composition of gases: hydrogen and a small amount of hydrocarbon gases. During disassembly, on the surfaces of the active part, a gray coating was detected with a thickness of up to 0.5 mm. This deposit (sludge) is probably the product of oil oxidation with a large amount of hydrogen released. No other visible defects, except for different heights and asymmetric distribution of the turns of the windings along their height and increased electric field strengths between the layers of the windings, were found.

Control turns in the form of two coils were wound on top of the regulating windings for detection of presence of asymmetry of the scattering field. The turns were located symmetrically relative to the middle of the windings and connected in parallel. Currents were measured in parallel connected branches of the control turns during the short-circuit experiment. Current in parallel connected turns can occur only in the presence of asymmetry of the transverse scattering field.

The measurement results of short-circuit impedance and circulating current in the control turns are given in table 1.

From the values given in table 1, it follows:

1. The technical characteristics of the transformer correspond to the volume of the standards for testing electrical equipment and the set of operational documentation of the manufacturer.

2. The presence of current in parallel connected branches of the control winding indicates the difference in the EMF in the branches induced by asymmetric transverse scattering fields, i.e. created by the uneven and asymmetric distribution of the load current along the height of the windings.

3. The difference between the short-circuit impedance measured from the sides of the higher and lower voltages given to one of the sides of the transformer is directly dependent on the magnitude of the circulating current, and expressed as a percentage, there is a percentage of the number of uncompensated turns of current windings.

Table 1 - The results of measurements of short-circuit impedance and circulating currents in the control turns of 4 MVA/35 kV transformer.

Position OLTC	Short-circuit mode	Short-circuit impedance $Z_{s-c.HV}$ $Z_{s-c.LV}$, Ohm	Circulating current in control turns, A	Short-circuit resistance difference $(\Delta Z_{s-c.})$,%	Quantity of uncompensated turns with electric current, Aw
1	2	3	4	5	6
1	HV-LV	30,54	5,2	5,87	3250
	LV-HV	2,307	4,8		
5	HV-LV LV-HV	23,91 2,19	3,6 3,15	5,62	3100
9	HV-LV	18,15	2,5	2,3	1200
	LV-HV	2,11	2,25		

In order to express the circulating current, some explanation is needed.

The phase power of the transformer is written as follows:

$$S_{n.ph} = U_{n.1ph} \cdot I_{n.1ph} = \frac{\omega}{\sqrt{2}} B_m S_{cw1} I_{n.1ph} \quad (3)$$

Rated phase voltage of HV winding:

$$U_{nom.1ph} = (\omega/\sqrt{2}) w_1 B_m S_s, \quad (4)$$

where ω -the circular frequency of the network; w_1 - the number of turns of the HV winding; B_m - the amplitude of the magnetic induction in the core in idle mode, as a rule for power transformers B_m = 1.65 T, a constant value;

S_s -the active section of the core. Here, the circular frequency of the network is ω = 2πf, where f - the network frequency.

The active section of a round core:

$$Ss = ks * kgeom\,(\pi / 4)\,D^2 \quad (5),$$

where D - is the diameter of the circumscribed circle of the core of the magnetic circuit,

ks -the fill factor of the packages of the magnetic circuit steel, approximately ks = 0.965,

kgeom - geometric coefficient filling the circular cross-section of the core with packages of electrical steel, approximately kgeom = 0.925.

Then

$$Unom.1f = (\omega / \sqrt{2}) \cdot w1 \cdot Bm \cdot ks \cdot kgeom \cdot (\pi / 4) \cdot D^2 = Bm\, w1 D^2, \quad (6)$$

Bm = const.

Circulating current can be expressed as follows:

$$Icir. = \left(\frac{\Delta Zs-c.\%}{100}\%\right) Inom.1f = {}^2 \quad (7)$$
$$= (\Delta Zsc./100\%) Snom.\, Bm\, w1D$$

where

Bm - the amplitude of the magnetic induction in the core in idle mode, as a rule for power transformers Bm = 1.65 T, the value is constant.

In this formula, the dimension $[kVA / m^2]$ is obtained due to the adoption of the condition Bm = const for most power transformers.

$Icir.$ - the total circulating current in short-circuited circuits, including in the magnetic system, A;

D - the diameter of the core of the magnetic system, m;

w1 - the number of turns of the HV winding;

$\Delta Zs - c.$- difference of short-circuit impedance measured from the sides of the higher and lower voltages, reduced to one of the sides of the transformer,%

$Snom.$ - rated power of the transformer, kVA.

4. The minimum value of the difference in short-circuit impedance at the minimum tap of the on-load tap-changer, and the maximum value of the difference of short-circuit impedance at the maximum tap of the on-load tap-changer indicate an asymmetric and uneven arrangement of the turns of the control winding relative to the lower and higher voltage windings.

5. Uncompensated turns of windings with current (3250 Aw at max position, 3100 Aw at nom. position, 1200 Aw at min position) are compensated by circulating currents in short-circuits, including in the magnetic system, causing electrical discharges at

the joints of the plates and their heating due to the asymmetric arrangement of the regulating turns of the winding, which is the cause of gas generation with the release of hydrogen H_2 and a small amount of hydrocarbon gases.

Conclusions

1. A method for identifying and localizing a defect by measuring short-circuit impedance on the sides of the higher and lower voltages allows to identification of defects that affect the gas generation that occurred during design, manufacture, operation, and repair, as well as determine the effect of the defect on operational reliability.

2. The difference in short-circuit impedance, measured from the sides of the higher and lower voltages, brought to one side of the transformer, is directly dependent on the magnitude of the circulating currents created by the scattering fields, expressed as a percentage, that is, the percentage of the number of uncompensated turns (circulating current) of the windings with current.

3. Uncompensated turns of windings with a current of more than 2.0% and and uneven load of the LV1 and LV2 windings of transformers with split windings of more than 20% lead to local heating of structural elements, including the yoke of the magnetic system and the occurrence of discharges in the contact joints of short-circuited circuits, including at the joints of the plates of the magnetic system.

4. In the presence of gas generation and the absence of a defect in the windings ($\Delta Zk < 2.0\%$), defects in the transformer are associated with a violation of the contact connections of the conductive circuits and ground circuits, the occurrence of repeated grounding with the formation of short-circuited circuits and the presence of structural elements under floating potential, as well as partial discharges under the influence of applied voltage, lightning and switching overvoltages.

5. In accordance with the recommendations of IEC-6099 and RD 153.340-46.302-00 for transformers with split windings and transformers for which $\Delta Z_{s-c.} > \pm 2.0\%$, and whose technical characteristics satisfy the volume of the standards for testing electrical equipment and passport values of the manufacturer, at an increased concentration for individual gases, higher boundary concentrations of gases dissolved in oil should be established, both for individual gases and for the volume of gas content.

6. Some future research directions are the modeling of processes in power transformers when defects associated with gas formation occur.

7. The use of artificial intelligence and neural networks will make it possible, based on this method and groups of defects that cause gas formation and identified by the results of DGA, to create an expert diagnostic system with elements of artificial intelligence for diagnosing a defect or damage and localizing the location of the defect.

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Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

The authors are greatly acknowledged for supporting this study to Mr. Avtaev P.N. and his research of method for identifying a defect in a power transformer. Cooperation of Universities and Innovation Development, Doctoral School project “Complex diagnostic modeling of technical parameters of power transformer-reactor electrical equipment condition”, 2009, has made publishing of this article possible

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.