Chapter 2
Standardized Technologies of Condition Monitoring for High Voltage

For monitoring the condition of transformer active parts, there are two main requirements that stand out: detection of defects at an early stage and diagnostics with voltage in operation and transformer bundling intact ("ON-LINE" mode). The monitoring of defects at an early stage makes it possible to largely extend the resource and service life of a transformer and to avoid unforeseen accidents that may cause severe technical catastrophes (fires, explosions) and economic losses (shortage of electricity, power outages, financial losses in fines). To meet such demands, advanced power systems show a growing tendency of moving away from regulated periodic technical examinations of transformers to their monitoring, with disconnection made to address the condition of transformer elements, in order to carry out a complex diagnostic test using methods that cannot be applied to a transformer in operation.

Technologies (methods) for monitoring the condition of a transformer can be divided systematically into the following two largely different groups: (1) non-electrical and (2) electrical.

Non-electrical methods include:

- physical and chemical control,
- vibration control,
- acoustic control (used mainly for PD registration, it will be discussed in Sect. 2.2.1).

Electrical methods include:

- PD registration,
- measurement of idling losses,
- measurement of the transformation ratio,
- monitoring the insulation resistance of transformer windings,
- measurement of the ohmic resistance of windings,
- control of changes in SC resistance (inductance),
- registration of responses in pulse probing of transformer windings.

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2.1 Non-electrical Control Methods

2.1.1 Physicochemical Control Methods

Physicochemical processes developing in insulation during the operation of oil-filled transformers can be examined by indicators used to estimate transformer conditions [1].

The acid number is the amount of caustic potassium (ACP), measured in milligrams, that is required to neutralize free acids in 1 g of oil. An increase in the acid number indicates the oxidation of the oil, which may cause corrosion of structure elements, emergence of soaps with metal ions, and development of colloidal-dispersed processes leading to a decrease in the electrical strength of the oil. Acids, due to their polarity, can also help increase the water absorption of paper insulation.

The content of water-soluble acids and alkalis that can form during oil manufacturing or as a result of oil oxidation in the course of operation. These ingredients are quite corrosive and contribute to the development of corrosion and the aging of paper insulation.

The moisture content, as an indicator of solid insulation and oil conditions, which is periodically monitored during the operation of transformers. Atmospheric moisture penetrates into the oil or emerges in it due to the following reasons: (1) absence or malfunction of dryers in transformers with free breathing, (2) suction of moist air or rain water into the oil in transformers with a forced cooling system when the latter is leaking, (3) suction of humid air through other leaks, (4) formation of moisture as a result of aging processes in insulation itself.

The gas content of the oil is monitored in operating transformers with a film protection of the oil from oxidation in order to estimate transformer tightness. An increase in the gas content (including the air) promotes more intensive oil oxidation and a decrease in the dielectric strength of insulation in the active part of a transformer.

The above physical and chemical indicators have been used for many years in traditional methods for diagnostics of power transformer conditions, elaborated in the vast literature available to English-speaking readers [2–9]. Therefore, such indicators are not considered in this monograph.

2.1.1.1 Chromatographic Analysis of Dissolved Gases

Chromatographic analysis of dissolved gases is the most common type of monitoring, used in almost every country. All major electrical companies and transformer manufacturing enterprises widely use the analysis of gases dissolved in oil, combined with diverse systems for evaluating and identifying the type of transformer defects.

This method (abbreviated as CADG) is attractive by its high sensitivity to electrical discharges in insulation (PD, dendrites, creeping discharges) and to local overheating, responsible for decomposition of paper insulation and oil. Special attention is paid to the content of furan derivatives, which may be indicative to the destruction of paper insulation. Thermolysis, oxidation and hydrolysis of insulation, causing partial destruction of cellulose macromolecules, lead to the emergence of furan series components released into transformer oil.

Regulatory documentation used since the 1980–1990s in all countries with a developed electric power industry provides for the CADG method to estimate the paper insulation condition for power transformers in operation. Since that time, a fairly large experience in using the method has been acquired in relation to power transformers with a voltage of 110–750 kV. This experience makes it possible to select a number of indicators that have a relatively high diagnostic value, and to determine the type and nature of defects identified for making decisions on further operation of a transformer.

The CADG method can be used to identify two groups of defects in power transformers:

- overheating of current-carrying connections and frame structure elements;
- electrical discharges in oil.

The concentration of the following seven gases is then determined: hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), ethylene (C_2H_4), ethane (C_2H_6), carbon monoxide (CO) and carbon dioxide (CO_2).

Defects in power transformers are identified using a division of gases into basic (key) and accompanying (characteristic) gases.

In the case of overheating in current-carrying connections and transformer frame elements, the basic gases are C_2H_4 (with oil-paper insulation and oil being heated above 500 °C) and C_2H_2 (during an arc discharge). The accompanying gases in both cases are H_2, CH_4 and C_2H_6.

In the case of partial discharges in oil, the main gas is H_2, while the accompanying gases with a low content are CH_4 and C_2H_2.

In spark and arc discharges, the basic gases are H_2 or C_2H_2, while the accompanying gases with any content are CH_4 and C_2H_4.

In the case of solid insulation overheating, the main gas is CO_2. It should also be noted that a concomitant indicator of destruction for cellulose insulation in a transformer is an increase in the content of oxide and carbon dioxide dissolved in transformer oil. At the same time, in accordance with the recommendations of The International Council on Large Electric Systems (CIGRE), the presence of a total CO and CO_2 concentration of more than 1% may indicate the degradation of cellulose insulation [10].

The basic gas is determined by relative concentrations of hydrogen and hydrocarbons, taking into account the corresponding boundary concentrations according to the formula

$$a_i = A_i \big/ A_{rpi} \tag{2.1}$$

where a_i is the relative concentration of a selected gas; A_i is the measured value of the selected gas concentration, % vol; A_{rpi} is the boundary concentration of the selected gas in volume percent (% vol).

According to calculated relative concentrations, the maximum value of a_i corresponds to the basic gas, except for CO_2, being a basic gas if $A_{CO2} >$ % (vol). In this case,

$a_i > 1$, characteristic gas with a high content;
$0.1 < a_i < 1$, characteristic gas with a low content;
$a_i < 0.1$, uncharacteristic gas.

It should be pointed out that in analyzing the composition and concentration of gases dissolved in oil, as well as in diagnosing the operational condition of power transformers, it is necessary to take into account the factors that cause transformers to experience alterations.

The operational factors causing an increase in the concentration of gases dissolved in transformer oil include: residual gas concentrations from a previous defect eliminated during repair (the oil has not been degassed); increasing the load of a transformer; topping up with used oil containing dissolved gases; performing welding work on the tank; overflow of gases from the expander tank of an OLVR contactor to the transformer tank. The operational factors causing a decrease in the concentration of gases dissolved in transformer oil include: a decrease in the load of a transformer; oil degassing; topping up with degassed oil; replacement of silica gel.

To diagnose defects developing in power transformers, the following main criteria are used:

- criterion of boundary concentrations;
- criterion of gas growth rate;
- criterion of pair ratios for characteristic gases.

According to regulatory documentation, the values of parameters exceeding some predetermined limits (limit values) should be regarded as indicators of defects that may lead to equipment failure. In this regard, the CADG method is different from the above ideology, since normative boundary gas concentrations are those whose occurrence indicates a mere chance for defects to develop in a transformer [11]. Such transformers are taken under control with increased oil samplings and CADG procedures.

The criterion of boundary concentrations permits selecting transformers with possible defects in development from the total number of units in a transformer stock, while the hazard degree for a defect to develop is determined by the relative growth rate of gas (gases). The amount of accumulated experience shows that once the relative growth rate of gas (gases) exceeds 10% a month, this indicates the presence of a rapidly developing transformer defect.

The nature of defects in development, according to CADG results, is determined by a criterion of concentration ratios for various gas pairs. It is customary to distinguish between thermal and electrical defects. Defects of thermal nature include the occurrence of short-circuited circuits, increased heating of insulation and contacts of on-load voltage regulators (OLVR) and those of control (switching) without excitation (SWE), taps, pins, and other frame and tank metal structures of a transformer. Defects of electrical nature include discharges in oil of various intensities. Naturally, the development of transformer failures may be of mixed character. Analysis of methods available for estimating the nature of defects in development (thermal or electrical ones), based on the results of CADG, shows significant differences in both types and gas pair ratios used. These ratios have been established in a number of techniques: Dörnenburg's method, Müller's method, CEGB/Rogers Ratios, Schliesinger's method, normogram method, Duval's method, IEC 60599.

Methods of interpreting CADG results for transformers used by companies in different countries are noticeably different. Thus, ABB has adopted the Dörnenburg's method using three basic gas ratios, according to IEC, with a set of four types of defects (thermal, partial discharges of low and high energy, powerful discharges) given a simple graphic interpretation. Limits of gas concentration have been recommended for transformers without defects, regardless of the time of their operation.

Spain has adopted the ASINEL system applying seven digital codes assigned to six gas ratios and hydrogen concentrations, as well as to a sum of the C1 and C2 hydrocarbons. Three of the codes correspond to IEC 60599 Codes and have the same meanings; one of the gas ratios corresponds to the Rogers Code, and another to CO2/CO, adopted for estimating the degradation of paper insulation. The ratio C2H2/H2 is used to estimate the location of a failure: once it is higher than 2, there is an OLVR defect, and once lower, the defect is located in the main tank of a transformer.

In Canada, the diagnosis is made using the Duval triangle based on relative concentrations of the H2, C2H2, C2H4, C2H6 gases for six main types of defects. The criteria for gas concentrations under normal, acceptable and hazardous conditions are significantly varied for different gases and, in particular, for different values of voltage and service life of transformers. To obtain a confident diagnosis, CADG data are entered into an expert system for estimating the condition of a transformer.

A detailed analysis of CADG efficiency for transformers has been made by the Canadian IREQ Institute. It is based on 25,000 samplings taken by the energy company Hydro Quebec [12].

The system by the LABELEC Laboratory (Portugal) is based on the IEC 599 gas ratios, as well as on the CO2/CO and C2H2/H2 ratios; however, it provides for a first-priority assessment of absolute values for gas concentrations. If the volume of at least one of the gases goes beyond the limit value, then five gas ratios are calculated. Additionally, the Schliesinger method is used to confirm the presence of more than one type of simultaneous defects.

RWE Energie (Germany) has adopted a system using five gas ratios and four limit concentrations. Depending on the value of a ratio, the severity of a defect is identified and compared with the concentration of gases. Significant basic gas ratios and concentrations are regarded as indicators of a significant stage of insulation degradation. The system distinguishes between five types of defects. A similar system (by KEMA Transformer) is adopted in the Netherlands.

Belgium has adopted a system based on the Laborelec Code Table. The codes represent concentrations of the H2, C2H2, CO gases and the sums of C1 and C2 hydrocarbons. In addition, the CH4/H2 ratio is taken into account. The system includes nine ways of identifying defects being distinct in severity. Depending on concentrations and gas ratios, 27 different types of diagnosis are provided, indicated by codes. The normal condition of a transformer corresponds to a hydrogen concentration of up to 200×10^{-6} rel. units, with the sum of C1 and C2 hydrocarbons being $300 \cdot 10^{-6}$ rel. units, and CO being 800×10^{-6} rel. units.

France has adopted the system by the LCIE Laboratory, based on comparing gas concentrations with a standard, taking into account the voltage, type of design (presence or absence of OLVR), terms and conditions of transformer operation. Once concentrations go beyond the standard values, gas ratios are analyzed to identify the type of defects. The rate of increase in gas concentrations is taken into account as well. The LCIE Laboratory also uses C_3 hydrocarbons to interpret the results of CADG.

The National Grid energy company (Great Britain) traditionally uses the Rogers Ratios method. It is believed that the C2H6/CH4 gas ratio, excluded from the IEC 60599 system, is efficient at identifying an increase in temperature as compared to an operating temperature. The method also takes into account an increase in gas emission over time, and a comparison of gas concentrations with the admissible one. The method continues to improve.

Siemens Trafo Union (Germany) uses concentrations of characteristic gases and their ratios as criteria. The concentration of acetylene, hydrogen and that of a sum of C_1 and C_2 hydrocarbons is analyzed for propylene, whereas the sum of CO and CO_2 is used for propane.

In Poland, gas concentrations and ratios of characteristic gases are also used as criteria taking into account increase rates for gas content in oil.

It is noteworthy that admissible concentrations of gases in oil, determined from practical experience, are assumed to be different for block and grid transformers, being 10^{-6} units, see Table 2.1.

Energopomiar, implementing CADG, annually conducts over 650 oil samplings from large transformers. CADG is also widely implemented by Elta Manufacturing, being the main transformer enterprise in the country [13].

According to the results of CADG [14, 15], it has been found that the IEC 60599 method, recommended for use in [16], offers the highest diagnostic capacity of identifying the nature of defects in development.

The practice of Russian power systems relies on gas chromatography as a basic method for estimating the technical condition of transformer equipment. Criteria are distinguished by the assignment of equipment to frequent control (limit concentration criterion), the type of defects in development (concentration ratio criterion), and the danger of defects (rise rate criterion). To identify thermal defects at early stages of their development, oil analysis is carried out to determine the presence (additional to the seven basic gases) of C_3 and C_4 hydrocarbons. For this analysis, the gas chromatographic complex Tsvet 500-TM is recommended, as well as the complex manufactured by OOO NPF “Elektra”.

Table 2.1 Admissible concentrations of gases in oil for block and grid transformers

Gas	Block transformers	Grid transformers
Hydrogen H_2	260	500
Methane CH_4	250	200
Ethane C_2H_6	160	170
Ethylene C_2H_4	250	260
Acetylene C_2H_2	20	70
Propane C_3H_8	40	30
Propylene C_3H_6	40	40
Carbon monoxide CO	280	260
Carbon dioxide CO_2	3500[a]	4000

[a] Higher concentrations of CO_2 are allowed only when the CO/CO2 ratio does not exceed 0.3

The experience of running CADG on transformers operated by various enterprises shows that it is advisory to take into account different factors when interpreting the results of analysis. Taking into account changes in gas concentration when comparing the results of two samplings conducted at different operation periods makes it possible to identify defects in development and estimate their danger. It should be noted that comparison of absolute gas release values for different transformers necessitates a reduction to one and the same oil volume. In particular, this technique is applied to study the on-load dependence of gas release.

Positive results are ensured by analyzing thermodynamic processes in a transformer prior to its damage: at the location of defect development there is a zone where the temperature is sufficient for releasing the primary decomposition products of complex oil molecules. These products penetrate into the cooling zone, where equilibrium is achieved. The relative concentration of constituent gases can be calculated as a temperature function and then applied to estimate the change.

In many systems, the presence or absence of OLVR is duly taken into account; the sampling of oil is made on a regular basis; the rate of increase in gas concentration is accounted for, and the use of CADG at the initial period of transformer operation is duly distinguished. In determining the limit values of gas concentration, one takes into account the voltage class, the load intensity, and the possibility of gases penetrating from the OLVR tank into the main transformer tank.

To interpret the results of analysis, other criteria are also used, developed using statistical and practical operating data. For instance, such criteria are given by an increase in gas concentration following 100 h of transformer operation (according to Russian and Ukrainian research), and by a difference between grid and block transformers.

The lack of a unified methodology for interpreting the results of CADG in power transformers makes it difficult to compare the condition of transformers operated and controlled by different enterprises. It is difficult to coordinate most of the criteria for

Table 2.2 Normal concentrations of basic gases according to the innovative method CIGRE WG 15.01

Basic gas, 10^{-6} rel. units	Excess concentration	Possible defect
C_2H_2	20	Intense discharges
H_2	100	Partial discharges
C_XH_Y *sum*		
C_1, C_2, C_3 gases	1,000	Thermal defects
C_1 and C_2 gases	500	Thermal defects
CO_2 and CO gases	10,000	Cellulose degradation

assessment of transformer conditions and put to use the experience of other power industry participants.

Based on efficiency analysis for monitoring transformer conditions by different methods using CADG, the CIGRE Working Group 15.01 has come up with an innovative method for interpreting CADG results, *CIGRE WG 15.01*. For large network and block transformers, the method normalizes the concentration of basic (key) gases, see Table 2.2.

The new method provides the following key gas ratios:

Ratio No. 1—C2H2/C2H6 (acetylene/ethane). Ratio No. 1 is considered to be crucial in determining the presence of electrical discharges; a value larger than a unity indicates a defect.

Ratio No. 2—H2/CH4 (hydrogen/methane). The presence of partial discharges is determined in relation to No. 2. Usually, the value is more than ten. (IEC 60599 uses a methane/hydrogen ratio).

Ratio No. 3—C2H4/C2H6 (ethylene/ethane). Ratio No. 3 is the ratio of unsaturated hydrocarbons to saturated hydrocarbons and reveals thermal effects. Usually, the value should be larger than a unity. Unsaturated hydrocarbons are formed mainly in overheated oil.

Ratio No. 4—CO2/CO (carbon dioxide/monoxide). Ratio No. 4 determines the degree of cellulose degradation. If the value is more than ten, then cellulose overheating takes place. If the value is less than three, then it is usually regarded as evidence of cellulose degradation under the influence of electrical defects. A furan analysis according to IEC 61198 is recommended to confirm the diagnosis.

Ratio No. 5—C2H1/H2 (acetylene/hydrogen). Ratio No. 5 is used to determine the penetration of gases into the common tank from the OLVR tank. In this case, the ratio usually equals two or more units, and the C_2H_2 concentration is no less than $30 \cdot 10^{-6}$ rel. units. Since hydrogen is less soluble in transformer oil as compared to acetylene, the latter diffuses from the OLVR tank more rapidly; only a small amount of hydrogen diffuses into the main tank. As a result, the amount of acetylene in the transformer oil exceeds that of hydrogen.

CADG result interpretation procedure

- ratios and concentrations of key gases dissolved in oil are identified;
- if all concentrations are below normal ones, then the result is indicated by K1. If at least one of the concentrations has exceeded the normal range values, then code K2 is assigned;
- if all key ratios are below their specified limits (inside the limits, in the case of CO and CO_2), the result is indicated by code E1;
- if any of the ratios exceeds the specified limits (reaches outside the limits, in the case of CO and CO_2), the result is indicated by code B2.

Combined results:

(a) K1 and E1: no measures are taken; the transformer most likely has no defects;
(b) K2 and K1: the transformer is likely to have a defect; further analysis is required;
(c) K1 and K2: defects in development are possible; further analysis is required;
(d) K2 and B2: more than one type of defect is likely; further analysis is required.

For the reliability of a diagnosis, sampling is repeated to calculate the above combinations of codes, with the exception of the first one. Further analysis and other examinations are carried out to find the nature of defects in occurrence. The obtained data are compared with statistical distributions of the probability of a transformer defect—as dependent on the content of H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, N_2, O_2 gases dissolved in oil—available in the databases of various organizations for different voltage classes, workload and service life of transformers. These diagrams show, for different voltage classes and workload levels of a transformer, that the hydrogen concentration does not affect the distribution pattern. For the distribution of a sum of hydrocarbons (C_XH_Y), such dependence does actually exist. The distribution of CO_2 is influenced by voltage classes; CO_2 concentrations are much higher for block transformers, normally operated at base load, than they are for grid transformers.

Research is in progress to determine the "normal" values for various classes of transformers. The innovative method CIGRE WG 15.01 is characterized by a step-by-step assessment of transformer conditions: first, one uses simple methods to determine a possible presence of defects and a need for further analysis of the transformer, and then the nature and severity of defects are identified by a more detailed analysis of CADG data. The new method not only complies with the IEC 60599 recommendations, but also develops them in a way suitable for practice.

According to the Transformers Gas Analyst™ method by Delta-X Research, division of Hydra-Centaurus Technologies Inc (Canada), results of analysis and trends of changes are displayed, and control data are documented. The database also contains monitoring rules and instructions, and thereby makes it possible to reflect the experience of equipment operation and operating conditions.

Analysis of gas from gas relays is regarded by some foreign enterprises as a particularly effective direction for diagnosing the condition of a transformer. Sampling is made when a gas relay is triggered by a signal; then diagnostic methods are used to determine the amount, location and nature of the defect.

Taken together, the results of CADG are indications for extraordinary measurements of winding insulation resistance, dielectric loss angle tangent, winding resistance to direct current, idling losses, thermal imaging control of transformer tank and cooling system surfaces, as well as for execution of CADG in contactor tank oil.

Based on the amount of measurements and their results, a number of questions can be answered:

- the amount and duration of overloading the transformer;
- the temperature in the upper layers of oil and air;
- the possibility of a decrease in the oil level relative to the top of the radiator;
- the operability of the transformer fans and radiators
- the orientation of the transformer in relation to the sunrays;
- the fact of the transformer being closed on three sides without blowing.

Based on the results, one of the following decisions, or a number of them, must be taken:

- retain the transformer in operation under enhanced CADG control;
- verify the operation of the oil pump engines;
- verify the presence of gas overflow from the contactor tank to the transformer tank;
- degass the oil;
- remove the transformer out for repair.

Each factor of this nature may cause an intense emission of methane. Discrete hotspots cause an increase in the concentration of ethane or ethylene, but if the basic gas is methane then this is caused by a cooling system defect or by personnel overloading the transformer. Numerous problems can be solved by adding heat sinks and fans or by changing transformer load.

2.1.1.2 Physical and Chemical Indicators for Estimating the Condition of Paper Insulation for Power Transformers in Operation

During the operation of a power transformer, the cellulose insulation of the windings is subject to destruction and dehydration processes aggravating its physical and chemical properties. First of all, this is reflected by deterioration of mechanical strength, oxidation, formation of pores, and chemisorption of acidic products due to the aging of transformer oil and metallic compounds of variable valence.

The electrical strength of oil-impregnated paper remains largely unaffected by aging, since the damaged areas of cellulose insulation are rapidly filled with oil, and the electrical indicators (insulation resistance and dielectric loss angle tangent) neither change significantly nor can serve as indicators of aging. Assessment of wear/aging for the winding insulation of any particular transformer should include a direct analysis of the physicochemical condition of cellulose insulation and of the related indicators for the degree of degradation in development. In addition, one needs a series of diagnostic features that allow one to make an objective conclusion on the amount of insulation wear and make a decision on the possibility and expediency of further transformer operation.

Due to a rather complex network of parallel and sequential chemical reactions leading to degradation, and the multiplicity of factors affecting the kinetics of their development, it is not possible to predict with the required accuracy the degree of deterioration of the winding insulation by analyzing the effects of operating factors. An assessment of deterioration for the winding insulation of any particular transformer should include a direct analysis for the physicochemical condition of cellulose insulation and for the related indications as to the amount of degradation development. It is evident that an acquisition of numerous diagnostic attributes for estimating the wear of winding insulation should be based on a profound study of physicochemical processes occurring in cellulose insulation under the influence of operational factors, among which the most significant ones are electric field, temperature, air (oxygen), chemically active impurities (aging products) and moisture.

The main physical and chemical phenomena causing the degradation of winding insulation during the operation of power transformers are as follows:

- thermal destruction and dehydration,
- hydrolysis of cellulose insulation,
- oxidative destruction when exposed to acidic products of oil aging and oxidants contained in oil,
- catalytic acid alcoholysis (alcoholysis is a general term for a group of exchange reactions between various organic compounds: epoxides, anhydrides and halides of carboxylic acids).

Electric field enhances the effect of most physicochemical factors and also promotes the adsorption (on the surface of cellulose insulation) of the aging products of transformer oil and construction materials. It also accelerates another important process of cellulose degradation, being catalytic acid alcoholysis under the action of hydroxyl-containing hydrocarbons (alcohols) in the presence of low molecular weight organic acids and other products formed in the oil during aging. The hydrolysis of cellulose insulation, which proceeds in parallel with the process of acid alcoholysis, makes, as compared to the latter, a substantially smaller contribution to overall degradation, which, in particular, is due to a rather low content of moisture in the insulation during normal transformer operation.

An important factor in the aging of cellulose insulation is its thermolysis, caused by elevated temperatures. Under the influence of high temperatures (more than 90 °C) in cellulose insulation, apart from an acceleration of the above-mentioned processes, thermal degradation is also activated, being destruction and dehydration in amorphous and mesomorphic regions with a formation of furfural and furan compounds. In addition, along with the indicated degradation processes, during transformer operation cellulose insulation is subject to oxidative destruction once exposed to acidic products of oil aging and to oxidants contained in these products. This process leads to the formation of oxidized (mainly carboxyl) groups and structure disturbances, as well as to the chemisorption of low molecular weight degradation products and acidic products of oil aging, copper and iron ions formed during the corrosion of metal elements of a transformer in the course of its operation. This process is accompanied by the release of carbon oxide and dioxide into the oil; a visual sign of catalytic thermal oxidative destruction of cellulose insulation of windings is its dark brown color.

In accordance with [16], two methods are provided for estimating the condition of winding paper insulation:

- according to the presence of furan compounds in oil;
- according to the polymerization degree of insulation samples.

It should be noted that the destruction of cellulose insulation during the operation of a transformer can be accompanied by a release of furan compounds into the transformer oil, the most of which should be regarded as furfural and hydroxymethylfurfural. Around 80% of furfural dissolves in insulating oil, and hydroxymethylfurfural is adsorbed mainly in paper insulation.

In accordance with [16], a permissible content of furan compounds (limiting the normal condition region) is set at no more than 0.0015% by weight (with furfural being no more than 0.001% by weight). For a number of reasons, discussed, e.g. in [1], this indicator does not reflect the actual degree of cellulose destruction, namely, the degradation dynamics for cellulose insulation. An objective indicator that makes it possible to assess the wear of winding insulation is the ***degree of polymerization***, which directly characterizes the depth of its physicochemical destruction. At the same time, a decrease in the amount of polymerization has a monotonous dependence and reflects a monotonous decrease in the mechanical strength of insulation, which determines a deterministic diagnostic value of using this indicator. The resource of winding paper insulation is regarded to be exhausted when the degree of polymerization is reduced to 250 units, since in this case there is at least a 4-fold decrease in the mechanical strength of insulation in comparison with the original strength. This, in turn, dramatically increases the risk of short-circuited turns and transformer damage when mechanical forces make appearance, primarily in the case of through SC currents.

For an objective assessment of the wear sustained by transformer winding insulation, it is necessary to measure the degree of polymerization of a sample of turn insulation, selected in one of the upper coils [17]. The sampling of coil insulation can be carried out using a disconnected transformer both during overhaul and when partially draining the oil through the hatches.

Moisture contained (dissolved or bound) in transformer oil is one of the most important factors affecting the insulating properties of oil-paper insulation. The immediate reason for a decrease in the electrical density of transformer oil is the presence of moisture dissolved in it. However, bound moisture readily transforms into dissolved moisture, so that it is believed expedient to determine the total amount of moisture in transformer oil. Moisture content up to 200×10^{-6} rel. units hardly affects oil conductivity and dielectric strength. Once this quantity of moisture is exceeded, treelike structures of increased conductivity start to emerge, and then free water inclusions (drops) begin to appear, sharply reducing the value of electrical strength. Electrical effects and thermal aging of cellulosic material in electrical equipment lead to the appearance of carbon oxides and water, and therefore paper in electrical equipment is not only an adsorbent and principal moisture carrier, but also the main source of water.

Monitoring the process of ***dehydration*** due to polymerization is highly effective, since it allows one to examine the amount of wear sustained by the paper insulation of windings. Output of water released by paper with a polymerization degree of more than 300 rel. units is around 10^{-3}–10^{-2} % of the mass and has no significant influence on the performance of insulation. Upon reaching the degree of polymerization below 250 rel. units, the release of water due to dehydration may be more than 6% of the mass, which leads to a decrease in the dielectric strength of insulation [17].

Measurements of polymerization degree carried out to obtain a reliable assessment of the wear sustained by the winding insulation of power transformers should be made by determining the viscosity characteristics of cellulose insulation solutions in a cadmium-ethylenediamine complex. This makes it possible to ensure the absence of significant destructive changes in cellulose samples under examination, including oxidized ones. The use of other solvents tends to cause a chemical degradation of cellulose. Analyzing the polymerization of insulation by converting the latter into ethers may lead to overestimated values of the indicator in question, resulting from dissolution sustained by the low molecular weight fraction, with subsequent erroneous conclusions.

Mechanical impurities contained in oil dramatically reduce the dielectric strength of insulating gaps.

The electrical strength of the oil depends on the size of the impurity particles, since particles of larger size have a larger effect on increasing the field inhomogeneity in the oil, especially if they possess an increased conductivity, in particular due to the presence of moisture. Initially, transformer oil contains very small particles, caused by impurities in crude oil or formed during oil processing. During the manufacture and assembly of a transformer, its oil may be penetrated by cellulose fibers, dust, resin and metal particles. During the operation of a transformer, the concentration of particles, such as cellulose fibers, as well as metal and resin particles, increases as the materials age. The particles are carried throughout the entire transformer bulk by forced circulation of the oil. Local overheating and partial discharges also increase the concentration of carbon particles.

Having determined the nature of contaminants and aging products contained in transformer oil, one may proceed to choose optimal methods for regeneration of the used oils: for some oils a simple cleaning from mechanical impurities is sufficient, while for others deep processing is required, sometimes using chemical reagents. Used oil recovery methods can be divided into physical, physicochemical, chemical and combined ones. In practice, combined methods are normally used to obtain high quality recovered oils.

One particular case of oil contamination is the formation of sparingly soluble colloidal particles of copper and iron naphthenates. To detect colloidal particles contained in oil, turbidity measurements are used to determine the decrease in intensity due to the scattering by the particles of light passing through an oil cuvette.

The above makes it clear that the basic regeneration methods for used oils cannot be applied separately; in practice, it is often necessary to resort to various combinations of methods in order to ensure that the maximum cleaning effect is achieved. When choosing a regeneration method or a combination of methods, it is necessary to take into account the nature of aging products contained in used oils and the requirements for regenerated oils, as well as the amount of collected oils. One also needs to be aware of environmental consequences inherent in certain regeneration methods, so as to choose the most appropriate ones under the circumstances. Having these data available, one can determine the physicochemical properties of oil that need be corrected, and therefore one can choose an appropriate method of recovery.

The problem of removing moisture and impurities is effectively solved by the adsorption purification of oil using thermosyphon filters with an adsorbent, silica gel, due to its good adsorption properties and large specific surface area, being 350–450 m^2/g.

Dehumidified air needed for the operation of a transformer is obtained using air-drying cartridges filled with adsorbent (silica gel) and a small amount of silica gel indicator. The latter helps to determine the degree of adsorbent humidification and the need for its replacement or regeneration.

In the course of transformer overhaul, silica gel reduces the acid number of used transformer oils and gives them a second life. These processes of adsorption purification are extremely important in power engineering and can be achieved using sorbents of high and proven quality.

2.1.2 Vibration Control

The weakening of winding pressing can be regarded as the initial stage of damaged condition, causing the development of more serious and dangerous winding defects, such as coil descent and buckling, or turn-to-turn short circuits. Vibration control technology is used to monitor the degree of winding pressing. The purpose of transformer vibration diagnostics is to estimate the condition of a mechanical system, as well as to identify and eliminate defects in both external equipment (damage to pipelines due to resonant vibrations, wear of bearings of oil pumps and fans) and internal systems (unpressing of windings and magnetic conductor, displacement of magnetic shunts due to vibration.

Transformer vibrations are polyharmonic vibrations with frequencies being multiples of 100 Hz. The source of transformer vibrations is a magnetic conductor. The cause of this phenomenon is magnetostriction. Electric motors of oil pumps and fans are vibration sources by themselves, but their energy is much smaller. The vibration frequency of attached equipment is due to the rotational speed of electric motors, being approximately 720–1440 rpm. Vibrations are transmitted from sources to other units and elements of a transformer. An examination begins with measuring the vibration of a transformer tank. The most important vibration characteristics are as follows [18, 19]:

- vibration velocity, characterizing the vibration energy whose values are used to estimate the condition of the transformer tank, as well as to assess the impact of the transformer on the foundation;
- vibration acceleration, characterizing the inertial forces acting on the transformer tank as a result of the movement of its internal elements;
- vibration displacement, characterizing the vibration loads crucial for the condition of the transformer tank, welds and other elements.

The frequency spectrum of vibration velocity allows one to identify the vibration sources. Measurements are carried out in the frequency range up to 1000 Hz, since more than 90% of the total vibration energy of a transformer is concentrated in this range.

For a general assessment of transformer condition, a need for additional examinations arises at the following parameter values:

- vibration acceleration being more than 10 m/s^2,
- vibration speed being more than 20 mm/s,
- vibration displacement being more than 100 microns.

The condition of fans and oil pumps depends on the cooling system design. It can be estimated on a basis of the following criteria:

- indicator of defects in a blower fan is a vibration velocity of the bearings being higher than 7.1 mm/s;
- damaged condition of an oil pump is related to a vibration velocity being higher than 4.5 mm/s.

The pressing quality of the windings and magnetic conductor can be determined by examining the vibration spectrum on the surface of the transformer tank. Measurements are carried out in two modes, idle and loaded. It is assumed that in the idle mode the vibrations are caused by magnetostriction in the magnetic conductor, while in the loaded mode the additional effect of electromagnetic forces in the windings is taken into account. A decrease in the compression force of magnetic conductor sheets below a nominal value leads to an emergence of frequencies of 300–500–700 Hz. A weakening of winding pressing leads to a decrease in the 200 Hz frequency component.

The quality of winding pressing can also be estimated by measuring the natural frequencies of winding vibrations under mechanical shock. The basic method is registration of EMF induced on the windings at the bushings of a bus-bar transformer during a pulsed mechanical action. This process has the form of damped oscillations. The spectrum of EMF induced under pulsed mechanical action on transformer windings at different degrees of winding pressing is different and is shown in Fig. 2.1, see [20].

The disadvantages of this method are as follows:

- higher requirements for mounting a vibration sensor;

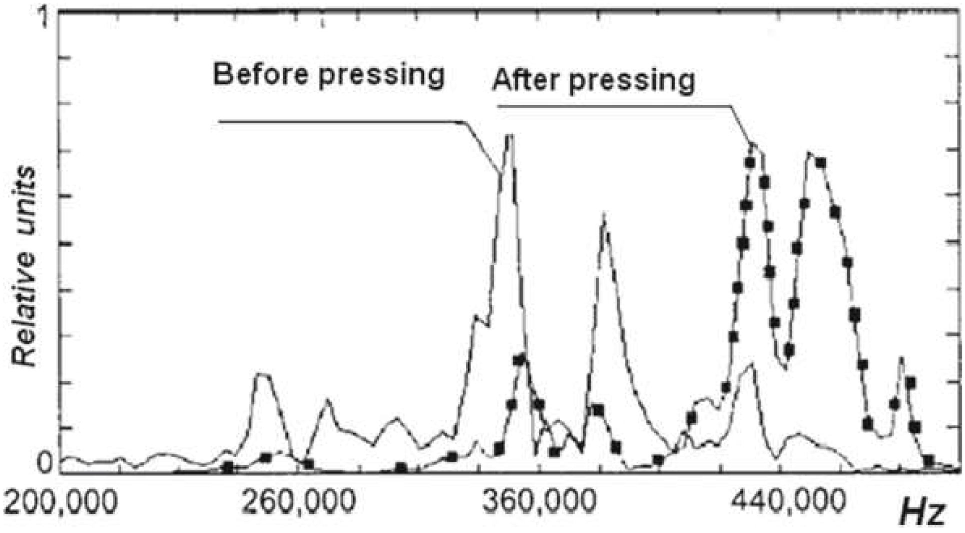


Fig. 2.1 EMF spectrum induced in the winding of a TTs-630000/500 transformer under pulsed mechanical action on the transformer winding at different degrees of winding pressing

- dependence of vibration parameters on a large number of factors, combined with the problem of isolating a vibration signal due to malfunction, which requires the use of methods of correlation and regression analysis.

Despite these disadvantages, the vibration control of the pressing degree in transformer windings is developing both in Russia [20, 21] and in other countries [22–25].

2.2 Electrical Control Methods

2.2.1 Insulation Condition Monitoring by PD Registration

Methods of PD registration are divided into two groups: non-electrical and electrical methods.

Non-electrical methods include the optical and acoustic methods.

The optical method is historically the first one and is based on a registration of PD glow. The method allows one to control PDs at electrode edges and in transparent materials. PD control inside opaque structures is impossible, which puts significant limits on its use in the diagnosis of high-voltage transformers, whose insulation is not transparent optically.

The acoustic method makes it possible to register PDs inside opaque objects. The apparent simplicity of the method does not compensate for its massive problems in determining the location of PD occurrence in high-voltage transformers.To detect such occurrences, supersensitive microphones are utilized, which detect sound waves located in the frequency range above the audibility threshold. Research on the improvement of the method is in progress.

The sensitivity of **electrical methods** is higher than that of non-electric ones, so they are more widely used at present. They allow one to detect the largest number of PD characteristics and use them to estimate the condition of transformers. Most electrical methods do not need the object under analysis to be supplied by electrical voltage being much higher than the rated operating values, so they are gentle on the insulation of electrical equipment. However, many of these diagnostic methods require the measuring instruments to be in contact with the object being diagnosed, which does not contribute to simplicity and convenience. Due to the high sensitivity of the methods, it is necessary to take a series of measures and use special equipment for debugging induced interference.

The electrical methods are divided into three main types:

(1) *Indirect methods of PD registration*
(2) *Electromagnetic or remote (PD registration with antennas)*
(3) *Registration of high-frequency (HF) electromagnetic radiation generated by PDs.*

(1) *Indirect methods of PD registration* include those that allow one to determine dielectric losses by measuring the tangent of dielectric loss angle in insulation (tgδ), or by measuring Volt–Coulomb characteristics. These methods provide an idea about the voltage of PD occurrence judging by a sharp increase in tgδ. Since the application of these methods involves a summation of different types of losses, it is difficult to single out the direct losses due to PDs. In addition, these methods have low sensitivity.

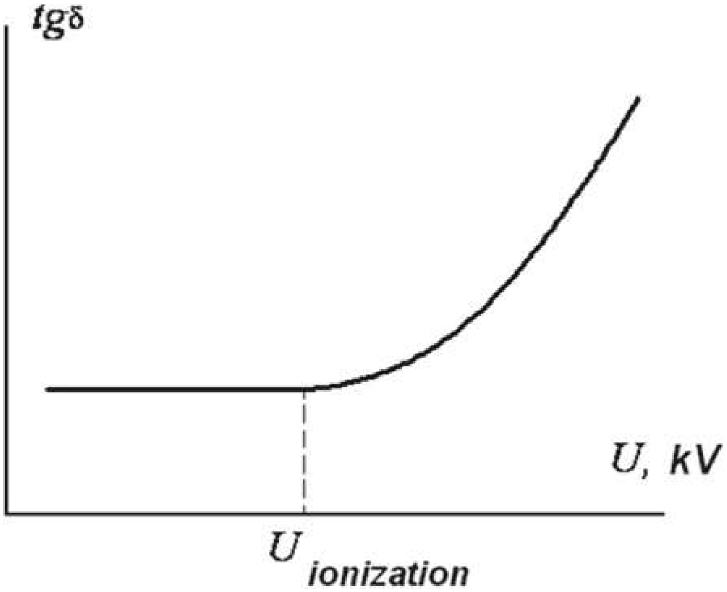
A practical implementation of this idea is the *control of an ionization curve when measuring tgδ*. The method is based on the fact that PD occurrence at an insulation defect causes a decrease in its resistance, and thereby an increase in active current (and hence tgδ); the reactive current is almost unchanged. The voltage dependence of tgδ is determined using a high-voltage Schering bridge. The voltage at which ionization starts in an insulating structure corresponds to the onset of growth in tgδ, and the inflection point of the curve is regarded as the onset voltage of ionization, Fig. 2.2.

The drawback of the method is that the recorded increase in tgδ is related not to the onset of discharges, but rather to an intense process of PDs repeated numerous times during the cycle, which covers a significant part of foreign inclusions in the dielectric volume. For this reason, the method can be classified as obsolete.

(2) *Electromagnetic or remote method (PD registration with antennas).*

This method is remote and allows one to detect PDs using a directional receiving microwave antenna device. The use of this equipment does not depend on the voltage class, which is an advantage. The disadvantage of this method is the inability to obtain any quantitative information about the processes and phenomena accompanying PDs,

Fig. 2.2 Curve for determining the onset of an ionization process



as well as the effect caused in the readings of a receiving device by electromagnetic radiation from external sources.

Research is currently in progress to improve the adaptation of the method to operational requirements. Even now the method allows one to carry out lasting continuous monitoring of equipment accompanied by information transfer to an operator with the aid of digital technologies.

The most active research on PDs in isolation began in the late 1950s and early 1960s. At that time, the destructive action of PDs was first encountered in a large group of ultra-high voltage equipment in the late 1950s during the operation of 400 kV transformers, and later on, 500 kV ones.

Since the 1980s, the strategy for diagnosing equipment in Europe and America has gradually changed: there has been a shift from the concept of routine testing to the concept of testing determined by estimating the technical condition of equipment. It is known from practice that positive results of testing equipment by high-voltage, which has been currently regulated in Russia, do not guarantee protracted trouble-free operation of the tested equipment. Besides, during the insulation test the condition of equipment significantly deteriorates due to the supply of voltages being 4–6 times higher than the nominal value. The diagnostic methods for PD registration, at the same time, allow one to give the most accurate estimation of the residual life of equipment, while not affecting the isolation in any significant way. This is ensured by applying lower voltages to an inspected object, in some cases being close or equal to the nominal value. In parallel, the task of creating a system of automated monitoring of equipment parameters under operating voltage has been undertaken. The largest success in this direction has been achieved by High Voltage Partial Discharge ltd (HVPD) that producing devices for on-line PD monitoring in the insulation of electrical equipment. To date, this is almost the only method that permits a detection of incipient local defects in the process of insulation degradation. A wide application of the method is constrained by the complexity of measurement techniques, the high costs of equipment, and the high requirements to qualifications of the personnel operating the equipment.

(3) *Registration of electromagnetic PD-generated HF radiation* has become the most widespread technique, since it allows for reliable measurements of basic PD characteristics and provides high sensitivity.

The method of registering high-frequency PD components, implemented using partial-discharge indicators (PDI), is also widely used.

The efforts of researchers and engineers are aimed at creating instruments and techniques that should make it possible to register the weakest PDs and provide measurements of energy dissipated by single discharges. This requirement has now been met by using PDIs connected directly to a discharge circuit. Such indicators consist of a receiving circuit, an amplifier and a measuring device. This is based on the measurement of an apparent charge:

$$\Delta Q_0 = \Delta U C_0, \tag{2.2}$$

where C_0 is the insulation capacitance.

Ripples of voltage ΔU are measured and fed through an amplifier to an oscilloscope. The moment the pulses appear on the screen determines the voltage of ionization occurrence, while the amplitude and frequency of the ripples determine the PD intensity. There are several options for this scheme. Two of them are shown in Figs. 2.3 and 2.4.

(a) An active resistance scheme is shown in Fig. 2.3.

Resistance R_1 is connected in series with a tested object and a voltage drop on the object is recorded by a PDI. The resulting oscillogram is interpreted as to the presence or absence of PD. The disadvantage of this method is its low noise immunity.

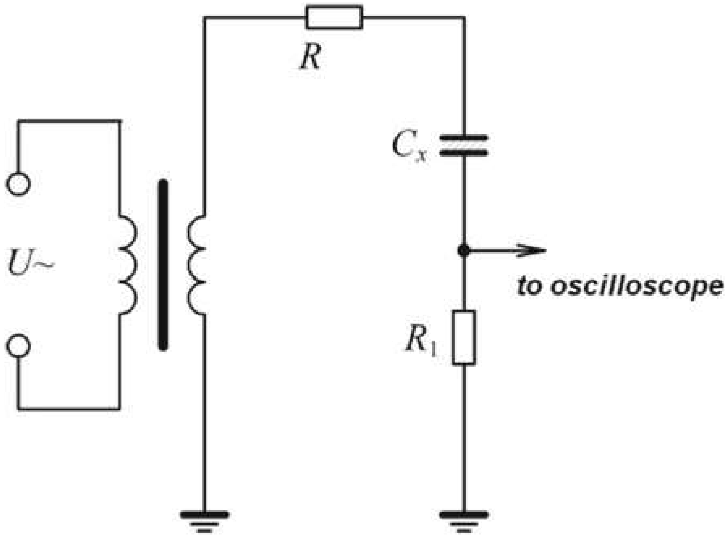


Fig. 2.3 Active resistance scheme for PD detection: R is a protective resistance; C_x is a tested object; R_1 is an active resistance

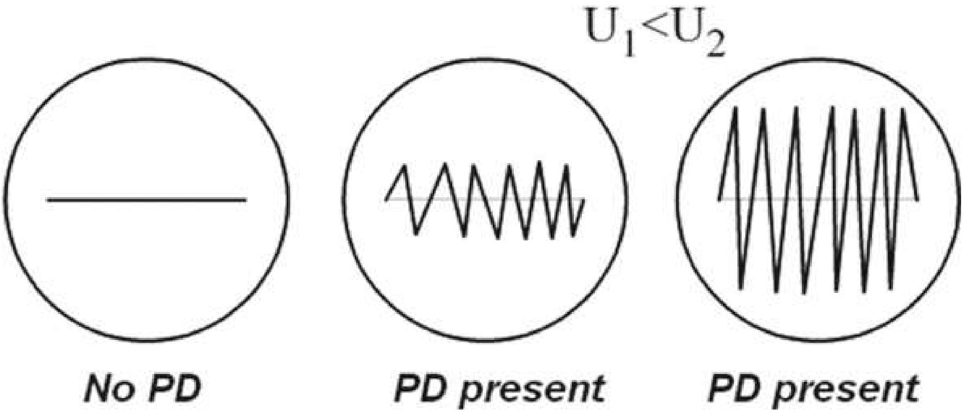


Fig. 2.4 Oscillograms for different PD intensities

On the oscilloscope, one can observe the picture shown in Fig. 2.4.

(b) A scheme with inductance and capacitance is shown in Fig. 2.5.

The PDI is connected to the tested object through the dividing capacitor C_{div}, which serves as a blocking filter for currents of the operating frequency. At the emergence of PDs in the object (C_x), chaotic voltage fluctuations in the object excite continuous periodic oscillations in the PDI with a frequency corresponding to the oscillation period of the circuit:

$$T = 2\pi\sqrt{LC}. \tag{2.3}$$

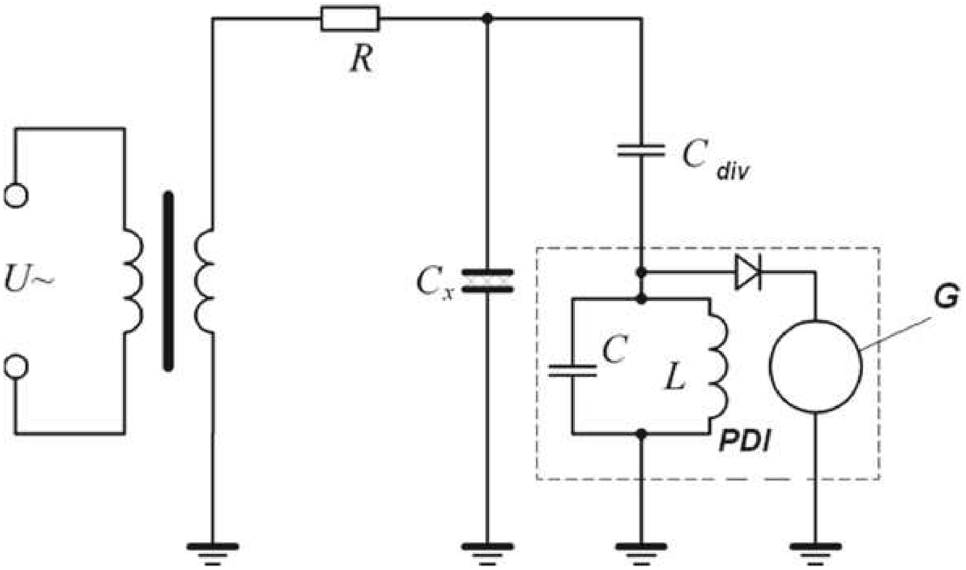


Fig. 2.5 PD detection scheme with an oscillatory circuit and a galvanometer: *R* is a protective resistance; C_x is a test object; C_{div} is a dividing capacitance; *L*–*C* is the oscillatory circuit; *G* is the galvanometer; *PDI* is a partial discharge indicator

The order of the PDI tuning frequency is usually chosen as several tens of kilohertz. The apparent intensity of ionization is determined using the value of ΔU given by formula (2.2).

In conclusion, it should be noted that the use of the PD method for preventive tests is very promising, since it allows for continuous monitoring under operating voltage. Unfortunately, it also has some drawbacks that demand it to be used in combination with some other methods:

(1) The presence of a large amount of interference that makes it problematic to decipher the results obtained (the source of interference may be the appearance of a corona on the wires, the sparking of the collectors of electrical machines, etc.);
(2) Rather than the presence of failures, the method detects the presence of PDs, while there may well exist dangerous defects without any PD involvement: cracks filled with water or some other conductive liquid, carburized pores in which PDs have stopped.

Technical implementations of the concept of insulation diagnostics by PD registering are extremely diverse.

Measurement of PD electrical characteristics and determination of PD origin location are successfully implemented by many high-voltage laboratories at large energy companies in the USA, Australia, Japan, Germany, China, Canada, Brazil, as well as transnational energy companies EDF and Enel, and others, where this control method is included in the mandatory insulation monitoring programs. Preference is given to automated systems and devices operating in real time. The principal contribution to these developments is due to such large companies as ABB, Siemens, Mitsubishi, Tettex, General Electric, Megger, Omicron, Haefely. To monitor the insulation condition of a power transformer of the highest voltage class (1000 kV), Mitsubishi has developed a highly sensitive PD monitoring system.

Tettex Instruments AG produces the multichannel PD analyzer Digital Partial Discharge Detector DDX9101, a digital meter with computer data processing. The software of this device allows displaying PDs both as Lissajous figures (with reference to the phase of the operating voltage) and as three-dimensional images showing the amplitude-frequency characteristics of discharges [26] (Figs. 2.6 and 2.7).

New opportunities have appeared for monitoring defects in insulation when measuring PDs on a basis of digital equipment. An example of such equipment is a partial discharge analyzer supplied to the world market by Haefely and Tettex.

Fig. 2.6 Digital Partial Discharge Detector (DDX9101)

Fig. 2.7 The DDX 9121b is the latest in the DDX family of partial discharge (PD) & radio interference voltage (RIV) testing instruments. It is a fully digital state-of-the-art high-performance PD detector [27]

Anti-interference is one of the most challenging tasks in detecting PDs and measuring their parameters in a production environment. Research is underway to overcome difficulties of PD measurements in operating transformers under the conditions of operating substations. For example, the University of Hanover (Germany) has developed a computer-aided system of filtering signals from interference. Acceptable signal-to-noise ratios in operating substation conditions have been achieved through the use of digital filters, adaptive limiting filters, and measurement circuits using the opposite directionality of PD signals from the transformer and that of noise coming from the power grid.

Researchers and engineers at ***OMICRON*** (Austria) have a large experience in digital PD analysis of high-voltage structures. The research center of the company maintains a database on the results of PD measurements in transformers and other high-voltage equipment. The analysis exploits the theory of pattern recognition and the three-dimensional spectra of PD distribution by repetition frequency, as well as by amplitude and location relative to the test voltage phase. One of the latest developments is a portable system for measuring and periodic monitoring of partial discharges in diverse high-voltage equipment, OMS 605, see Fig. 2.8.

The OMS 605 is a portable system for measuring and online monitoring of partial discharges on equipment in operation according to IEC 60270. In contrast to offline diagnostic tests, online PD monitoring ensures the assessment of insulation condition during the operation of equipment. Data on the trends in insulation condition allow one to estimate the rate of wear and tear. This is critical information that helps one optimize the equipment maintenance schedule and maximize the return on investment.

The system is used to periodically assess the insulation condition of medium and high voltage equipment under operational load. All the necessary devices for diagnostics and monitoring of partial discharges are housed in a sturdy case with wheels, which is easy to transport from initial place to other one. The OMS 605 system is used with a range of capacitive and inductive PD sensors to cover the entire frequency range in which frequency discharges can be detected, including the

Fig. 2.8 Portable system for measuring and periodic monitoring of partial discharges in diverse high-voltage equipment, Omicron OMS-605

microwave range. These sensors can be permanently installed, so that frequently tested equipment is not taken out of service each time they are installed.

Thanks to a synchronous data collection using three channels, the operator receives a comprehensive set of PD information. A fourth channel can be added for an optional PD sensor or strobe. Advanced noise suppression and source separation techniques enable accurate partial discharge location. The OMS 605 software visualizes the acquired data, as well as allows one to record data streams in real time and save them for later analysis. The OMS 605 can be used for periodical monitoring the status of diverse high-voltage equipment. One portable device can be used to monitor different objects. A convenient auto-tuning system and versatile software make it easy to adapt the OMS 605 for monitoring any type of high-voltage equipment. The features of the OMS 605 system are as follows:

- Ease of transportation for periodic monitoring of various objects;
- Easy-to-use self-adjusting modules for quick system preparation for work;
- Synchronous data collection through several channels for a comprehensive estimation of PD activity;
- Compatibility with various PD sensors;
- Rugged and reliable industrial grade design (IP65);
- Automated noise suppression and source separation for accurate PD detection;
- Powerful software for analysis and visual display of PD data.

The system is used by personnel specialized in testing and maintenance of companies, being equipment manufacturers, network and industrial enterprises, power plants, as well as by personnel of service companies for periodic inspection and monitoring of equipment for PD presence and subsequent assessment of the insulation condition of power transformers of all voltage classes.

Another example of OMICRON's productive creativity is the Omicron MPD 800 universal partial discharge measurement and analysis system, Fig. 2.9.

Fig. 2.9 Omicron MPD 800 universal partial discharge measurement and analysis system

The MPD 800 is used during standard-compliant PD testing for routine and type tests, factory and on-site acceptance tests, as well as for troubleshooting aimed to localize or analyze PD sources in all types of high voltage equipment.

The MPD 800 system consists of an MPD 800 measuring device, an MCU2 control unit, and an MPD Suite of software. Depending on the measurement, the MCU2 connects to one or more MPD 800 devices via fiber optic technology. The MPD 800 and RBP1 batteries are connected to a test object directly or via CPL1 or CPL2 couplers. MCU2 connects via USB to a laptop or PC with MPD software installed for analysis. This approach has several advantages:

- Safe approach to testing due to galvanic isolation
- Battery powered
- Minimum environmental impact
- High synchronicity for improved partial discharge analysis

Among other companies involved in the study of electro-physical PD processes and technical means of their control, the companies ***MEGGER*** and ***ABB*** stand out. The companies use a continuous PD registration system using digital technology. Based on the study of relations between the measurements produced by electric and acoustic sensors, a technique for identifying the location of PD occurrence has been developed.

MEGGER's engineers have developed the *Power Diagnostix ICM compact*, a standalone PD measurement tool, shown in Fig. 2.10.

The Power Diagnostix ICM compact has a simple push-button interface and on-screen menus on a built-in liquid crystal (LCD) panel. The LCD display modes include a simple PD meter with adjustable "needle" sensitivity, phase-resolved monochrome PD charts for defect classification, and an oscilloscope-type display showing phase-summed charge pulses superimposed on the applied voltage wave. Although the ICM compact is a stand-alone device, it can be connected to a computer running Power Diagnostix software to take screenshots or remotely control the device.

By instantly displaying information in an intuitive interface, the ICM compact is a good choice for applications such as proof-testing in the manufacture of electrical products, and such as quality assurance in municipal and industrial equipment, starting from capacitors and bushings to gas-insulated switchgears, voltage transformers, etc.

Fig. 2.10 Autonomous complex for measuring partial discharges *Power Diagnostix ICM compact*

To adapt the ICM compact base unit to specific measurement requirements, it can be equipped with various options:

- Locating cable damage.
- Analog strobing to eliminate external noise. The option offers sensitive measurements even in noisy environments.
- MUX4, a four-channel multiplexer for testing three-phase equipment such as power transformers. The device supports individual configurations and calibrations for each channel.
- MUX12. The option provides a built-in 12-channel multiplexer or a remote 12-channel breakout box for acceptance testing of large power transformers.
- AUX4. Provides recording of up to four additional parameters as 0 (4)-20 mA or 0–10 V signals for long-term testing.

Fig. 2.11 ABB Ability—SWICOM switchgear condition monitoring device

- RIV measurement. Adds a function of measuring the strength of radio emission to the device.
- Modem. Provides communication with the device via an analog telephone line.

At the same time, measurements can be made using both acoustic and antenna methods.

Among the ABB developments, the ABB Ability—SWICOM switchgear condition monitoring device stands out (Fig. 2.11).

The ABB Ability—SWICOM switchgear condition monitor with partial discharge detection is a cost-effective solution for monitoring equipment condition. SWICOM is a diagnostic tool that monitors the running order of the entire stock of mechanical and electrical equipment. The device collects data from IEC 61850 compliant protection relays, as well as additional sensors, and converts it into diagnostic information. It can be installed on virtually any new or existing air or gas-insulated switchgear of medium voltage. Due to the high cost of efficient and reliable equipment, it was only high-voltage switchgear that had been tested for such discharges earlier, and the equipment had to be switched off to examine the insulation. The ABB Ability—SWICOM switchgear condition monitoring device with PDCOM sensors compensates for this disadvantage and represents an effective solution for monitoring the condition of medium-voltage equipment.

The SWICOM system has a number of advantages:

- Monitoring the circuit breaker drive, the temperature at critical points in the primary circuit, and the partial discharge using an indicator.
- Complete retrofitting of any existing panel, regardless of age, design features or device type, while ensuring compatibility with ABB digital.
- Fast and easy integration into truly digital switchgear, also when the panel design is not specified for this application.

Acoustic methods, despite their inherent disadvantages, have found extensive use in PD detection and location during measurement on operating equipment due to their lower sensitivity to extraneous electrical signals (interference). An acoustic assessment of PD intensity is recommended as part of diagnosing the condition of power transformers. Particularly effective are acoustic PD sensors placed inside the transformer tank. Such sensors are used to control of particularly critical transformers and also in type tests.

Research on acoustic waves arising from discharges in oil has been conducted by a number of scientific institutions in Japan. Techniques for locating the PD site in a transformer have also been developed. In particular, a 1000 kV high-voltage power transformer produced by Mitsubishi is equipped with acoustic sensors in the tank.

At the Polytechnic Institute in Poznan (Poland), the mechanism of sound wave propagation from a PD source has been studied in detail. An innovative technique for measuring and locating the PD site in a transformer has been developed using an acoustic method. The result of PD registration with the site localization is shown in Fig. 2.12.

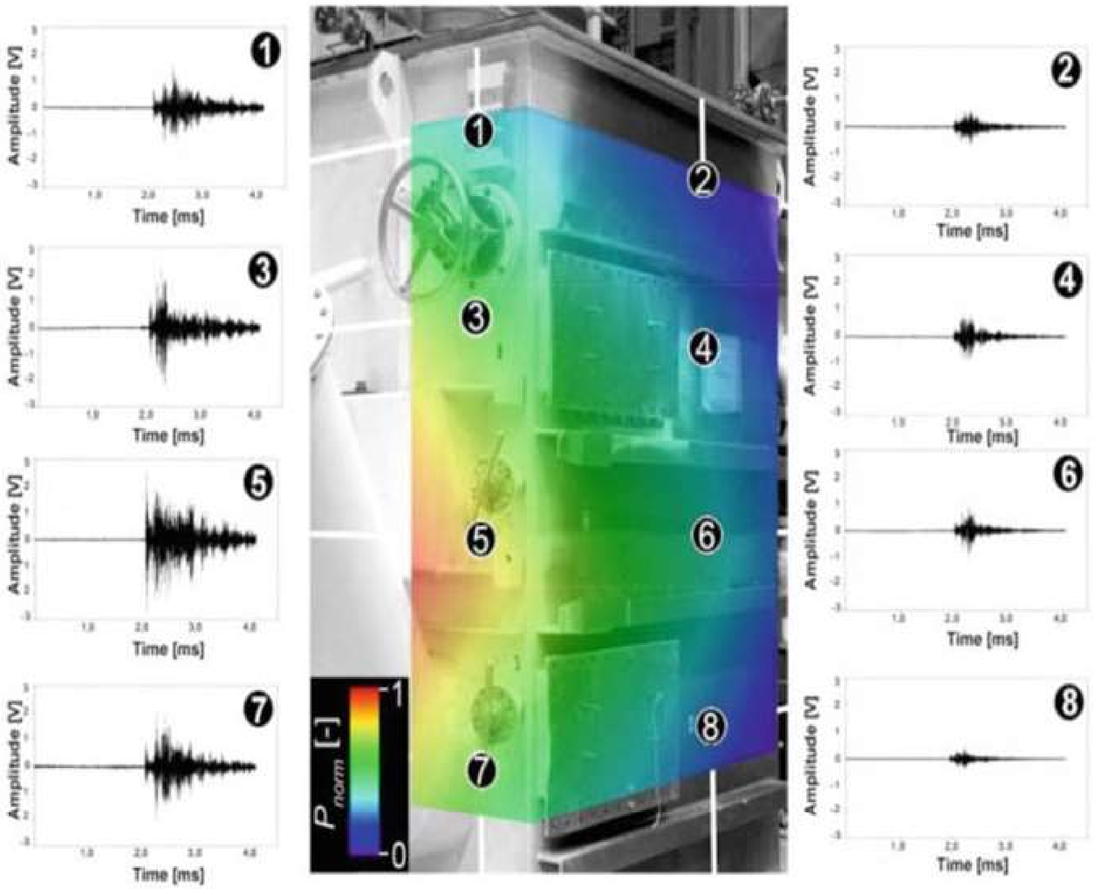


Fig. 2.12 The result of partial discharge source location with advanced auscultatory technique and example of AE waveforms recorded in 8 locations on the transformer tank [28]

Acoustic PD sensors, both inside and outside the tank, have been part of the EPRI control system for testing a 525/345 kV, 300 MVA transformer at the Ramapo substation in the ConEd electric power system.

The PTCSM automated system for monitoring the condition of 400/161/161 kV transformers with a power of 195/97/97 MVA of the FennoScan DC cable line, operated since 1988, is equipped with acoustic sensors for PD detection.

PD sensors (electrical and acoustic) are included in automated systems for a continuous monitoring the condition of large power transformers, developed by Westinghouse, Siemens, ABB, see [29].

In Russia, the most profound issues of monitoring PDs in electrical equipment under operating voltage have been worked out by Dimrus Company and by Siberian Research Institute of Power Engineering (SRIPE). The researchers of SRIPE regard the control of PDs in combination with CADG as a basis for transformer diagnostics in operating mode.

Monitoring the condition of transformers by PD characteristics using electrical and acoustic sensors is widely used in the power systems of Russia. As an example, we can name some Russian enterprises that successfully use such diagnostics: Electrosetservice, Technoservice-Electro, JSC "Firm ORGRES". They use a technique well-protected against interference for acoustic measurements and PD location in power transformers. Among the PD sensors of the latest generation, one can point out indicator of PD characteristics with Russian name IChR-201, Fig. 2.13.

The main technical parameters of the IChR-201 device are given in Table 2.3.

The IChR-201 device implements all the recommended by State Standard 20074 and IEC 60270 schemes for measuring PD characteristics. The device simultaneously measures in real time the values of all the PD characteristics recommended by the standards:

- Maximum apparent charge of PD pulses (according to State standard) 20074 or IEC 6028);

Fig. 2.13 Partial discharge indicator IChR 201

Table 2.3 Main technical parameters of IChR 201

Parameters and characteristics	Value
Test voltage frequency, Hz	40–400
Sensitivity (when a signal is applied directly to the device input), pC, no worse	0,1
Minimum measurable apparent PD charge, pC, no more	1,0
Maximum measurable apparent charge of PD, pC	10000
Measurement error of PD charges in the range of 1–10 pC, pC, no more	±1,0
Measurement error of PD charges in the range of 11–10000 pC, pC, no more	±10
The highest repetition rate of measured PD pulses, kHz, no	100
Bandwidth limits, kHz	45–700
Pulse resolution time, μs, no more	6,0
Digitization of the signal, bit	14
Test voltage input characteristics: – input impedance, Mohm, no less – input capacitance, pF, no more – maximum voltage of frequency 40–400 Hz, V, no more	1,0 50 100
Supply voltage (50/60 Hz), V	220 ± 10%
Power consumption, VA, no more	60
Dimensions, mm	110 × 170 × 250
Weight of measuring units (excluding cables and computer), kg	6,0
Packing dimensions, mm (LxWxH)	552 × 250 × 430
Weight of the complete set in the package (including cables, computer, packaging, documentation), kg	23

- Repetition rate of PD pulses;
- Average current of PD pulses;
- Pulse power of PDs;
- Root-mean-square parameter.

The apparatus provides real-time visual display of various (at the option of an operator) types of measurement oscillograms, including three-dimensional ones, as well as the graphs of a test in progress with PD characteristics measurements. The device software (PDScanner 2.0) allows the operator to select the modes and ranges of PD characteristics measurements in the object, to calibrate the measurement scheme (in manual or automatic mode), and also to save the results of calibration and measurements as test reports automatically generated by the device. In the course of measurements, the operator can record any moment of measurement in a protocol as an oscillogram with all the PD characteristics measured at that moment. The noise, threshold and position filtering of a measured signal executed by the device ensure a high noise immunity of measurements. The device, as a rule, does not require any special, carefully shielded chambers: it is successfully used in the production of electrical equipment.

Electrosetservice uses a system for diagnostics and isolation of power transformers developed by the Special Design and Technology Bureau of the Mosenergo Association. The system detects the presence of PDs by an acoustic method in the frequency range of 40–100 kHz; it has 20 acoustic sensors and a stationary recorder unit. To determine the coordinates of the location of discharges according to the Mosenergo method, the sensors are placed in the form of a three-pointed star on the surface of the tank, the location being determined by the difference in the time of signals arrival. The intensity of discharges is determined by the magnitude of the signals, taking into account the depth of the occurrence of the site of discharges.

The Research and Development Center ZTZ-Service, which has performed surveys of many transformers in Russian power grids, considers the detection of PDs as a promising technique for monitoring the insulation condition of power transformers. At the same time, according to the experts, the difficulty of protecting against interference during measurements poses a serious problem.

DIMRUS stands out amongst Russian developments and equipment manufacturers. The appearance of one of its latest developments is shown in Fig. 2.14 (Tables 2.4 and 2.5).

The operation principle of the meters is based on a conversion technique using an analog-to-digital converter of information about PD signals, which is extracted by sensors included in the meters. There are two basic modes of operation:

- mode of periodic measurements of the maximum voltage amplitude and the number of PDs per one second,
- “temporary” monitoring mode [30].

Fig. 2.14 R2200 designed by ***DIMRUS***

Table 2.4 R2200 parameters

No.	Parameter	Value
1	Number of channels for PD measurement	9
2	Frequency range of measured discharges	0,5–15,0 MHz
3	Dynamic range of registered PD	70 dB
4	Synchronization of PD pulses registration	Internal–External
5	Color screen resolution of the device, points	480*640
6	Computer interface	USB
7	Operating temperature range of the device	$-20 + 40$ C
8	Operating time powered by the built-in battery, h	5
9	Device weight without sensors, kg	3,5
10	Overall dimensions of the transport case, mm	520*430*220
11	Kit weight in a transport case, kg	21,5

Table 2.5 AR200 device parameters

No.	Parameter	Value
1	Number of channels for PD measurement	1 acoustic
2	Frequency range of measured discharges	30 kHz–300 kHz
3	Data presentation	LCD backlit display
4	Color screen resolution of the device, points	128*64
5	Standby mode	At least 15 h
6	Overall dimensions of the transport case, mm	160*120*38
7	Device weight, kg	1

To register PDs acoustically, ***DIMRUS*** has developed an AR 200 sensor (Fig. 2.15).

The apparatus for detecting PDs acoustically consists of a primary transducer (sensor) and a measuring device. The acoustic sensor converts a pressure pulse into an electrical signal. Piezoelectric transducers are commonly used. During operational inspection, the sensors are placed on the surface of an oil-filled transformer tank. This device has a significant drawback: it does not record low-intensity PDs (Fig. 2.16).

A similar device UltraTest has been developed for registering PD in the ultrasonic frequency range. The appearance of the device is shown in Fig. 2.12 [30].

To date, several models of devices and system architectures have been developed and used for detecting and measuring PD parameters by using their electromagnetic radiation. For example, Fig. 2.17 shows a directional antenna device with an HVPD Longshot operating unit and an HFCT sensor. The system allows detecting PDs by oscillations of electromagnetic waves in the frequency range from 300 MHz to 3 GHz. Its disadvantage is the impossibility of controlling the intensity of the discharges.

Fig. 2.15 AR 200 sensor

TEV (Transient Earth Voltage) sensors, which are capacitively coupled devices, are effective for measuring local PDs in insulation. For PD measurements, a TEV sensor must be fixed to a grounded metal surface (Figs. 2.18 and 2.19).

Among the promising methods of PD detection, a technique based on a registration of ultrasonic PD vibrations stands out, using sensor detectors and data analysis through wireless communication in ON-LINE mode. A technology based on the acoustic method is being developed in China [31]. The concept of the method implementation is shown in Fig. 2.20.

High-performance sensor detectors located at a certain angle in relation to the equipment and to each other capture the slightest ultrasonic waves and transmit the data to a cloud server, where they are analyzed and decoded in detail.

An effective system for analyzing PD pulses in the time and frequency ranges has been proposed in Switzerland.

The correct analysis of PD-current impulses in the time and frequency-domain requires wideband-coupling devices directly connected to the terminals of the power transformer. High frequency current transformers (HFCT) with a frequency range between 0.1 to 30 MHz have been successfully applied for this purpose [32].

To provide multi-terminal detection capability, which is important for the PD-analysis in the complex insulation systems of transformers or generators, the HF-CT’s are directly connected to the capacitive tap of each transformer bushing (including

Fig. 2.16 Portable device for acoustic PD registration in the ultrasonic range

Fig. 2.17 HVPD antenna device by Longshot

low voltage bushings and neutral terminal bushing), or to the external coupling capacitors at the generator terminals. Advanced PD-detection systems (see Fig. 2.21) were introduced to analyse both, PD-pattern (statistical analysis of the PD-signal magnitudes) and PD current impulses in the time- and frequency-domain [33].

The main components of the advanced PD-detection system consist of commercially available instruments: (1) Spectrum analyser with a typical frequency span

Fig. 2.18 HVPD Longshot TEV sensor

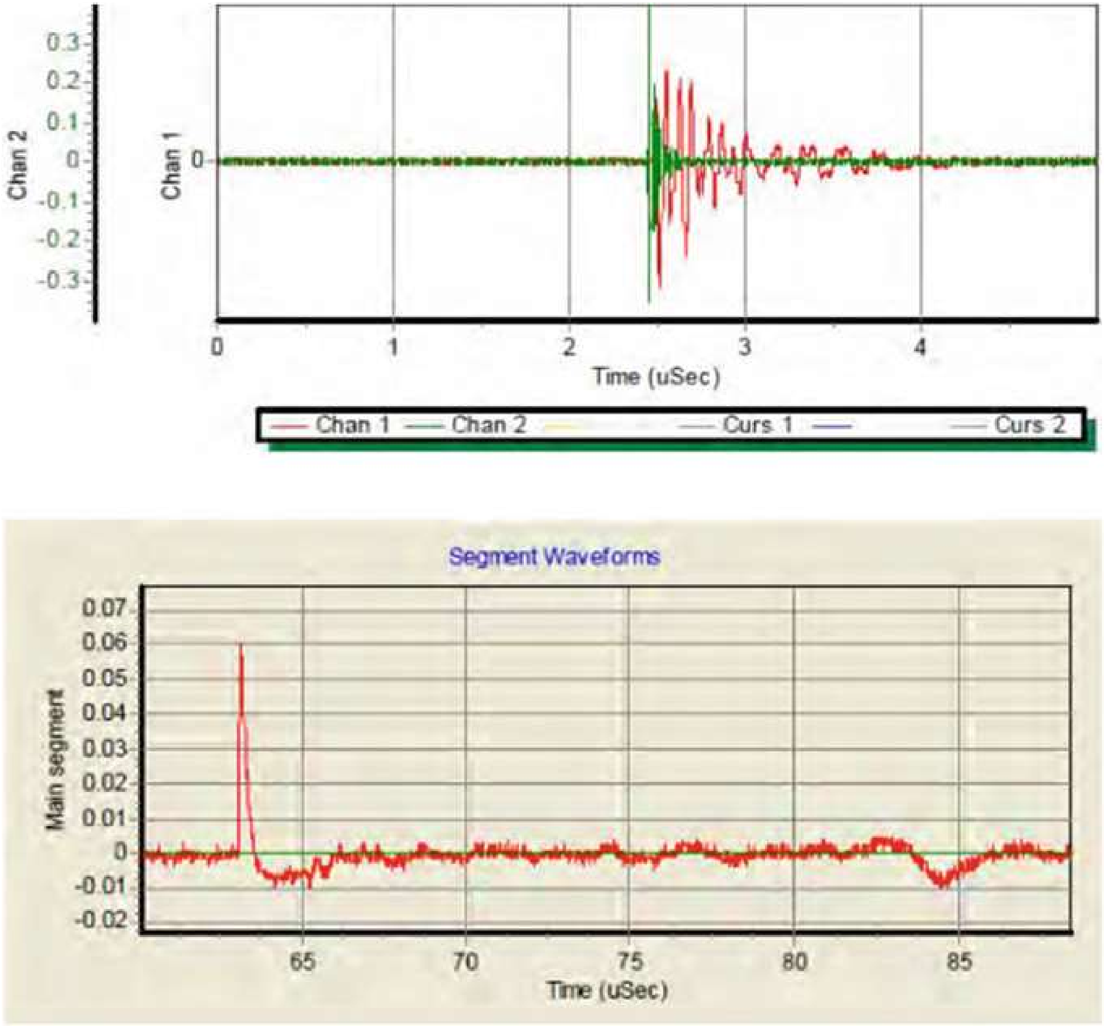


Fig. 2.19 PD pulses measured with a TEV sensor

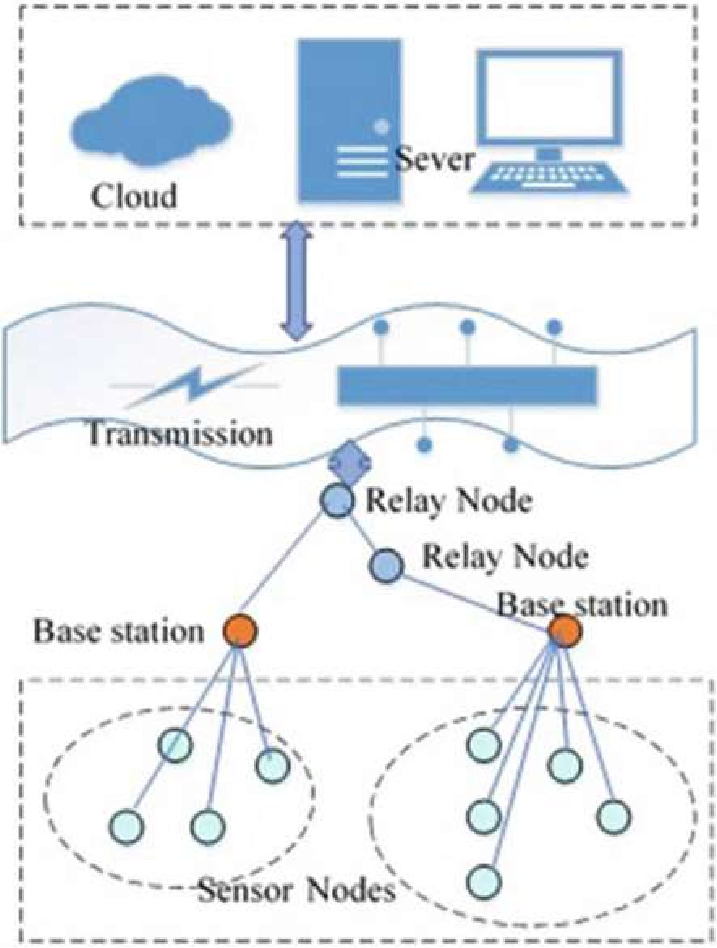


Fig. 2.20 PD registration based on highly sensitive detectors and wireless communications

between 1 kHz and 20 MHz. The spectrum analyser can be used for the analysis of PD-signals in the frequency-domain (full span mode) or for the quasi-integration of PD-signals to evaluate the value of the apparent charge using the variable band-pass filter (zero span mode). Normally the band pass filter of the spectrum analyser is utilized as a front-end of a PRPDA-system to record PD-pattern. (2) The multichannel digital oscilloscope is an analyzing device for PD-signals in the time-domain. The oscilloscope must have at least two channels with a bandwidth larger than 500 MHz. (3) The PD-analyser (PRPDA-system) is a computer controlled impulse acquisition and digital signal processing system preforming statistical analysis of recorded PD-data (PD-pattern). In a typical measuring set-up for power transformers or power generators, multi-channel PD analysers are used to record and process the signals from all terminals simultaneously.

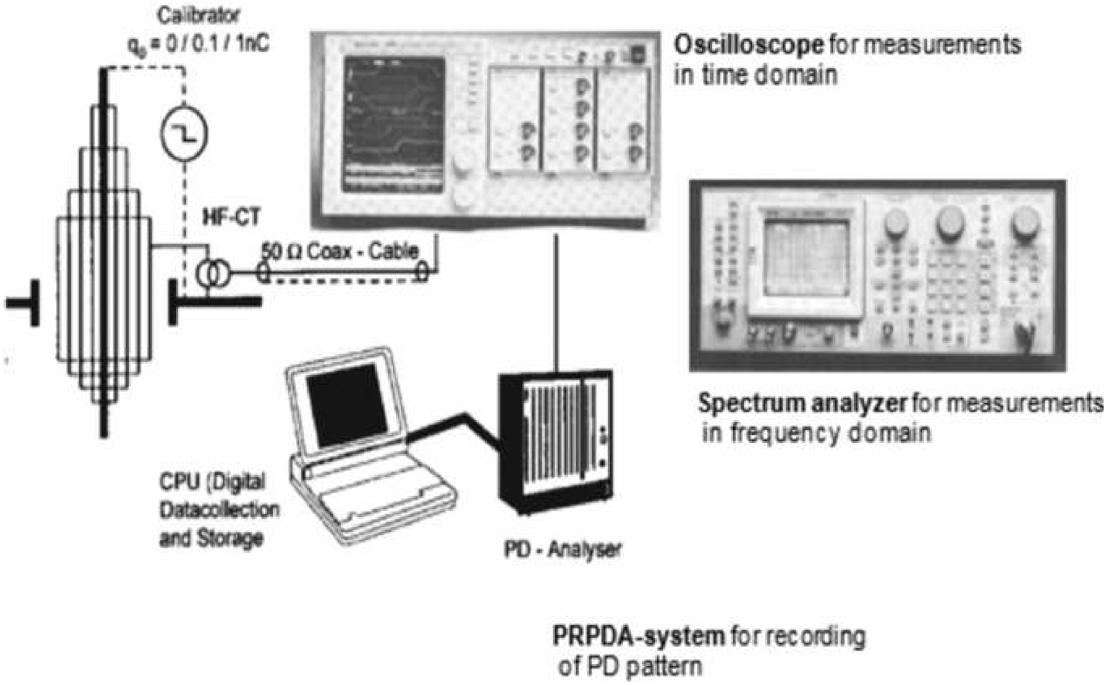


Fig. 2.21 Advanced PD-detection system: (1) spectrum analyzer, (2) digital oscilloscope, (3) PD-analyser (PRPDA system, (4) wide band current transformer (HF-CT) connected to bushing tap

2.2.2 Idling Loss Measurement

The losses in a power transformer are known to consist of so-called copper and steel losses. Copper losses are associated with a flow of load current through winding conductors, having a certain electrical resistance. Losses in the steel of a core are due to eddy currents, being magnetizing currents arising in a magnetic conductor.

According to the Rules for Electrical Installations (REI), measurements are made for transformers with a capacity of 1000 kVA and higher, at a voltage on the LV winding equal to that specified in the factory test report (passport), but not higher than 380 V. Idling losses of three-phase transformers are measured at a single-phase excitation according to the manufacturer scheme. When commissioning a transformer, the ratio of losses on the different phases of three-phase transformers should not differ from the factory data by more than 5%, and for single-phase transformers, the difference of the measured of losses from the original ones should not exceed 10%.

An open-circuit test for single-phase transformers is made at a voltage of 380 (220) V or less, supplied from the LV side at a frequency of 50 Hz in accordance with Fig. 2.22a, b. The supplied voltage must not exceed the rated voltage.

The applied voltage, the current, and the power P consumed by the tested transformer and the measuring devices are measured in accordance with Fig. 2.22a. Then the power consumed by the measuring devices $\sum P_{MES,DEV}$. is measured in accordance with Fig. 2.22a, b.

Losses in the transformer (P_0) are calculated using the formula

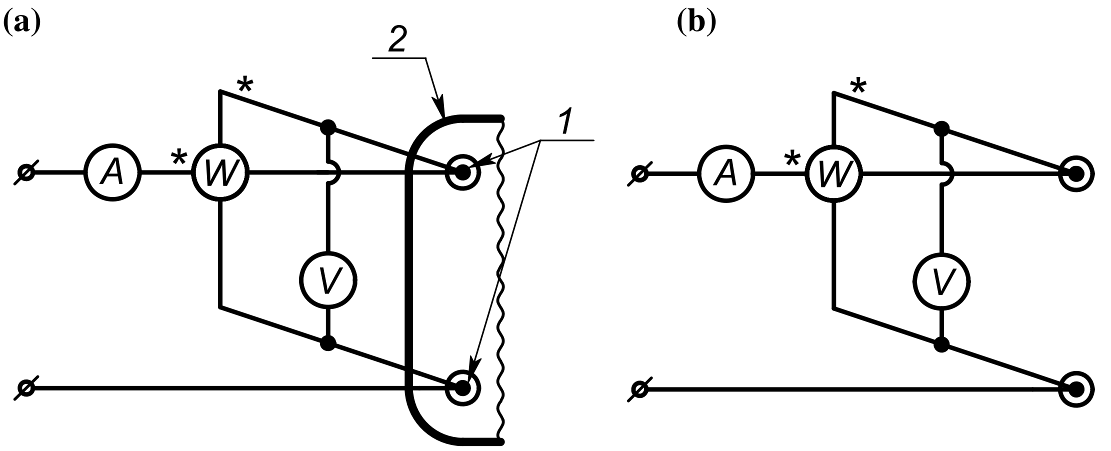


Fig. 2.22 Scheme for measuring the losses of a single-phase transformer XX: **a** measuring the losses of a tested transformer, **b** measuring the losses of measuring instruments: A—ammeter, V—voltmeter, W—wattmeter

$$P_0 = p - \sum P_{MES,DEV}. \tag{2.4}$$

Note. In the circuits of Fig. 2.22, it is allowed to use current-measuring instrument transformers.

Experiment of a three-phase transformer at low voltage is carried out in as the following three single-phase experiments made in accordance with experiment for single-phase transformers.

The first experiment: the windings of phase A are short-circuited; phases B and C of the transformer are excited and the losses are measured.

The second experiment: the windings of phase B are short-circuited; phases A and C of the transformer are excited and the losses are measured.

The third experiment: the windings of phase C are short-circuited, phases A and B of the transformer are excited and the losses are measured.

Short-circuiting of any phase is made at the corresponding terminals of any of the transformer windings (high, medium or low voltage).

Any of the transformer windings can be used to short-circuit one phase. The connection diagrams of transformer windings are shown in Fig. 2.23.

A measurement is usually made by applying voltage to two of the phases and short-circuiting the third phase of the low voltage (LV) winding, which results in more excitation of the magnetic system. The lower voltage makes it easier to measure voltage, power and current, therefore it is common to conduct experiment from the side of the LV winding.

The disadvantage of this method is the limited accuracy and reliability of identifying the winding defects.

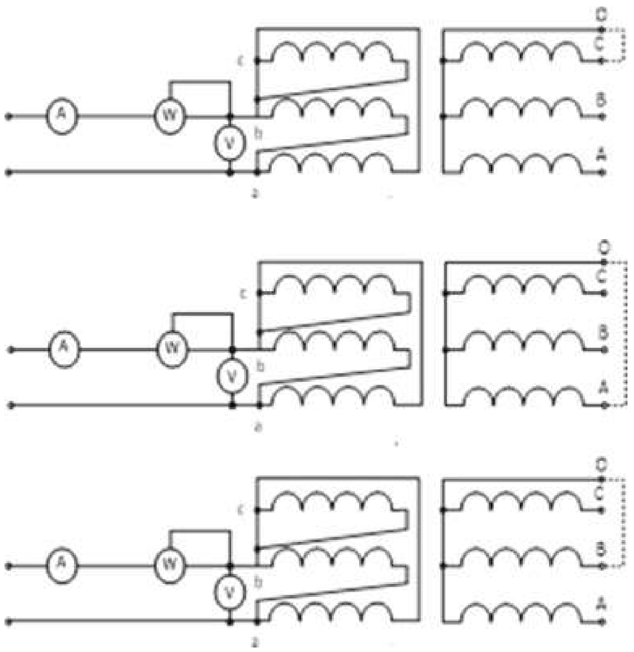


Fig. 2.23 Connection diagrams for the windings of a three-phase transformer

2.2.3 Transformation Ratio Measurement

The transformation ratio (TR) of power transformers is tested in order to confirm the compliance of the actual TR with the nominal one. TR is determined on all the winding branches for all the phases; on those winding branches that are inaccessible for switching on an assembled transformer this is determined before the complete assembly of a transformer. When testing three-winding transformers and transformers with split windings, TR may be examined for two pairs of windings, and measurement on all the branches of each of the windings is sufficient to be conducted once.

If a tap changer of winding branches has a tap selector, which is used to reverse the adjusting part of a winding or switch the coarse-control steps, then measurements can be carried out with one position of a tap selector corresponding to the lowest of the voltage values on the regulated winding. In addition, one more measurement is carried out in all other positions of the tap selector.

When testing three-phase transformers with three-phase excitation, line voltages are measured, corresponding to the same line terminals of the tested windings. If it is possible to measure phase voltages, it is allowed to determine the transformation ratio by the phase voltages of the corresponding phases. The transformation ratio for phase voltages is checked with single-phase or three-phase excitation of the transformer.

When testing three-phase transformers with windings connected according to the “star-delta” and “delta-star” circuits, the transformation ratio for phase voltages is determined with an alternated short-circuiting of phases. In this case, one of the phases connected in a “triangle” (for example, phase A) is closed, then, with single-phase excitation of the linear ends, the transformation ratio of the remaining free pair of phases is determined, which, in this method, should be equal to $2\ \text{К}_{ph}$ (if the HV winding is connected as a “star”) and 0.5 $К_{\mathrm{ph}}$ (if the LV winding is connected as a “star”), where $К_{\mathrm{ph}}$ is the phase transformation ratio. Measurements are carried out in the same way with short-circuiting phases B and C.

When testing transformers with the same winding connection schemes, it is allowed to carry out measurements with three-phase excitation, if it is established that the difference between the highest and lowest line voltages does not exceed 2%.

The transformation ratio is determined using two voltmeters. Voltage is applied to one of the transformer windings and is measured with one of the voltmeters. At the same time, the voltage on the other winding of the transformer is measured with the other voltmeter.

It is allowed to use measuring voltage transformers, as well as external resistors additional to voltmeters. The accuracy class of voltage transformers and additional resistors must be at least 0.2. The supplied voltage must not exceed the rated voltage of the transformer, but must be no less than 1% of the rated voltage. It is allowed to supply a voltage of less than 1% of the rated value if a voltage transformer is required when supplying a voltage exceeding 1% of the rated value. A voltmeter on the side of supplied voltage is allowed to be connected to the supply wires if this has no significant effect on the measurement accuracy. When measuring the transformation ratio, the resistance of the measuring circuit wires should be no more than 0.001 of the internal resistance of the voltmeter.

Conclusions on the consistency or inconsistency of measurement results are made on the basis of analysis for the measured value of transformation ratio.

The main disadvantage of the method is a limited number of identifiable defects, having a high degree of development.

2.2.4 Insulation Resistance Monitoring for Transformer Windings

The insulation resistance measurement method is the simplest and most accessible one. It is based on the characteristics of a change in the electric current passing through the insulation after applying a constant voltage to it. The insulation of transformer windings is a non-uniform dielectric. In the general case, an electrical equivalent circuit of insulation can be represented in the form of three branches (Fig. 2.24): the geometric capacitance of the dielectric C_1, the geometric capacitance of the dielectric layers C charged through the resistance of the dielectric layers R, and the insulation resistance of the dielectric R_1.

When a constant voltage is applied to the terminals of a circuit, the current will consist of an arithmetic sum of three components:

(1) capacitive current I_r, due to the so-called geometric capacitance C_r; the current I_r almost instantly drops to 0, since the capacitance C_r is connected to a source without resistance and does not affect the results of measuring the resistances R_{15} and R_{60};

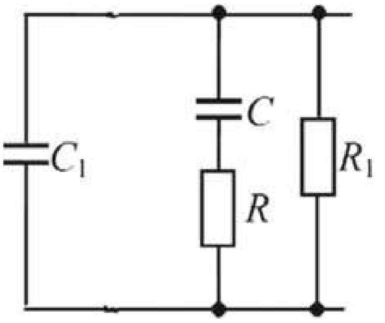


Fig. 2.24 Isolation-equivalent circuit

(2) absorption current I_{abs} flowing along the R_{abs}–C_{abs} branch; this current reflects the process of charging a number of dielectric layers through the resistance of the previous layer. When the insulation is moistened, the resistance R_{abs} decreases, and the capacitance of C_{abs} increases, and therefore, for a more humidified insulation, the current I_{abs} has a greater value and drops faster to 0. In dry insulation, the resistance R_{abs} is high, the charge of the capacitor C_{abs} flows slowly, so the initial value of the current I_{abs} is small, and the current takes a long time to drop;

(3) through conduction current I_{thr}, flowing through a resistance R_{thr}, depending on the characteristics of both external pollution of the insulation and on the paths of through leakage; this current is established almost instantly and does not change over time.

The total insulation resistance, measured by a megohmmeter, is inversely proportional to the sum of the indicated current components; at the beginning of measurement it has the lowest value, and then, as the current falls, I_{abs} increases, reaching a steady-state value determined by the current I_{thr}. In order to have comparable results, the insulation resistance is measured 60 s after the voltage is applied, although in some cases the current I_{abs} has not completely dropped by this time.

Measurement of the insulation resistance of transformer windings is carried out in accordance with GOST 3484.3–88. The insulation resistance value indicates the average condition of insulation and decreases as this condition worsens, mainly due to moisture and pollution. To estimate the condition of the transformer insulation, the insulation resistance of all windings is measured. When measuring, all the winding leads of the same voltage are connected together. The rest of the windings and the transformer tank must be grounded.

When assessing the condition of insulation, simultaneously with a measurement of the resistance R_{60} the absorption coefficient is measured. The absorption coefficient is the ratio of insulation resistance measured 60 s after the voltage is applied to the resistance measured after 15 s; its values do not depend on the geometric dimensions of insulation and characterize only the intensity of the drop in the absorption current. With the removal of moisture from the insulation, the absorption coefficient increases, and with moisture it decreases.

Table 2.6 Insulation resistance of transformer windings

Winding temperature, t °C	10	20	30	40	50
Insulation resistance 35 kV, Mohm	450	300	200	130	90
Insulation resistance 110 kV, Mohm	900	600	400	260	180
tgδ winding insulation,%	1,8	2,5	3,5	5,0	7,0

The value of absorption coefficient $K_{\mathrm{abs}} = R_{60}/R_{15}$ must be no less than 1.3 at temperatures of 10 to 30 °C. For well-dried insulation, the values of absorption coefficient normally range from 1.3 to 2.0, see [34]. During commissioning and preventive tests, insulation resistance is measured in accordance with schemes used by the manufacturer, and additionally also in the insulation zones. During preventive tests, measurements are only allowed in the isolation zones.

The insulation temperature when measuring the insulation resistance of windings must be no less than

10 °C—for transformers with voltage up to 150 kV inclusive;
20 °C—for transformers with a voltage of 220–750 kV.

The insulation resistance of the windings of transformers up to 35 kV inclusive should be no lower than the values presented in Table 2.6.

Being combined with other control methods, this method can be useful for detecting contamination and moisture in insulation at relatively early stages. Measurements are usually carried out with a 2.5 kV megohmmeter using a clamp on the "shield" for measurement by zones. The insulation resistance is highly dependent on the winding temperature and the stability of the megohmmeter voltage. Thus, the difficulty of determining the temperature with reliability (by its resistance to direct current) reduces the value of insulation resistance as a parameter for estimating the winding condition.

The disadvantages of this method include restrictions on the temperature range at which the insulation resistance is measured, while the detection of damage occurs at the stage of insulation aging, which is close to critical. This method allows one to determine only gross defects in equipment: through burnout, strong moisture or contamination of insulation [7].

2.2.5 Measurement of Winding DC-Resistance

The measurement of winding resistance to direct current is made to examine the condition of electrical contact connections and the integrity of the electrical circuit of transformer windings. Defects identified during this measurement are caused by the following reasons:

- reakage of one or more of parallel wires in the taps;
- violation of soldering;

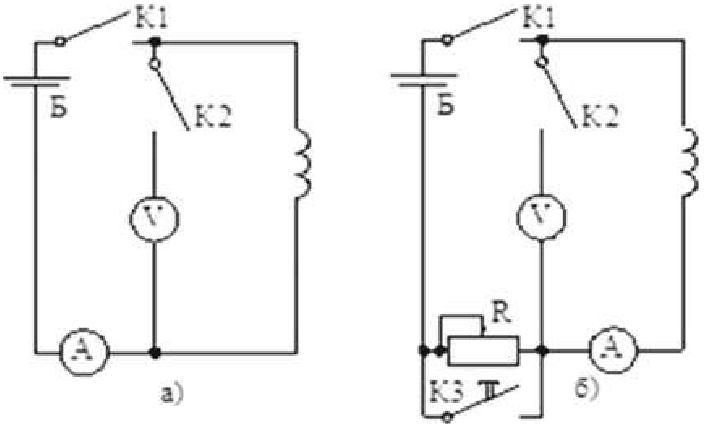


Fig. 2.25 Winding DC resistance measurement circuits

- poor-quality contact of connecting the winding taps to the bushings;
- poor-quality contact in the off-circuit tap-changers and on-load voltage regulation devices (OLVR) of the transformer;
- incorrect installation of an off-circuit tap-changer.

In installation conditions, resistance is usually measured by the ampermeter and voltmeter method. Figures 2.25a, b show two schematic diagrams of connecting instruments for measurements. The diagram in Fig. 2.25a is used when measuring small resistance values: starting from fractions of Ohm to several Ohms, and the circuit in Fig. 2.25b is used when measuring large values of resistance. A correct choice of measurement circuit eliminates significant errors due to voltage drops in the devices, which are usually not taken into account when calculating the resistance value.

Basically, in practice, the circuit shown in Fig. 2.25a is used. In this scheme, the current and voltage circuits are separated. They are made with separate wires in order to exclude from the measured resistance the resistance of the wires of the current circuits and the transition resistances at the points of connection of the voltage circuits to the inputs of the transformer. The voltage measuring circuit must be connected directly to the current-carrying pins of the bushings of the tested winding. Typically, resistance is measured at voltages up to 24 V and currents up to 10 A. In this case, the excess current should be no more than 20% of the rated winding current.

For single-phase transformers, the resulting values should not differ by more than 2% of the values specified in the passport, at the same temperature and with the same control taps.

For three-phase transformers, the resistances measured on the same branches of different phases should not differ from each other by more than 2%, unless there are special instructions in the passport.

The resulting values of the winding resistance to direct current lead to the temperature specified in the transformer passport. They are determined using the formula

$$R_x = \frac{R_0(235 + t_x)}{235 + t_0}, \tag{2.5}$$

where R_x is the resistance value at the temperature t_x specified in the passport, Ohm; R_0 is the resistance value at the measurement temperature t_0, Ohm; t_0 is the measurement temperature, $°C$; t_x is the temperature $°C$ specified in the passport.

The temperature of the upper layers of oil is taken as the temperature of an oil transformer which has not yet been turned on and heated, provided that the resistance is measured no earlier than 30 min later after oil filling for transformers up to 1000 kVA inclusive, and no earlier than 60 min for transformers of higher power.

The considered circuits for measuring the resistance of windings and the method itself have the following disadvantages:

- measurements must be made at temperatures no lower than +10 °C;
- all devices used must be of high accuracy class;
- only highly developed defects are registered.

2.2.6 Short-Circuit Resistance Monitoring

This control method, due to its relative simplicity, is widely used in power systems, both when testing transformers for short-circuit resistance, and in operation.

The essence of the method is exemplified in Fig. 2.26. It consists in measuring the voltage drop across the resistances in each phase of a transformer and the current flowing through them, and in determining the resistance value from the result obtained.

Let us denote by R_1 and L_{S1} the active resistance and leakage inductance of the primary winding of the transformer; R_2 and L_{S2} are the values of active resistance and scattering inductance of its secondary winding reduced to the primary winding; R_0 and L_0 are the active resistance and inductance of the primary winding, which

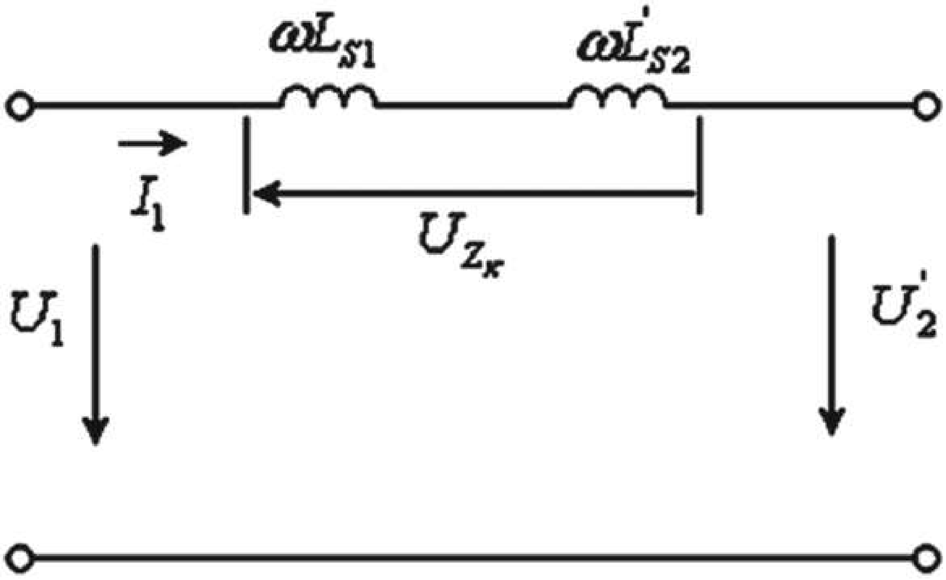


Fig. 2.26 Equivalent circuit of a transformer

determine the no-load current of the transformer. For power transformers, the typical relation between element parameters in a circuit meets the conditions

$$\omega L_{S1} >> R_1,\ \omega L_{S2}^{'} >> R_2^{'}\,\omega L_{S1} << \omega L_0 >> \omega L_{S2}^{'}$$

Under these assumptions, the electrical circuit of a transformer can be presented in a simplified form, Fig. 2.26.

By measuring the voltage U_{Z_K} and current I_1, one can calculate the modulus of Z_K, since the leakage inductance of a winding is directly related to its geometric dimensions; changes in the latter are unambiguously reflected in changes in the values of $L_{S1} + L_{S2}$. Therefore, monitoring changes in leakage inductances is a direct method for measuring winding deformation. It should be noted that the leakage inductance of transformer windings is small, and it is necessary to measure its change with high accuracy. Therefore, a measurement should be organized according to the first harmonic, taking measures to minimize the level of higher harmonics, first of all, the third harmonic, which occurs when the magnetization reversal of a transformer core is due to the nonlinearity of the magnetization curve of a steel core. This creates additional inconveniences in control. The main disadvantage of the method is that it is highly sensitive only to those types of deformations of transformer windings that lead to a change in the size (volume) of the scattering channel. Therefore, having a relatively good sensitivity to the loss of radial stability of windings, due to the fact that this increases the volume of the main scattering channel, the Z_K method turns out to be insensitive to other types of damage, such as lodging of turns, slipping of winding turns, and unwinding.

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