Chapter 1

Causes of Power Transformer Failure

A high-voltage transformer is a complex device in both design and materials. Accordingly, the causes and effects of failures affecting both the structure elements of a transformer and the entire apparatus are quite diverse. Figure 1.1 shows the most common defects occurring in three transformer elements being the main assembly units.

Monitoring the condition of high-voltage power transformers, being expensive, critical and long-term elements of power systems, is based on registering alterations in the physicochemical and mechanical properties of materials, as well as in the geometric parameters of assembly units and structure elements, which are ultimately responsible for transformer failures. The origin of failures lies in electrical, thermal, mechanical and other influences on the normal operating mode, as well as in emergency situations, see Fig. 1.2.

1.1 Failure Statistics of Transformer Construction Elements

To determine the reasons for transformer failures, a study of incidents affecting two groups of transformers from different series and classes of voltage and rated power has been carried out. One of the groups of transformers under study included three-phase three-winding oil-filled power transformers with forced air circulation and natural oil circulation, transformers with voltage regulation under load, as well as three-phase two-winding oil power transformers of 110/6 kV with low-voltage split winding, forced air circulation, natural oil circulation, and voltage regulation under load. Analysis of incidents affecting the mentioned series of 110 kV voltage transformers with a rated power of 16,000–40,000 kVA makes it possible to state the reasons for transformer failures as listed below.

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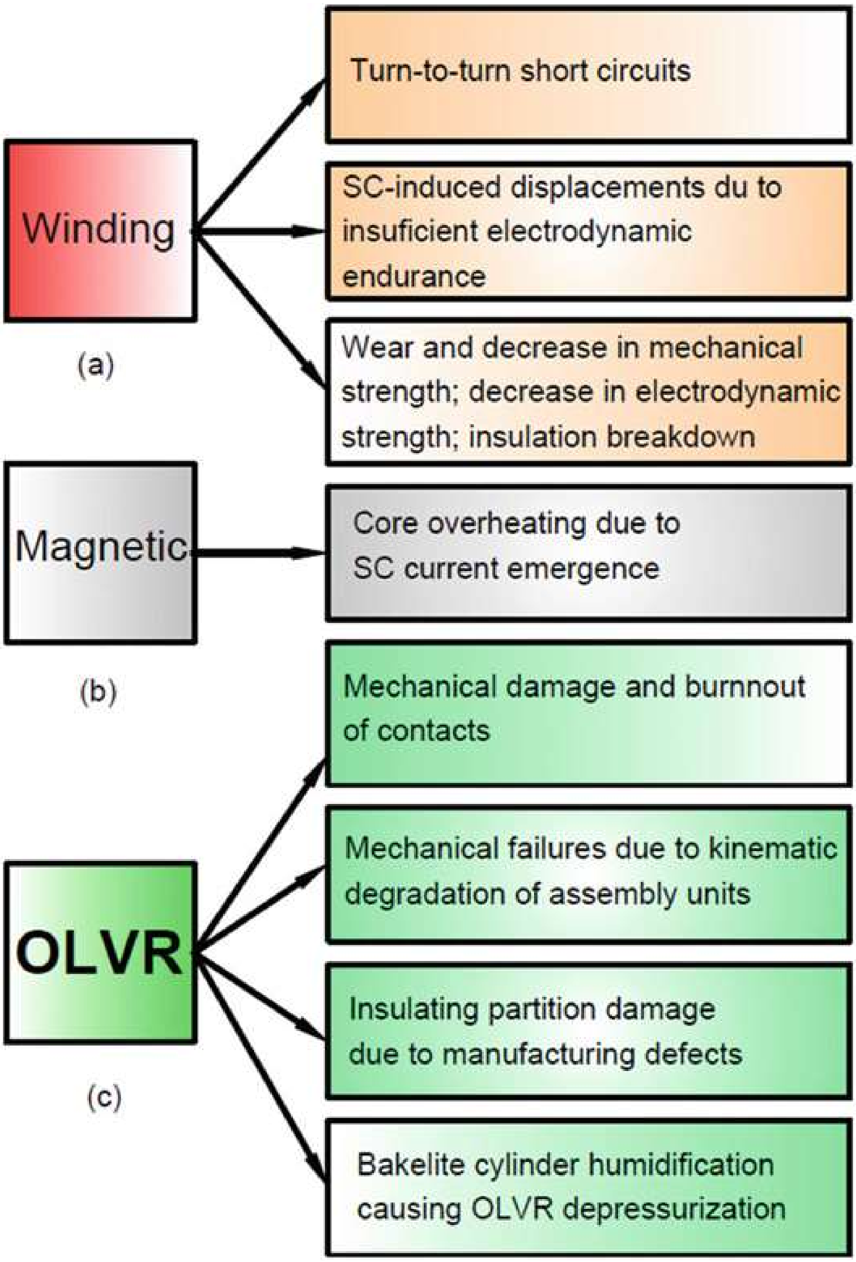


Fig. 1.1 Common types of defects in transformer active parts; **a** winding defects; **b** magnetic conductor defects; **c** OLVR defects

The share of various reasons for transformer failures is as follows:

- 25%—turn-to-turn short circuit;
- 45%—mechanical displacement of windings;
- 30%—other damage.

In some cases (8% of the total), incidents affecting transformers in the specified voltage class and rated power occurred due to reasons unrelated to any winding issues, namely, activation of the gas and differential protection systems of a transformer and gases (mostly acetylene) formation.

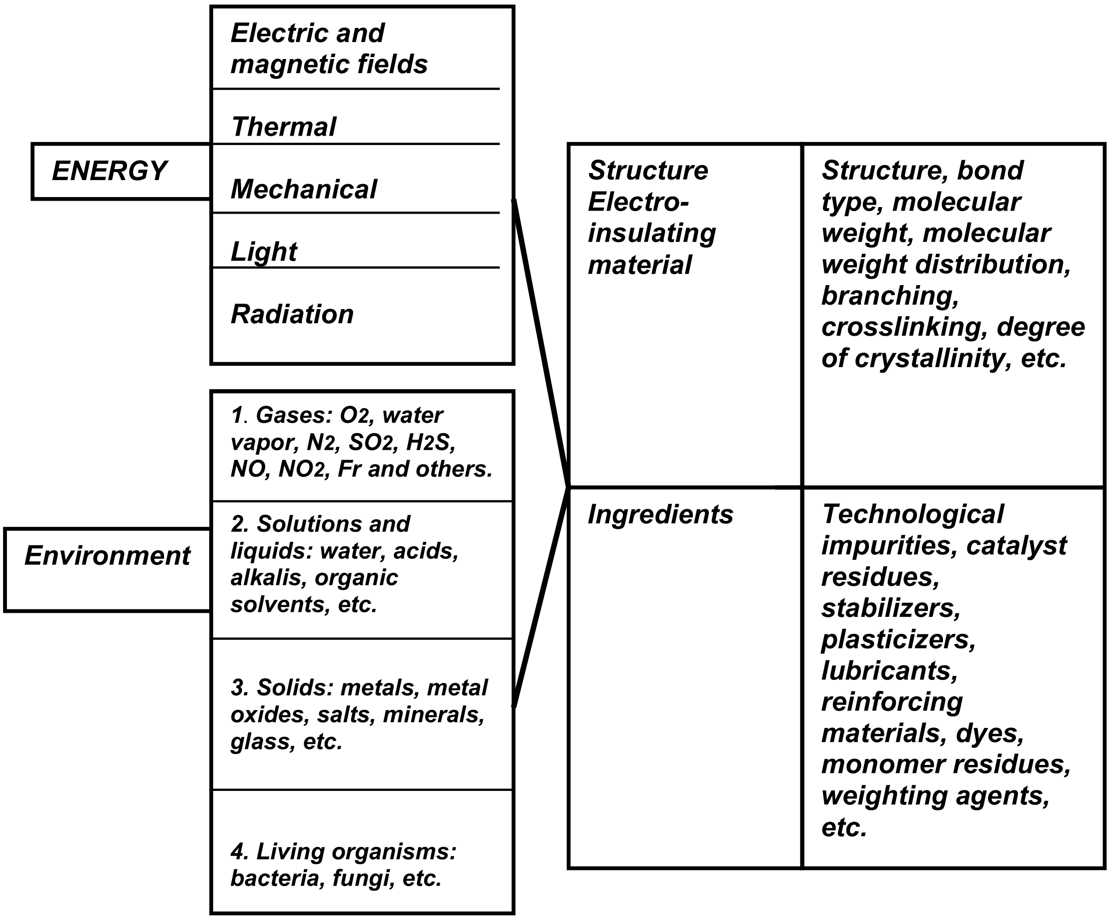


Fig. 1.2 Factors causing the aging of insulation and their dependence on the structure and ingredients of insulation

The next group under study included general-purpose 10/0.4 kV transformers of capacity between 10 and 630 kVA, with natural oil cooling and with a switch without excitation, connected to an alternating current network with a frequency of 50 Hz and intended for power transmission and distribution in moderate and cold climate. Analysis of problem-related situations involving 401 units of 10/0.4 kV 10/(10–630 kVA) power transformers taken out for repair revealed the following: mechanical displacements are responsible for 100 cases, turn-to-turn short circuit explain 74 cases, other defects (oil leakage, switch and contact connection issues, destruction of bushings, burnout of tightening pins) comprise 227 cases. In percentage terms, the result of analysis for 10/0.4 kV transformers is shown in Fig. 1.3 and Table 1.1.

Analysis of the data in Fig. 1.3 and Table 1.1 shows the following:

1. Winding defects account for 43% of the total number of incidents.
2. Mechanical displacements prevail among the winding defects and comprises 25% of the cases; turn-to-turn short circuits in one or both of the windings are responsible for 18% of the incidents in the total number of damaged transformers.

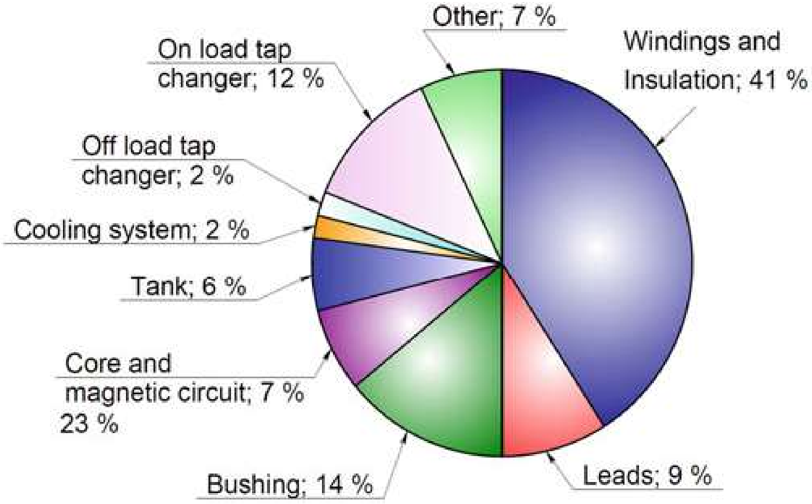


Fig. 1.3 Failure statistics for power transformers [1]

Table 1.1 Failure statistics and main types of damage affecting power transformers of 10/0.4 kV in the distribution grids of one the Russian power systems

Total number of transformers	Number of transformers with mechanical displacement of windings	Number of transformers with turn-to-turn SC	Number of transformers with other damage
200	46	22	132
134	30	10	94
36	13	23	0
31	11	19	1
401	100	74	227

3. Reasons for taking equipment out for repair, other than defective conditions of windings (oil leakage, anzapf switch issues, burnout of contact connections, destruction of bushings, burn out of tightening pins), make up 57%.

The state of events described and exemplified above is typical not only for the energy system of Western Siberia, but also for other electric power systems of the Russian Federation. Thus, according to JSC Samaraenergo, for transformers and autotransformers with a voltage of 110–500 kV, around 30% of the total number of outages has been accompanied by internal SC emergence.

According to conclusions made by a general inspection of 110–500 kV transformers and auto-transformers with a capacity of 63 MVA and above, operated at enterprises of power and intersystem grids in Russia, around 30% of the total amount of technological failures related to disconnection of equipment by protection devices or personnel on an emergency request has been accompanied by internal SC emergence.

The main reasons for such shutdowns are wear and tear, turn-to-turn circuits, breakdowns of taps and winding insulation, insufficient electrodynamics endurance of windings to short circuits, internal insulation breakdowns in high-voltage bushings, and damage to OLVR. One of the main reasons for transformer damage is the insufficient endurance of windings against short circuits, leading to the occurrence of mechanical and electrical defects.

Thus, the analysis of factual material on transformer failures at power system facilities in the Russian Federation shows that one of the main reasons for this state of events are defects in the active parts, namely, the windings, which make up 43% for 10/0.4 kV transformers and over 30% for transformers of the 110 kV voltage class and rated power of 16–40000 kVA. Such statistics are typical for most electric power systems in the Russian Federation.

Detailed accounts of transformer failures in other countries do not appear on a regular basis. According to the Union of German Power Engineers, VDEW, the damage rate for power transformers in 1980–1993 was 0.36% for 110 kV units, 1.54% for 220 kV units, and 2.07% for 380 kV units. Statistics over 13 years for 60 blocks operated in the Netherlands during 700 block-years show a damage rate of about 1.4% per year, with the unit availability factor around 0.995. Calculations show that an increase in the availability factor up to the desired value of 0.998 can be achieved by increasing the transformer stockpile.

The damage statistics of 1970–1986 for large transformers with a voltage of 33–500 kV in Australia revealed a damage rate of around 1% per year. The damage rate in the series of 765 kV transformers operated by American Electric Power (USA) from the beginning of their operation until 1985 amounted to 2.3% per year, while in the series of 345 kV transformers it was 0.7% per year. Based on these data, specialists concluded that it was necessary to develop a new series of 765 kV transformers with an endurance increased to damage, which was accomplished by Westinghouse Electric Corporation. Transformers designed for higher voltage tests replaced the damaged ones. The ANSI/IEEE standard voltage regulations for testing the insulation of HV and LV windings were increased by 14% and 30%, respectively [2].

According to research on the causes and effects of power transformer failures in the Nordic countries, namely, involving Finnish, Swedish, Norwegian and Danish grid companies and conducted from 2000 to 2010 by Vaasa University, Finland, the main reasons for the failures were overvoltage, winding defects and insulation destruction. More than half of the damaged transformers had a service life of 20–40 years [3].

Fig. 1.4 Distribution diagram for transformer defects (Finland)

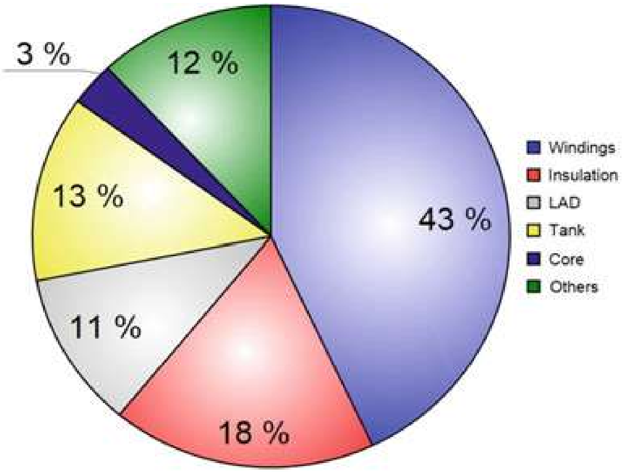
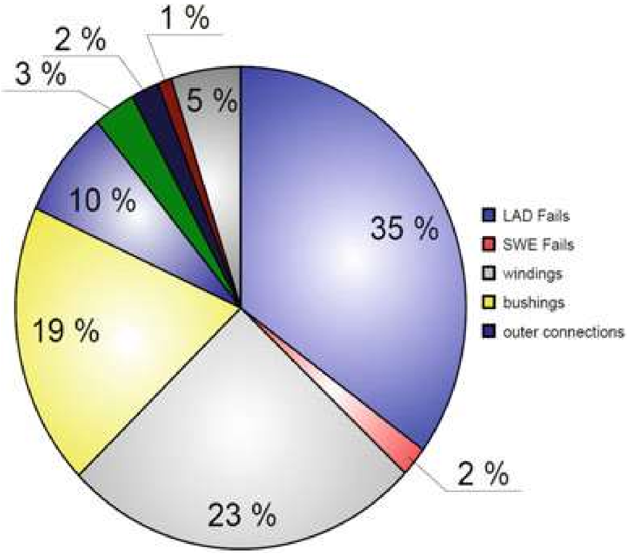


Fig. 1.5 Distribution diagram for transformer defects (Poland)



The companies that participated in the study were Finnish (3), Norwegian (6), Danish (1) and Latvian (1). A total of 105 transformers were examined. The most vulnerable components of a transformer proved to be the windings. Almost half of all failures occurred in the windings, OLVR and bushings. Figure 1.4 shows a diagram of damage distribution in percentage terms.

Analysis of the causes of identified internal damage showed that the most frequent defects of 110 kV transformers in Poland were due to local heating of the core and winding, internal short circuits, and simultaneous influence of several types of internal defects [4]. The share of different types of damage is shown in Fig. 1.5 (statistics for 22 years).

It was found that, among all the transformer equipment components, OLVR held the first place in terms of malfunction probability, 35%, while the second place belonged to transformer windings.

Table 1.2 Distribution of damage according to the PN criterion

Damage	PN
Windings	6–48
Insulator	24–48
OLVR	28–52
Core	6
Tank	18
Protection system	22–64
Cooling system	26–48

The results of analysis for the nature and causes of failures in 11 kV/220 V step-down transformers carried out by PESCO, Indonesia, for 5 years (2010–2015) are shown in Table 1.2. The distribution of damage is presented according to the PN* criterion.

* The PN (Priority Number) criterion that determines the degree of urgency for taking action and is described as follows:

$$PN = Severity \times Defect\ Manifestation \times Detection$$

The minimum PN number for any damage is assumed to be 1, with the maximum being 120).

Analysis shows that damage manifests itself most often in the protection system, being 27% of the total amount of damage, and also in the windings, 15%, [5]. The distribution in percentage terms is shown in Fig. 1.6.

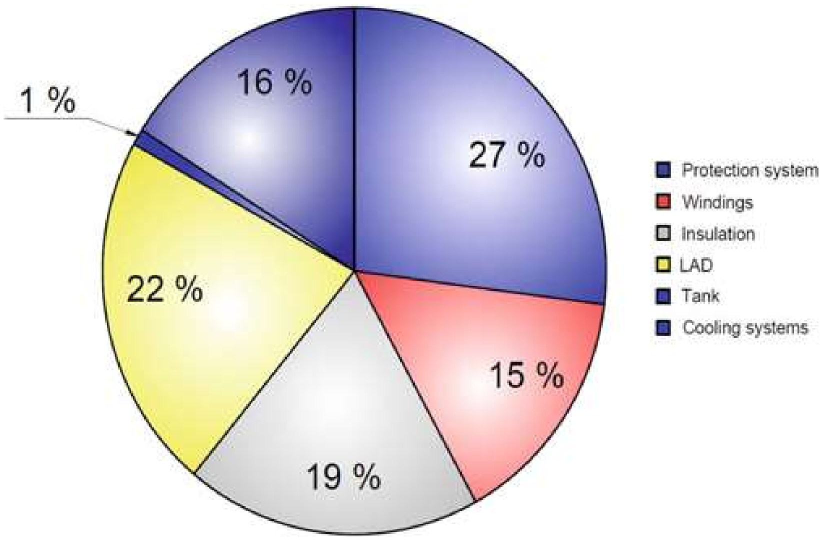


Fig. 1.6 Diagram of transformer defect distribution (Indonesia)

Analysis of statistics on transformer failures in Russia and other countries, as well as research on causes of failure or forced decommissioning of transformers, allows one to conclude that the main indicator of correct and reliable operation of a transformer is the absence of alterations in the geometry of its windings. The latter occurs mainly due to exposure to long-term SC currents, which increases the probability of turn-to-turn short circuits, fires and explosions, with serious consequences. Studies show that around 80% of winding failures in Russia are caused by short circuits. Among the incidents involving internal SC, 24% of the cases were accompanied by transformer ignitions and subsequent fires. The dynamic instability of windings to SC is explained by a weakening sustained with time by the pressing of the core and windings due to mechanical influences in the course of transportation, installation, aging of the insulation, and dynamic forces acting during SC. Windings having some previous displacements show a weakened endurance to subsequent SC currents, which may cause unacceptable damage.

1.2 Technical and Economic Consequences of Failures in Standard Operation of Transformers

The economic damage caused by failures of high-voltage transformers consists of both the cost of failed equipment and the economic damage of consequences inflicted by the accidents. Damage sustained by a single transformer is often the reason for a sudden emergency stop of an entire technological chain involved in an integrated manufacturing process. The result of such an incident is a fire, accompanied by an explosion of high-voltage bushings, an oil spill, environmental pollution and vast economic damage. In this case, neighboring equipment of an electric power system (EPS) may be damaged by scattering of emergency equipment fragments, as well as by high temperatures and other destructive factors. In addition, losses sustained by power systems are increased due to undersupply of electricity, which is an inevitable consequence of accidents. It is also necessary to take into account the environmental damage due to hazardous combustion products released by damaged equipment materials. In this regard, improving the reliability of EPS equipment, including high-voltage power transformers, is one of the most important tasks in ensuring reliable power supply to consumers (Fig. 1.7).

As already noted, the part of equipment that has exhausted its resource in the global electric power industry is increasing, which means the “aging” of electrical equipment, and, primarily, transformers, being the most important and expensive part. In Russia, after a transition between the planned and market economy models, power companies have abandoned a planned system of repair and replacement for electrical equipment and switched on to a “condition-dependent” service system.

Fig. 1.7 Fire in a block transformer of a power plant, the city of Omsk, July 2011. The transformer passed a routine inspection with a complete set of preventive tests and measurements a month before the incident

Recent failures of oil-filled high-voltage equipment are related not only with its moral and physical deterioration. Accidents involving new equipment frequently occur due to a weakening of manufacturing quality control. The probability of such events often exceeds the probability of failure for similar equipment manufactured under strictly controlled conditions, even if it has been in operation for a long time. In this state of events, the task of preventing an operation of newly-made, but low-quality equipment at power industry facilities acquires priority.

The failure of detecting dangerous equipment defects in a timely manner increases the probability of severe accidents, with an increasing amount of repair work and a decreasing service life of equipment. The prevention of serious man-made accidents and catastrophes necessitates the use of even more technologically advanced diagnostic solutions, with a substantiated forecast of the operability of transformers (generally, respective critical structures and equipment). Expert assessments show that up to 80% of defects causing failures of substation equipment and power transmission lines can be timely identified by effective methods and means of monitoring and diagnostics.

Another strategic task is to assess the possibility of continuing the operation of equipment after its pre-assigned service life. The adoption of an optimal decision in this case is based on economic feasibility, which is assessed by comparing the damage resulting from equipment failure with the costs of prevention measures: equipment replacement and diagnostic examination, installation of continuous control (monitoring) systems, recovery (current or capital) repairs based on the results of a diagnostic examination.

In this regard, the immediate task of the global electric power industry is the development of effective diagnostic systems, methods and diagnostic tools that make it possible to confirm the operability of equipment (defect-free condition), or detect damage at an early stage of development, and, ultimately, estimate the residual resource and take measures to increase the latter.

Below we examine two main groups of reasons for transformer failures in case no timely prevention measures have been taken: (1) insulation degradation, (2) integrity violation of transformer windings.

1.3 Insulation Aging (Degradation)

During operation, a prolonged exposure to operating voltage and short-term exposure to overvoltage, combined with other factors (elevated temperature, mechanical stress, environmental conditions, etc.) leads to a decrease in the dielectric strength of insulation and its failure due to aging and a subsequent breakdown. Aging is the development of an involved combination of physical, chemical, electrical and other processes in the insulation [6]. Each of them, at a sufficiently high intensity, can be registered and studied due to certain external manifestations being characteristic only for a specific process. This is the basis of present-day methods to study the aging of electrical insulation and monitoring of its current state.

As regards the combined insulation of high-voltage transformers (paper-oil, oil-barrier, paper-film-oil) characterized by a high intensity of aging processes, some methods of condition monitoring have been developed and are effectively used at present. They are based on registering partial discharges (PD), controlling the intensity of gas evolution and alteration of chemical compositions, as well as measuring the dielectric loss tangent (tan δ), insulation resistance and absorption currents, etc., [7, 8].

Taking into account a large PD contribution to the damage and degradation of transformer insulation, as well as a complexity of the related characteristics and their nature, below we examine all of them in sufficient detail. Other degradation mechanisms for transformer oil and cellulose (chemical, thermomechanical, etc.) are considered in the sections devoted to a brief description of control methods on a basis of their research and registration.

PDs in gas pores, gas wedges and interlayers provide the main cause of degradation and failure of transformer insulation. In choosing permissible electric field strengths in such and similar insulation (capacitors, bushings, cables with monolithic insulation), PD characteristics are decisive. Material discontinuities, hereinafter called “inclusions”, are formed in the course of manufacturing electrical insulating materials and insulating structures on a basis of the former, which makes such inclusions inevitable in practice. Once an electric field is applied to insulation, ionization processes are initiated in the inclusions, being limited by the insulation volume, and thereby called ***“partial discharges”*** (PD). A primary PD occurrence in the inclusions is caused by two reasons: (1) a lower electrical strength of the medium filling the inclusion, (2) increased electric field strength in the inclusion caused by its redistribution due to a difference in the dielectric constant of the base material (higher) and the material of the inclusion (lower). Electron-avalanche processes in inclusions begin with auto-electron emission from an electrode (wire) in case the electrode adjacent to the cavity is of negative polarity, or, in the case of holes being emitted once the electrode polarity is reversed, as well as in the case of closed pores. PD in cavities ranging in size from a few microns to fractions of a millimeter is basically a Townsend discharge. However, the duration of a single PD (hundreds of picoseconds), being a very short one, given a pore size (ranging from tens to hundreds of microns), indicates that secondary emission is due to the action of photons rather than positive ions. The threshold energy and quantum yield of photoelectron emission from the surface of an organic dielectric are not very different from those in metals: in dielectrics, the threshold energy is slightly higher, and the quantum yield is lower. For this reason, all other things being equal, the breakdown voltage of a gas microcavity in a dielectric is somewhat higher than the microgap between the metal electrodes. When the size of a cavity is tens of microns and the gas pressure in it is close to atmospheric, the breakdown voltage is near the minimum of the Paschen curve, i.e., is 250–300 V.

An electric discharge in a gas cavity of larger size is a streamer discharge with its characteristic features: a contracted channel, a high rate of development (elongation) of the channel, and a high plasma temperature [9].

The destruction of walls in micron and submicron cavities is caused not by the development of a partial discharge, but rather by the bombardment of cavity walls by emitted electrons. Thus, the size of a cavity and the gas pressure inside of it determine the mechanism of processes developing under the field action, as well as the intensity of material destruction. The prevalence of one or several factors of insulation destruction over the others is determined by many variables: field strength, dielectric properties, gas cavity parameters [10]. In particular, an increase in the PD intensity in relatively large cavities with an increase in the field strength leads to the fact that the process of point erosion in the cavity walls begins to prevail over the oxidation process. An increase in the rated energy release and the rated power of the PD is one of the reasons for a low long-term electric endurance of dielectrics with the cavities elongated along the force lines of the electric field.

If there are points of significant increase in the electric field (micropoints) on the electrode (wire), PDs can appear even in the absence of macroinhomogeneities (inclusions) in the insulation at the initial state. (For transformer insulation, this case if unlikely). Then, charge carrier emission, ionization, panderomotive forces, and thermodynamic processes may lead to cavity emergence, accommodating PD occurrence [11]. PDs cause erosion of pore walls and gradual destruction of insulation with its subsequent through breakdown. For a significant thickness of solid insulation, predominantly polymeric, PDs can degenerate into electrically conductive tree-like or bushy shoots, ***dendrites*** [12].

The entire sequence of processes, from the formation of inhomogeneities (when they are absent at the initial state) to the breakdown of insulation, is shown in Fig. 1.8.

During the combustion of a discharge in the channels of a dendrite, the electrical conductivity is provided by gas-discharge plasma filling the channels, and during the quenching of the discharge, by carbon deposits on the walls of the channels, as a result of the thermochemical decomposition of organic insulation. Under certain conditions, the channel cavities are filled with liquid. Such dendrites, observed mainly in monolithic polymer insulation, are called ***water dendrites.*** They are unlikely to occur in transformer insulation and, are therefore not considered here, or in Subsection 2.7. Information in their respect can be found in [13].

A certain variety of dendrites is regarded as ***sliding* or *creeping discharges*** that develop along the surface of solid insulation surrounded by a liquid or gaseous medium [14–16].

Despite the fact that they develop in an environment, their plasma channels cause erosion and carburization of the surface layers in solid insulation, namely, the formation of conductive tracks. The tracks slowly penetrate the insulation and at some stage lead to the growth of a dendrite through the insulation. Dendrites and creeping discharges are shown in Fig. 1.9.

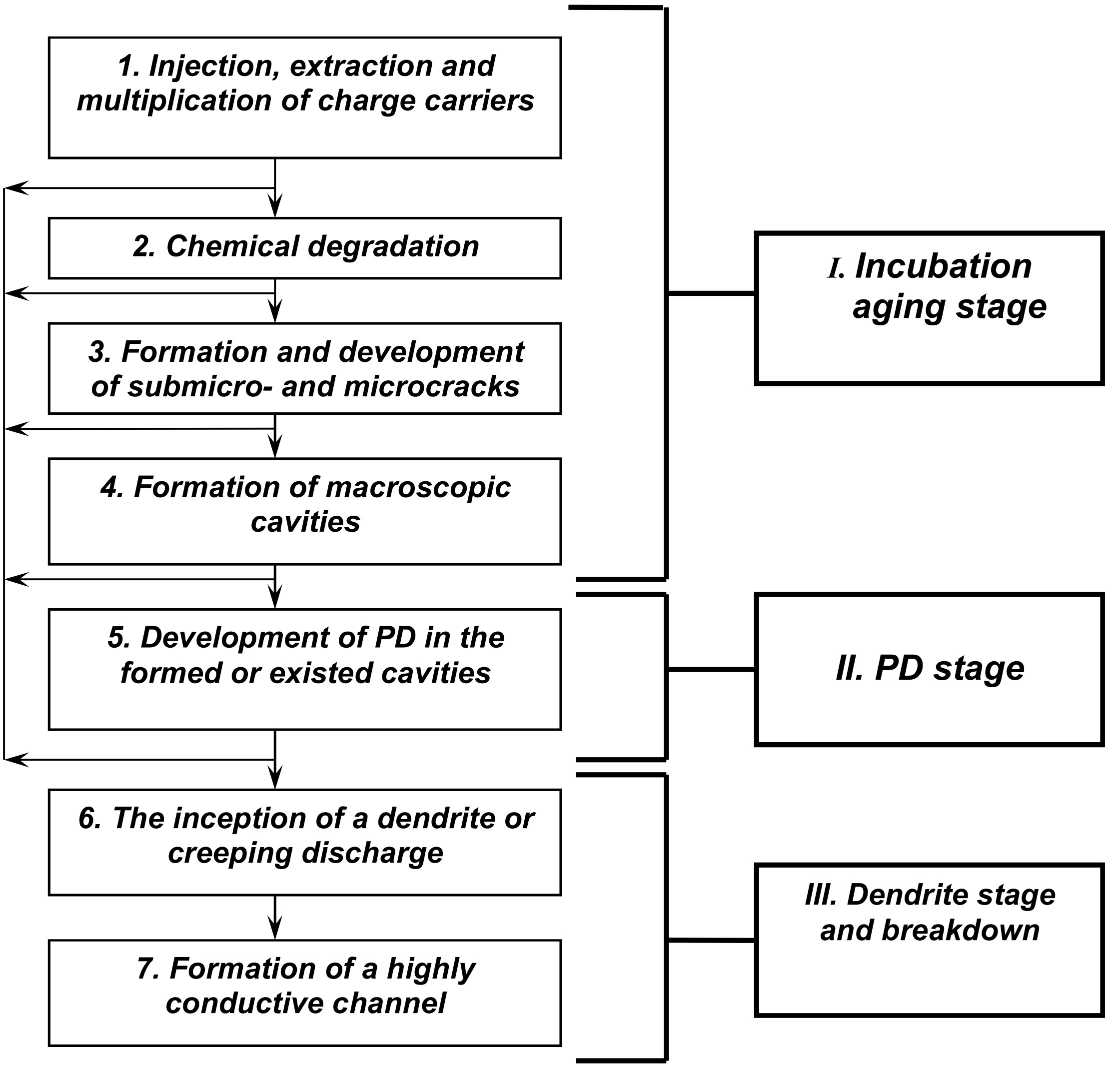


Fig. 1.8 Sequence and mutual influence of degradation processes for an insulating material in an electric field

Establishing the emergence of PDs and measuring their characteristics makes it possible to assess the quality of insulation manufacturing and to identify local defects both in the insulation and on the current-carrying parts of a structure. In registering PDs during the operation of a high-voltage device (for example, a transformer), it is possible to control the rate of natural or accelerated aging of this device. PD characteristics correlate fairly well with the size and number of defects, i.e., they allow making a reasonable conclusion about the degree of defectiveness of an insulating structure at different operation stages for a high-voltage apparatus. The study of PD characteristics is a task of paramount importance for all high-voltage devices, and, primarily, for those in which multilayer (hence, non-uniform) insulation is used [17].

When considering the mechanism of PD initiation, an equivalent circuit with a total capacitance C_E is used to replace a dielectric, Fig. 1.10.

Fig. 1.9 Photo of a dendrite in a translucent polymer dielectric

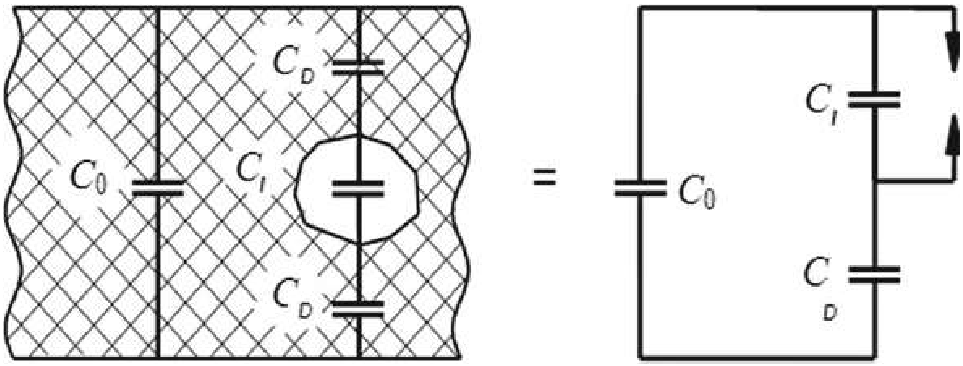


Fig. 1.10 Equivalent circuit for a solid dielectric: C_0 is the capacity of non-defective insulation; C_I is the capacity of an air inclusion; C_D is the dielectric capacitance in series with the inclusion; U_I is the breakdown voltage of the air inclusion

$$C_E = C_0 + \frac{C_I \cdot C_D}{C_I + C_D}. \tag{1.1}$$

PDs occur when the switch-on voltage reaches the breakdown value U_I, in this case being the discharge ignition voltage at the switch-on. The electric field strength in the inclusion E_I is related to the strength in the rest of the dielectric as follows:

$$E_I = E_D \cdot \frac{\varepsilon_D}{\varepsilon_I}, \tag{1.2}$$

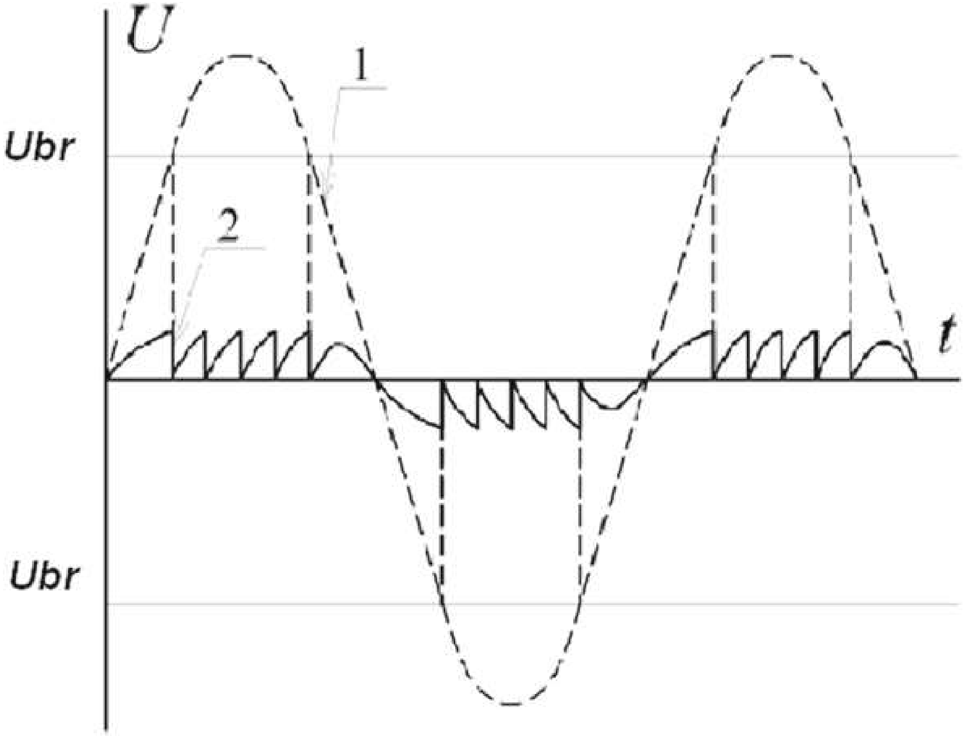


Fig. 1.11 Diagrams of voltage on an air inclusion in a solid dielectric: 1 is the voltage on the sample; 2 is the switch-on voltage; U_{br} is the voltage on the sample at which an air inclusion breakdown takes place

where: E_D is the electric field strength in the dielectric, ε_D is the relative dielectric constant of the dielectric, and ε_I the relative dielectric constant of the inclusion.

Based on (1.2), the electric field strength in a gas inclusion (or any other inclusion with $\varepsilon_I < \varepsilon_D$) is always higher than it is in the rest of the dielectric. The voltage diagrams at the switch-on when alternating voltage is applied are shown in Fig. 1.11.

For an inclusion size of tens of micrometers and a pressure close to atmospheric, the breakdown voltage is near the minimum of the Paschen curve, while exhibiting small changes with a change in the inclusion size, and being equal to 250–300 V.

PDs are especially hazardous at alternating or impulse voltages.

PD can be classified by qCR value in the following way.

1. When a certain voltage threshold is exceeded, PDs appear in insulation with an intensity of $q_{PD} = 10^{-12}$–10^{-11} **C**. Such PDs do not cause rapid destruction of insulation, and, in many cases, are acceptable for long periods of equipment operation. Such PDs are referred to as ***initial***.
2. Any further increase in voltage, or an increase in the size of inclusions in the course of long-term operation of the insulation, leads to a sharp increase in the PD intensity, primarily with q_{PD} increasing up to 10^{-10}–10^{-8} C. The occurrence of such PDs drastically shortens the life of insulation, and thus they are called ***critical***. Dendrites can be regarded as a final stage in the development of critical PDs.

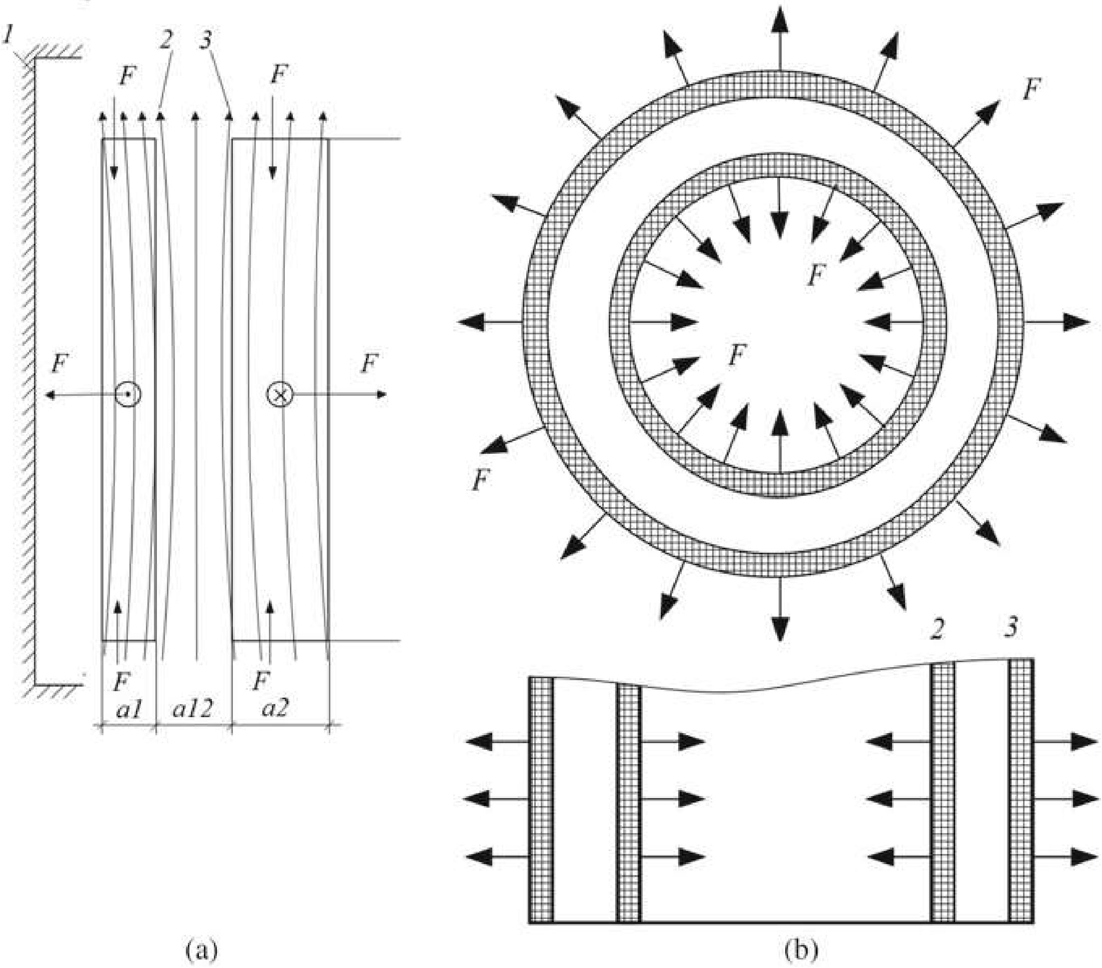


Fig. 1.12 Axial forces in longitudinal section **a** radial forces in a cross section **b** 1 is the magnetic circuit of a transformer; 2 is the inner winding; 3 is the outer winding

Under the influence of critical PDs in oil channels, the process of destruction is intensified, initially in oil-barrier insulation and then in coil insulation, at the locations of inclusions with the emergence of damaged areas. This is intensified by the heating of the oil caused by the closure of the magnetic conductor plates. Destruction processes take place in both the oil-barrier insulation and the high- and low-voltage insulation windings. In the area of the coil insulation sections that have undergone destruction, there occurs a strong heating of adjacent insulation sections and transformer oil; in the heated oil there emerge bubbles supporting PD occurrence. Sliding discharges begin to form along the dielectric surfaces. Sliding discharges on the surface of barriers and coil insulation, as well as PDs in oil interlayers, and corona-shaped PDs in a bare edge area of the winding wires cause significant heating of the oil. This heating, combined with heating due to the plates closure (***steel fire***), increases the destructive effect on all the elements of insulating structures. The total heating leads to an increase in the intensity of all electrophysical and thermochemical processes in the insulation, which reinforce each other and accelerate the rate of destruction sustained by the insulation (accelerated aging), resulting eventually in a complete electrical breakdown and destruction of the entire electrical insulation system of a transformer.

Fig. 1.13 Radial displacement of winding turns

Fig. 1.14 Complex displacement of winding turns

1.4 Integrity Violation of Transformer Windings

Mechanical defects of windings come in two main types: axial (longitudinal) and radial (transverse) displacements. Diagrams exemplifying the radial effect of ponderomotive forces are shown in Fig. 1.12.

Ponderomotive forces acting on a winding cause a radial displacement of the winding turns, Fig. 1.13, with a subsequent complex displacement of the turns, Fig. 1.14.

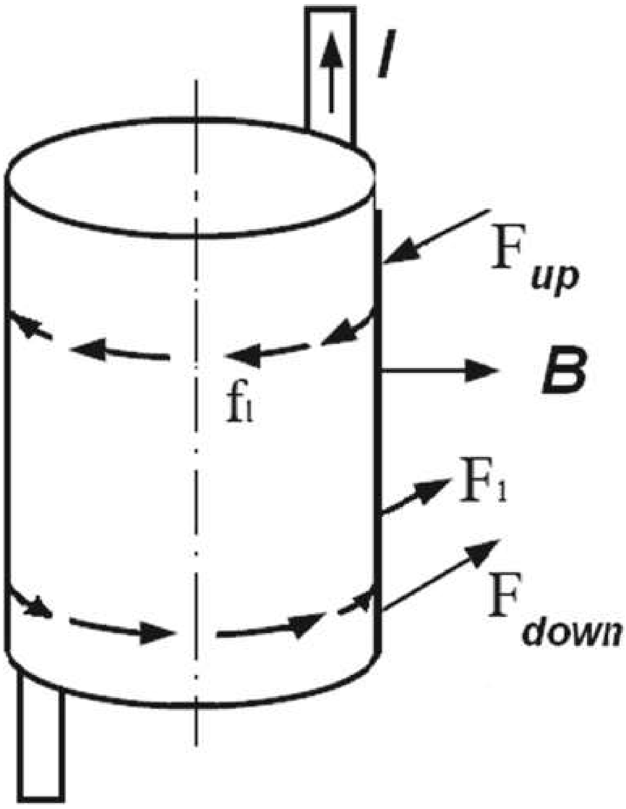
Diagrams exemplifying the tangential effect of ponderomotive forces are shown in Fig. 1.15.

The tangential component of ponderomotive forces acting on a winding causes an axial displacement of winding turns, Fig. 1.16, with a subsequent defect of "lodging of conductors", Fig. 1.17.

A defect of the "short-circuited turn" type occurs when the turn insulation is damaged by SC currents or switch over-voltages. The appearance of a "short-circuited turn" defect is shown in Fig. 1.18.

One of the main causes of damage to transformer windings (dynamic instability deformation) is due to SC currents in power grids. Currently, such damage to transformers has a prominent position. Calculations show that approximately 1.7% of 220–500 kV autotransformers may be exposed once a year to dangerous SC current effects, which are especially hazardous for autotransformers with reduced electrodynamic stability. For example, at the substations of RAO UES such a "risk group" is

Fig. 1.15 Impact of tangential forces on a winding



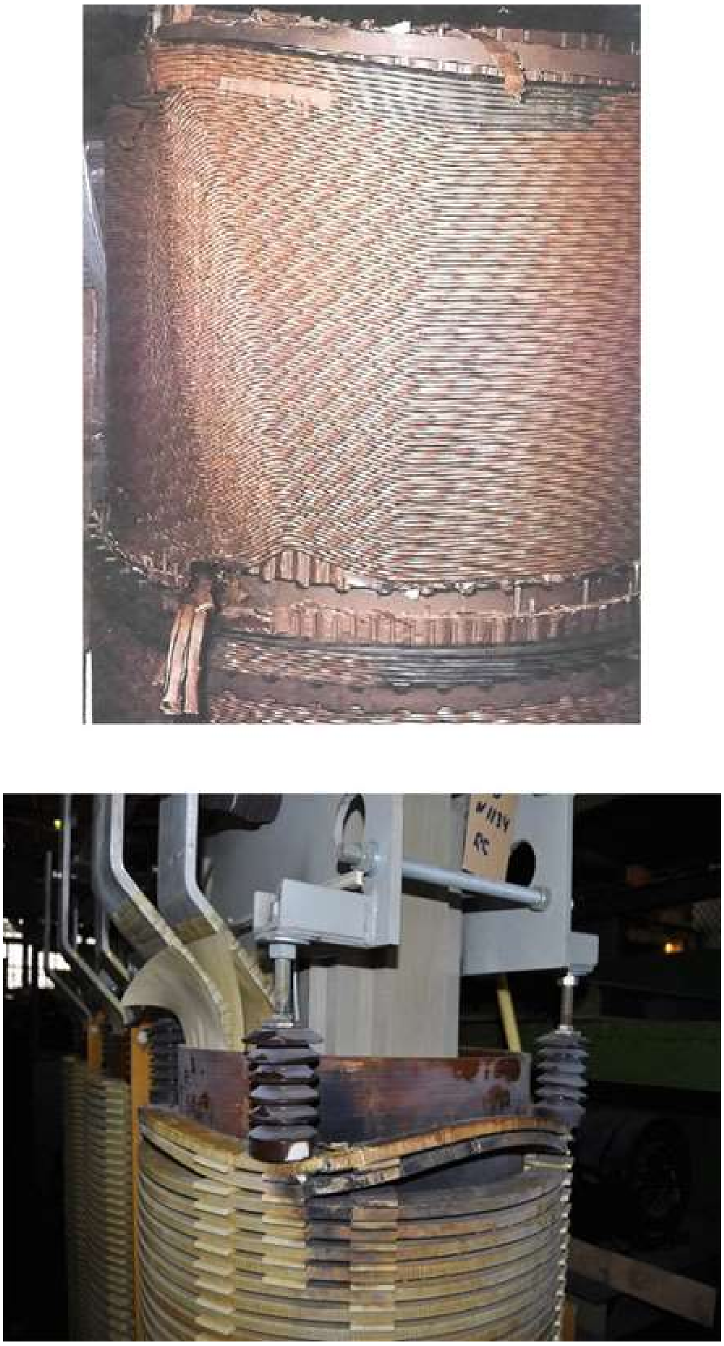


Fig. 1.16 Axial winding displacement

estimated at 25% of the total number of autotransformers in the 330–750 kV voltage classes. Recently, significant long-term voltage rises in power grids (abnormal operating modes in energy systems) have become a factor of danger for power transformer operation. The problem of dynamic instability of winding design has also become more serious due to a steady growth of SC intensity in power systems.

Fig. 1.17 Defect of the winding type “lodging of conductors”

Fig. 1.18 “Short-circuited turn” type of winding defects

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