Insulation System and Aging Phenomenon

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electrical machines winding insulation diagnostics

1. Insulation System

The insulating system of the windings of electrical machines is multi-layer and consists of coil and main (slot) insulation [1][2][3][4][5]. The thickness of the insulation is selected with a margin so that its durability to breakdown is greater than the existing voltage. The safety factor of the dielectric strength of the main insulation k_{iz} is expressed by the equation:

$$k_{iz} = \frac{U_p}{U_N}, \quad (1)$$

where: U_p—insulation breakdown voltage, U_N—rated voltage.

The breakdown safety factor for new insulation is $k_{iz} > 5$. The dielectric strength of the insulation is checked during the withstand voltage test, where the test voltage U_{PR} is selected according to the following requirement:

$$U_{PR} = 2U_N + 1000. \quad (2)$$

Gas inclusions (air) inside the insulation and between the insulation and the slot are important elements which reduce the safety factor. Three areas can be distinguished in the winding along the length of the windings:

- End winding area;
- End extension area;
- Coils sides (slot area).

There is a serial layering of solid dielectric and air with high and low dielectric permeability in the end winding area. The air increases the dielectric strength of the insulating system in the end winding area. The end extension area is located at the exit of the coil sides from the slots and near the radial air channels. The slots area, as the name suggests, is located in the slots. The presence of air gaps in the insulation of the slots and end extension area deteriorates the dielectric properties of the insulation [4].

If there is an air layer in the insulation, for which the dielectric permittivity ε_P is 1 compared to other insulation materials for which ε_K is between 4 and 10, the dielectric stress in the air layer is $\varepsilon_K/\varepsilon_P$ times greater than in the dielectric layers. Then, electric discharges occur in the air layer, especially during surges, which are common phenomena in networks supplying electric drives. Progressive electric erosion can, over time, reduce the dielectric strength of the insulation and lead to its breakdown [4][5][6][7][8].

Testing of partial discharges arising in insulation is one of the diagnostic methods of winding insulation. The occurrence of air gaps favors the penetration of dusts, which are usually conductive in an industrial environment (metals, carbon). Therefore, more sophisticated technologies are used for applying the insulation and varnish. The varnish should fill the free spaces of the slot. From the known impregnation technologies, the best results are achieved by the VPI (vacuum pressure impregnation) technology. The impregnation varnish should meet the following basic requirements [7][9]:

- Flexible, as the windings vibrate especially during direct starts of asynchronous motors;
- High heat resistance (temperature class F or H);
- Low viscosity, which allows it to penetrate the free spaces in the slot.

An example of the winding insulation of a high-voltage double-layer electric machine is shown in **Figure 1**.

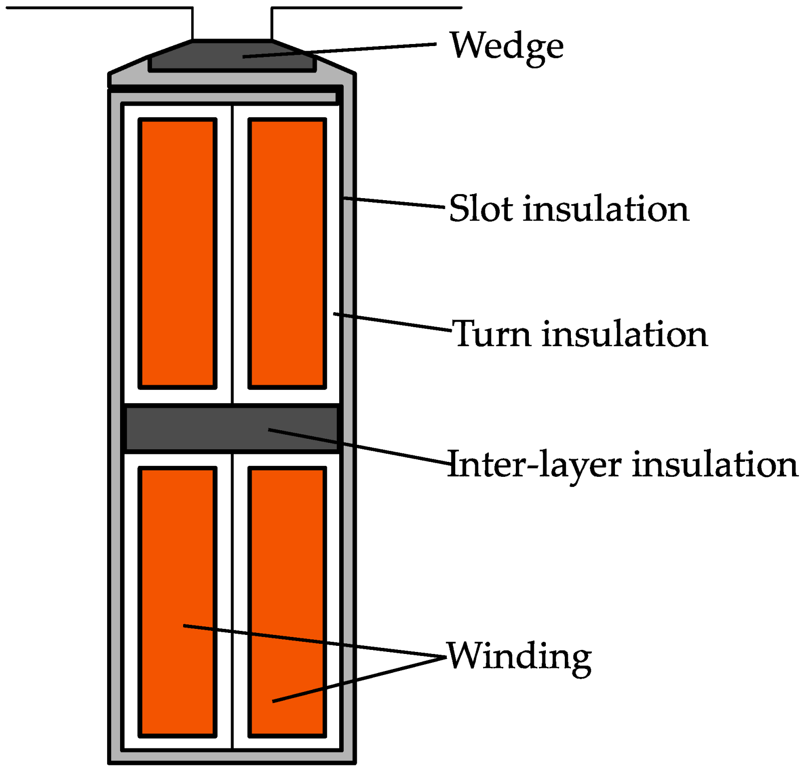

Figure 1. Cross-section of a slot of an electric motor with a double-layer winding.

Particularly noteworthy is the implementation of epoxy resins in the insulation system of electric machines. These resins are applied to the surface of the stator core and the rotor in the form of a powder. Then, these cores are exposed to high temperatures. As a result, a very good, uniform and durable insulation is obtained, both for the edge sheets at the exit from the slots, as well as the entire slot. This method reduces the mechanical stresses on the winding due to packaging imperfections. Due to the technology, this method is used mainly for small machines. An example of coating a core with epoxy resin is shown in **Figure 2**.

Figure 2. An example of coating a core with epoxy resin [10].

The reduction of existing exposures is also achieved by vacuum impregnation. As a result of using an appropriate technology and the right mixture of impregnation varnish ingredients, it is possible to guarantee very good heat dissipation from the motor and greater resistance to shocks, vibrations, chemicals, water, dust and other external factors, as shown in **Figure 3**.

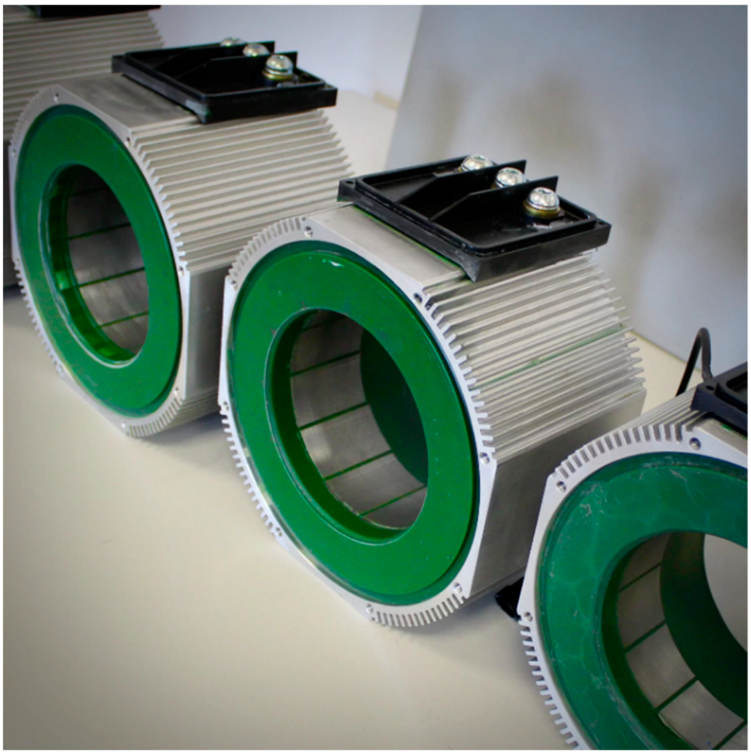

Figure 3. The winding ends sealed with epoxy resin [11].

2. Insulation Aging Phenomenon

During many years of operation of electrical machines, it is important to monitor the process of insulation aging. Proper assessment of the degree of wear of the insulation of the windings of electrical machines is the basis for planning their repairs.

Each insulation system, turn-to-turn insulation and main insulation is characterized by a capacitance and resistance to the stator core and to other turns of this coil and this winding. In polarization methods for diagnosing winding insulation, electrical phenomena occurring in the capacitance and resistance of the insulation are used. During many years of operation, the insulation system of electrical machines is exposed, among others, to the surrounding environment, which causes the insulation system to age. The factors determining the aging of the insulation system are:

- Temperature;
- Mechanical vibrations;
- Atmospheric environment.

The operating temperature of electric machine windings varies over a wide range. Large fluctuations in the temperature of windings lead to constant changes in their length resulting from the phenomenon of thermal expansion of solids. Changes in the length of windings caused by large and frequent temperature fluctuations expose the insulation to a significant reduction in its service life. The aging of insulation under the influence of an alternating electric field develops as a result of two overlapping phenomena: the alternating polarization of the dielectric, causing the formation of losses in the insulation (which is greater the greater the dielectric loss factor) and incomplete discharges. Incomplete discharges occur in gaseous inclusions inside the dielectric and between the insulation surface and the walls of the machine grooves, as well as on the insulation surface of the winding facing the metal parts of the machine. These discharges lead to high local temperatures, combined with the formation of chemical compounds that destroy the insulation. The above phenomena affect the insulation temperature, and both lead to irreversible changes in the structure of the dielectric, especially when it is accompanied by vibrations, moisture and gases contained in the air, e.g., ozone. The insulation parameters deteriorate. New, modern insulation systems, especially those made using the VPI technology, have very good insulation parameters. The dielectric strength changes slowly during the operation of the machine. However, this insulation also ages and changes its parameters. This is influenced by [2][3][6][8][9][12][13][14][15][16][17][18]:

- Electrical exposure;
- Thermal exposure;
- Mechanical exposure;
- Thermomechanical exposure;
- Environmental exposure.

2.1. Electrical Exposure

The electric field is the main source of continuous electrical exposure to the insulation system [8]. The dielectric strength of new insulation systems is usually not less than five times than of the rated voltage. Therefore, it is possible to rule out the possibility of an electric breakdown mechanism occurring only under the influence of operating voltages. At the operating voltage, the action of the electric field may also manifest itself in the ionization of the gases contained in the gaps of the layered system. The effect of partial discharges in the gap on the change of the structure of the insulating system is a complex phenomenon. It is related to the energy released pointwise causing local overheating of the insulation system. In the case of local partial discharges, very active ozone O_3 and nitrogen oxides are formed [8]. Mica is the most resistant to partial discharges. Papers, pressboard, oilcloth and electro-insulating varnishes have low resistance. Obviously, the effect of partial discharges must be taken into account when electrical machines are designed and constructed. Prolonged exposure to high intensity of partial discharges can lead to the deep erosion of insulating materials and the reduction of dielectric strength [6][7]. Therefore, discharge-resistant materials, such as mica and mica products, are used in the insulation systems of electrical machines [3][4][14]. The possibility of gaps in the insulation is limited by the use of an appropriate manufacturing technology. Based on tests of actual insulation systems, it has been shown that partial discharges at operating voltage do not cause changes in the structure that would significantly reduce the dielectric strength.

Therefore, the isolation technology does not exclude the existence of gas gaps in the insulating system. A complete elimination of the gaps is difficult to achieve and increases production costs. A high electrical exposure to winding insulation also occurs in machines supplied from inverters [6][7][19][20]. Switching overvoltage is also dangerous. This occurs in transient states when switching electrical machines on and off, in particular when using high-speed vacuum circuit breakers. When discussing the exposures caused by the action of electric fields, the risks that arise during withstand voltage tests cannot be ignored. According to the applicable standards, any new electric machine supplied with a rated voltage of 6 kV and above must be tested both to the frame and between the phases with an industrial frequency and RMS value of test voltage U_{PR} = (2U_N + 1000) V for 1 min. It is a safety test and therefore is obligatory. This test should not be repeated. In some operating manuals of electrical machines, it is recommended to carry out this test after a longer standstill, renovation and general inspection, but using a reduced voltage. This test has a negative effect on the durability of the insulation.

2.2. Thermal Exposure

The heat is released during normal operation inside the electric machine as a result of losses, which determines the temperature distribution [18]. On the basis of thermal calculations, materials and technologies for the execution of insulation systems are selected [1][2]. High winding temperature affects insulation materials. When the working conditions are unfavorable, it causes permanent changes in the structure of the material, such as:

- Dielectric loss;
- Permittivity;
- Dielectric strength;
- Carbonization of the insulation at very high temperatures;
- Changes in mechanical properties, in many cases irreversible, especially when the impregnating varnish dries (evaporates) or hardens. This changes the strength properties, cracks occur and the insulation delaminates.

When the permissible temperature is exceeded for a short time, gas bubbles and ruptures will form. The deformation caused by the action of mechanical forces (different temperature coefficients for insulation and copper, changes in linear dimensions) and mechanical loads increases. Increased temperature accelerates the phenomena of oxidation, thermal breakdown and surface discharges. This is the result of a change in electrical permittivity, depolymerization and dissociation of synthetic resins, and the release of active chemicals. All these phenomena lead to a deterioration of the properties of the insulation system over time and, consequently, to a reduction of the breakdown voltage.

2.3. Mechanical Exposure

The reason for the mechanical exposure of the insulation system is electrodynamic forces and, in rotor winding, centrifugal forces [18]. These activities are manifested primarily in transitional states. The maximum value of the current determines the value of the electrodynamic forces. The significant exposures occuring in the area of the winding ends during the operation of short-circuit currents. As the machine's rated power increases, the value of the short-circuit currents also increases. Since the voltage and the reactance of the winding also depend on the rated power, the electrodynamic forces depending on the square of the surge current are approximately proportional to the power.

For insulation systems, the most dangerous are bending stresses occurring in the end winding area, causing their permanent deformation and damage in the end extension area where bars exits from the slots [14]. The effects of these exposures are cumulative. Destructive changes in the winding's copper and in the insulation system increase as a function of the number of exposures. Fatigue phenomena occur, leading to cracks in the copper and in the winding insulation as well. Serious damage to the fastening structures of the end winding area and cracks in the bandages on rotors windings surface also occur. The circumferential forces also act on the slot insulation. These are the forces of inertia depending on the mass of the bars and the acceleration of the rotor, increased by the electrodynamic forces resulting from the interaction of the current and the radial component of the magnetic field in the slots. The consequence of the magnetic core packing is uneven side surfaces of the slots. The occurrence of these forces causes permanent dents in the insulation in the core assembly. Such dents are visible on almost every disassembled winding. The deformations damage the outer surface of the insulation, which reduces its dielectric strength to breakdown.

2.4. Thermomechanical Exposures

Thermomechanical exposures are of particular importance during the operation of electrical machines and are often the cause of the most serious changes in the insulation system. These exposures lead to dangerous delamination, cracks and other deformations of the insulating system, which reduce its electrical strength. This is mainly due to the movements of the windings in relation to the stator and rotor cores as a result of cyclical temperature changes [2][17]. With different thermal expansion coefficients of the copper windings and core, temperature differences and different thermal time constants of the copper windings and cores, dilatation movements arise, causing the windings to shift in the slots. This causes damage to the slot insulation.

2.5. Environmental Exposure

Environmental exposures are defined as a set of factors occurring in the surroundings of an electric machine. Factors influencing the deterioration of the insulation system are:

- Moisture in the windings;
- Ambient humidity;
- High ambient temperature [17];

- High pressure [17][21];
- Leakage and penetration of oil from bearings or gears;
- Exposure to chemical agents related to the location [18];
- Presence of filings in the coolant;
- Dust and powder;
- Exposure to radiation.

The above factors, both individually and collectively, affect the condition of the machine’s insulation system.

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