The Primary Aspects of Improving the Electrical Strength of Cast Epoxy Insulation on High-Voltage Devices

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Abstract: - Various technical solutions are used to meet existing requirements for insulating high-voltage equipment, and the widespread introduction of solid insulation is one of them. Recently, there has been a noticeable wide transition to composite materials with improved strength properties. To justify the use of such materials, it is necessary to be guided by statistical laws of electrical strength distribution from various parameters, particularly the size of insulation, and its volume, to analyze breakdown probabilities. When selecting an appropriate type of material, one should also rely on the filler's type, size, and structure, temperature coefficient difference of linear expansion for electrode and cast insulation materials, and a possible increase in adhesion of metal elements epoxy compounds.

The article considers in detail the issues of determining the distribution of electrical strength from various parameters, describes the theories of dielectric failure and ways to increase insulation, and also presents for the first time the experience of high-quality adhesion of electrodes with composite materials in the absence and pre-application of a small layer of compound on the electrode surface before the main filling with solid insulation. The presented results cover experiments on the strength of cast epoxy insulation samples when activating the electrode surface with alkali, potassium dichromate, and in the absence of activation. At the same time, for a better understanding of the ongoing processes and changes in the electric field strength, the main influencing factors and the mechanisms of the electrical breakdown development are taken into account.

Key-Words: - Adhesion, breakdown probability, composites, linear expansion coefficient, breakdown, solid insulation, electrical strength.

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1 Introduction

Currently, solid high-voltage insulation is used in almost all areas of the electrical power industry: in production, conversion and distribution of electrical energy in substations, and the transmission of this energy (within power cables, overhead and gas-insulated lines). Generally, high-voltage insulation means insulation under rated voltages of several kilovolts or higher.

Even before the middle of the XX century, rubber, glass, and porcelain were used as solid types of insulation. At the same time, synthetic organic materials were used soon after that: instead of rubber insulation in electrical cables, instead of glass and porcelain as insulators of overhead transmission lines. However, widespread use of this type of insulation in the energy industry was hampered by generally recognized disadvantages of original polymers, such as their relatively low (compared to steel) mechanical strength, insufficient thermal resistance, and also organic insulation's susceptibility to weathering and aging [1].

It should be noted that specific technical requirements for solid insulation of highvoltage devices include high electrical and mechanical strength, thermal stability and thermal conductivity, and resistance to defect creation during operation. The requirement for insulation plasticity, which is typical for highvoltage cables, has not become the main one for most of other high-voltage insulating structures in substation and line equipment.

Nevertheless, the progress curve in the development of insulation types [2] indicates a significant increase in the use of composites and

polymers compared to glass and ceramics since the 1960s.

Specific technical requirements for solid insulation of high-voltage devices include high electrical and mechanical strength, thermal conductivity, thermal stability, and resistance to defect creation. Various composite materials with improved strength characteristics increase electrical and mechanical strength.

It is worth noting that the requirement for insulation plasticity, which is typical for highvoltage cables, has not become the main one for the most other high-voltage insulating structures in substation and line equipment. As a result, the use of thermoplastic compounds for highvoltage insulators as the main insulating material is unjustified. Since some drawbacks characterize them, the main ones being a creep and sharp deterioration of mechanical properties at elevated temperatures, up to the loss of form thermosetting compounds stability. have become the most widely used in substation equipment.

Among thermosetting compounds in high voltage electrical engineering, epoxy compounds and their modifications are the most promising since they feature a number of the following advantages [3]:

- sufficient dimensional stability of cured devices;

- good resin/filler compatibility;

- excellent electrical and mechanical properties preserved up to 130-150°C with a properly selected composition;

- high chemical resistance;

- good adhesion to the metal parts to be cast.

Cast epoxy insulation (CEI) has been finding broader use in high-voltage power, plants and switchgears, power and instrument transformers [4]. So, for example, in the manufacture of dry transformers with cast insulation, as a rule, epoxy insulation with special fillers providing low spontaneous combustion is used [5]. In the case of switchgears structures, the surfaces of all elements are covered with solid insulation. Epoxy insulation is a significant material used to insulate SIS-type switchgears and gasinsulated switchgears (GIS) [4]. Currently, epoxy resins are the main binders used for CEI [1, 2] – sometimes, they are also referred to as ethoxyline resins.

It was possible to overcome the thresholds of mechanical strength properties of polymers, including epoxy compounds, by transitioning to composites, mainly when composing polymers with glass and carbon plastics. However, the necessity to reduce the dimensions of highvoltage devices and the creation of equipment for higher voltage classes requires the usage of solid insulation with even higher electrical strength. For this purpose, the article considers the influence of the electrical insulation strength of composite materials on various parameters, which are presented in Table 1 [2-3, 6-9].

Table 1. Dependence of the electrical strength with solid insulation on various factors

Indicator	Literature	Dependence	Formula in the article
Breakdown time τ	[6]	Life curves	1
Probability of breakdown	[2, 7, 9]	Weibull's Law	2
Probability of breakdown time	[6, 7]	Life curves, Weibull's Law	1 and 2
Active volume	[7, 8]	Weibull's Law, empirical formula	2 and 4

A detailed analysis of the influence of these factors will improve existing materials and allow combining various ways to improve strength characteristics. In addition to the theoretical analysis of the influencing factors on the composite material insulation, the article also provides practical experience in the applicability of methods to increase electrical strength: both scientists from different countries and the authors of the article. Thus, the article has beneficial interest for people studying composite materials, employees of the current electric power market, as well as workers in the production of insulation and electrical equipment. This in turn allows us to use the article as a guide when designing.

It should be understood that the insulation strength is determined by the dielectric breakdown. The latter, in its turn, are associated with the presence of electrodes with a small radius of curvature and inhomogeneities (at the molecular level, micro-and macro-levels), or rather internal thermomechanical stresses near these inhomogeneities. Therefore, to increase the electrical strength, the choice of insulation should also be based on:

1) The type, size, and structure of the insulation filler [1, 2], which significantly increases the insulation strength when micro and nano-sized particles are introduced;

2) Differences in the temperature coefficients of linear expansion for the electrode material and cast insulation. The difference in these coefficients is reduced by using special damping layers at the boundary between the electrodes and the compound or by introducing an improved type of compound and its manufacturing technology;

3) Increasing the adhesion of metal elements and epoxy compounds by activating the surface layer of the poured metal elements.

The authors of this article have done a lot of work not only to determine the distribution of electrical strength from various parameters, describe the theories of dielectric failure and ways to increase insulation, but also, for the first time, present the experience of high-quality adhesion of electrodes and composite materials without a small layer of compound on the electrode surface before the main filling with solid insulation and with this layer. This method has not been described anywhere in the literature before.

The article discusses the issues of increasing the electrical strength of the CEI. At the same time, for a better understanding of the ongoing processes and changes in the electric field strength, the main influencing factors are taken into account, as well as the mechanisms of the development of electrical breakdown.

Thus, the work is aimed at:

1) analyzing the dependence of the strength of composite materials on various factors based on voltage-time characteristics (life curves), probability theory, as well as theories of breakdown development (theory of shock ionization by electrons, kinetic thermal fluctuation theory, etc.);

2) determination of ways to increase electrical strength.

It should be understood that the considers the main influencing factors on electrical strength and ways to increase it.

The authors' practical experience of this article is limited only to such a way of increasing the insulation strength as adhesion. The work aims to demonstrate the improvement of adhesive properties in various ways.

2 Effect on Electrical Strength

2.1 Voltage-time Dependencies

In addition to short-term electrical strength, the electrical strength of cast polymer insulation during long-term exposure to voltage is also important to ensure the reliable operation of the equipment. Indeed, the electrical strength of insulation during prolonged exposure to voltage can be 3 or more times lower as compared to short-term exposure to voltage, even in a weakly heterogeneous electrical field the long-term electrical strength falls even further - Figure 1.



Fig. 1: "Life curves" of cast epoxy insulation when exposed to industrial frequency voltage [6], where: 1 – average values of electrical strength for CEI (weakly heterogeneous electrical field);

2 – electrical strength at breakdown probability 0.05 (weakly heterogeneous electrical field);

3 – average values of electrical strength (sharply heterogeneous electrical field);

4 – the lowest limit value of electrical strength of insulation in a weakly heterogeneous electrical field; 5 – permissible electrical strength of insulation in a sharply heterogeneous electrical field

As a rule, the voltage-temporal dependences (or "life curves") of electrical strength of cast epoxy insulation in a weakly heterogeneous electrical field when exposed to industrial frequency voltage are well approximated for average values by the following ratio:

$$E_{\tau} = E_{st} \left(\frac{\tau}{\tau_{st}}\right)^{-1/m} \tag{1}$$

where τ is the time to insulation breakdown when exposed to the electrical field with intensity E_{τ} ; τ_{st} is the time before insulation breakdown when briefly exposed to the electrical field with intensity E_{st} ; m is the power characterizing the aging rate, equal to 10-15 for a weakly heterogeneous field, and about 12 on average.

In a sharply heterogeneous electrical field, when "life curves" are approximated by kpyratio (4), the dependence differs from a linear one, and power m decreases significantly with short voltage exposures (Figure 1).

Thus, the question of improving the electrical strength of CEI, with both short-term and long-term exposure to voltage, remains relevant.



Fig. 2: The functions of the CEI electrical strength distribution in short-term exposure to

voltage (1), including partial discharges (3) and without PD (2); $E_{es.limit}^{l}$ =13 kV/mm

For weakly heterogeneous electrical fields of real structures characterized by a large dielectric volume, the electrical strength distribution function, Figure 2 shows, is best described by Weibull's law [2, 7, 10]:

$$P(E) = 1 - \exp\{-\left(\frac{E - E_{\rm l}}{E_{\rm 0} - E_{\rm l}}\right)^{\beta}\}$$
(2)

where E is the electrical strength at a given breakdown probability P; E_1 is the lowest limit of electrical strength; E_0 is the electrical strength at breakdown probability P equal to 1-1/e; β is a measure of dispersion.

2.2 Breakdown Time Distribution

When selecting admissible values of the CEI electrical strength in weakly heterogeneous electrical fields in prolonged exposure to operating voltage, taking into account statistical features of dispersion of the experimental data, the optimum approximation of the volt-temporal dependences, as Figure 3 shows, is achieved by using the ratio (3).

This ratio accounts for the lower electrical strength limit and compliance of the time distribution to breakdown function to the statistical Weibull law [7]:

$$\tau = \tau_{st} \left(\frac{E_{st} - E_{\tau_1}}{E_{\tau} - E_{\tau_1}} \right)^m \left(ln \frac{1}{1 - p} \right)^{\frac{1}{\beta_{\tau}}}$$
(3)

where $\tau_{\rm kp}$ is the most frequent value of time to breakdown in short-term exposure to the electrical field with strength $E_{\rm st}$; E_{τ} is the electrical field strength in prolonged exposure to voltage; $E_{\tau 1}$ is the lower electrical strength limit in prolonged exposure to voltage; P is the breakdown probability; $\beta \tau$ is a measure of dispersion.



Fig. 3: The time distribution to CEI breakdown function (b), particularly with partial discharges (a) and without PD (c) at different electrical field strengths $(1 - E_{\tau}=14\pm 2 \text{ kV/mm}, 2 - E_{\tau}=17\pm 2 \text{ kV/mm}, 3 - E_{\tau}=20\pm 2 \text{ kV/mm}, 4 - E_{\tau}=24\pm 2 \text{ kV/mm}, 5 - E_{\tau}=14\pm 2 \text{ kV/mm})$



Fig. 4: The CEI electrical strength in a weakly heterogeneous electrical field in prolonged exposure to voltage and different breakdown probabilities (solid, dash and dash-dot lines mean all the samples, without and with PD, respectively; for broken samples, the experimental data is straight horizontal lines with constraints, unbroken samples are depicted by points with arrows; numbers indicate the number of samples) Subject to [8], the calculation for ratio (3) corresponds well to the results of experiments shown in Figure 4.

Scientists from China [9] also conducted similar studies of the breakdown probability distribution versus time. The main conclusion of their work [9] is the explanation of the effect of temperature on the aging rate. Namely, at higher temperatures, the breakdown time is reduced.

2.3 Active Volume

Statistical regularities can also explain the existing dependence of the CEI electrical strength on the insulation size.

By assuming that the electrical strength of some single volume of dielectric does not affect the electrical strength of another single volume, and at the same time, the breakdown probability of every single volume is equal to P^* , and where the breakdown of one single volume entails breakdown of the entire insulation gap with the volume V times larger than the single volume, we can determine the breakdown probability of the entire insulation by the formula

$$P(E) = 1 - (1 - P^*)^{V}$$
(4)

Using ratios (2, 4), it is easy to achieve the dependence of insulation electrical strength on the dielectric volume:

$$E(P) = (E_0 - E_l)[-\ln(1 - P)]^{\frac{V}{\beta}} + E_l \quad (5)$$

Paper [7] has shown the defining effect of "active" compound volume (where the electrical field strength is at least 85% of the highest strength in the gap) on the electrical strength in samples with cast metal electrodes. However, it is precisely in this volume where electrical and internal thermomechanical stresses have the highest values since this "active volume" is located near the cast electrodes.

It should be noted that the electrical strength value determined for the same material depends very strongly on the method of electrical strength testing. In Russia, for epoxy compounds, there are standardized testing methods to determine the electrical strength in a sharply homogeneous heterogeneous and electrical field [11]. In global practice, standard ASTM D149 - 20 [12] is one of the main regulatory documents for determining the electrical strength of cast insulation.

The effect of a lower electrical strength limit on volt-temporal dependences of electrical strength is experienced at low breakdown probabilities (Figure 1 - curve 2) since in this case, the dependence becomes nonlinear, and the results of processing of various statistical data show that the electrical strength limit in a weakly heterogeneous electrical field is 5 kV/mm or higher. and in a sharply heterogeneous electrical field it is about 2 kV/mm [3].

Despite numerous theoretical and experimental studies of electrical strength in dielectrics, particularly polymers, there is still no unambiguous understanding of their breakdown mechanism when exposed to high voltage.

3 Mechanisms of Electrical Breakdown

When explaining the electrical breakdown mechanism in solid dielectrics, two scientific areas have formed in the literature. Most of the experimental data show that the electrical breakdown of solid dielectrics emerges due to electron impact ionization [13-15]. However, several papers [16, 17] deny that electron impact ionization can develop in solid dielectrics, particularly polymers, at least in the initial phase: electrical breakdown of solid dielectrics is explained in the context of overheated electrical instability and electronic detonation during solid dielectrics breakdown.

In particular, the kinetic thermofluctational theory of material breakdown [18] assumes that material breakdown is caused by the breakage of chemical bonds due to the combined action of energy of molecular thermal motion and some external force (mechanical load, electrical field, etc.).

This theory proposes to consider the breakage of chemical bonds due to the energy of thermal vibrational motion as a mechanism of solid dielectric breakdown, such breakage being facilitated by the distortion of energy zones under the influence of the electrical field. Here, chemical bond breakage and polymer breakdown occur in the initial phase not under direct electrical field effect but rather due to the energy of atomic and molecular thermal vibrational motion, taking into account energy zone distortions due to the electrical field effect:

$$E_{\rm np} = \frac{DN_A\rho R}{\beta\eta a M \sqrt{gM\varepsilon_0(\varepsilon-1)}} \frac{\sqrt{1-2x} - \frac{2kT}{D} ln \frac{^{\rm np}}{\tau_0}}{\ln\left(\frac{1}{x} + \frac{1}{x}\sqrt{1-2x-1}\right)} \tag{6}$$

where *D* is the chemical bond dissociation energy, N_A is the Avogadro number, ρ is the material density; *R* is the interatomic equilibrium distance, *x* is the relative load affecting the chemical bond, *K* is the universal gas constant, *T* is temperature, τ_{np} and τ_0 is time to breakdown under prolonged and short-term exposure to voltage, β is the dielectric structure heterogeneity factor, η is the electrical field heterogeneity factor, a is the constant, *M* is the molecular weight, g_M is the elastic modulus, ε_0 is the absolute permittivity, ε is the relative permittivity.

This theory implies that the destruction of the dielectric is associated with the sequential destruction of molecular bonds: after the break of one bond, other breaks follow. This phenomenon is due to the fact that when bonds are broken, new charges are formed, transferring part of their energy to neutral atoms [18].

The equations presented by the authors of the theory show that the electrical strength of polymers increases with increasing chemical bond dissociation energy and decreases with increasing temperature and voltage application time, which does not contradict experimental data on dielectric breakdown.

This approach also makes it possible to justify the existing varieties of dielectric breakdown:

- purely electric;
- electrothermal;
- electromechanical;
- electrochemical.

It has been found experimentally that manifestation of some type of breakdown depends on the electrical field form, dielectric structure, properties, presence of defects, cooling conditions, voltage exposure time, etc., which also does not contradict the thermofluctational theory of dielectric breakdown.

It should be noted that the thermofluctational theory does not consider the discharge development mechanism and the breakdown channel formation process. After all, the low mobility of ions formed during the breaking of chemical bonds does not provide a short time for discharge development [18]. Therefore, in this theory, there is no criterion for considering the discharge's development. However, this theory describes the main directions of the increase in electrical strength of polymers convincingly.

4 Ways to Increase Electrical Strength

There are various ways to increase the electrical strength of the insulation. Recently, the most common method is the introduction of nanofillers into the structure of the compound [1, 2]. However, traditional methods such as increasing the adhesion of dissimilar materials (metal elements and insulating compounds of high-voltage electrical equipment) should not be excluded.

The following technological methods of increasing the adhesion of the compound and metal are usually adopted:

- increasing the active adhesion area (creating roughness) of the metal;

- selection of materials with similar linear expansion coefficients [19];

- activation of the metal surface itself by its chemical treatment [20];

- degreasing of the connected surfaces [20];

- application of intermediate substrates having average thermal expansion coefficients between similar parameters of metal and compound;

- using constructive techniques by shaping and placing the reinforcement in a polymer material, providing compression due to shrinkage phenomena.

4.1 Features of Polymer Microstructure and Its Effect on Electrical Strength

Paper [21] also notes the difficulties in calculating the electrical strength of complex polymer dielectrics based on existing quantum-mechanical theories. Considering polymers structure in the context of modern views on their structure suggested that the so-called "free" volumes, i.e. areas in polymer volume induced by loose packing of macromolecular chains, play an essential role in the electrical breakdown.

resins Cured have epoxy а microheterogeneous structure of globular type [22]. Sizes of globular particles (about 100 angstroms) depend on the ingredients of composition and curing conditions (particle sizes decrease with increasing temperature). As globule sizes decrease, the polymer electrical strength increases. Glass transition temperature, compressive strength, chemical and thermal resistance increase as distances between mesh nodes become shorter, but this generally increases the polymer brittleness.

When epoxy resin compositions comprise low molecular weight compounds (such as plasticizers) or oligomers of other types (such as oligoethers) that contain too few or no reactive groups, such components do not participate in mesh formation, but rather accumulate at globular formation interfaces, thereby causing a significant decrease in mechanical and electrical strength, and also thermal and chemical resistance.

Therefore, the electrical strength of different cured epoxy compounds can vary significantly and manifests generally in the range of 15-35 kV/mm (for a standard electrical strength definition in a slightly heterogeneous electrical field) in short-term exposure to industrial frequency voltage and 20° C temperature.

It should be noted that electrical strength is determined not only by molecular level heterogeneities, but also by micro-level insulation heterogeneities (e.g., CEI filler particles) and even by macro-level ones, namely gas inclusions (pores, cracks, and delaminations).

In the meantime, it is exactly the levels of internal thermomechanical stresses near some heterogeneity, particularly near the cast metal elements, that form some additional external force affecting intermolecular bonds, that determines the electrical strength.

Thus, increasing the CEI electrical strength can be achieved by selecting resins and compounds with increased chemical bond dissociation energies and low levels of local thermomechanical stresses in the material. Therefore, the selection of type, size, and structure of epoxy insulation fillers [1, 2, 23] is one of the most important areas for improving the electrical strength of cast insulation.

In [24] it is shown that the electrical strength of epoxy insulation increases by using nanosize particle (7 to 80 nanometers) filler, and the use of micro-size (i.e., about one micron) particles can increase electrical strength by improving volume dispersion (Figure 5).



Fig. 5: Breakdown voltage of 1mm CEI samples with presence of filler, its type and filler particle size [24]

It is generally believed that an increase in electrical strength and other parameters of epoxy compounds with a decrease in filler particle sizes is associated with an increase in the surface of interaction between filler particles and epoxy resin [1, 2, 4].

Japanese researchers [25] have created an epoxy compound where electrical strength increased about 1.5 times (Figure 6). The glass transition temperature (Tg) is 30°C higher than conventional epoxy compounds. Breakdown probability due to adhesion or temperature fluctuations is decreased greatly by a very low value of the thermal expansion factor.

The new compound uses a special type of filler, namely spherical silica (instead of a conventional amorphous one) and a small number of rubber particles.



Fig. 6: Electrical strength of conventional and optimized compounds according to [25]

Conventional material consists of a biphenol-type epoxy resin, phthalic acid anhydride, and amorphous silica filler. Material of this type is used widely for high-speed automatic injection molding. The developed material consists of another type of biphenolic epoxy resin and phthalic acid anhydride, and it is filled with a large amount of spherical silica and a small number of rubber particles.

The glass transition temperature of the compound developed is increased due to the changed structure of epoxy resin, thereby improving such parameters as strength, elasticity, electrical properties, etc.

Also, in the literature [1], there were presented results indicating an increase in the insulation characteristics of high-voltage insulators with the introduction of insulation nanofillers, such as SiO₂ and h-BN. Due to better bonding of fillers and nano- or microsizes, scientists managed not only to increase various characteristics of the component, including increasing the resistance to corona discharge, but also to slow down the aging process of insulation.

The most common synthetic inorganic fillers that are used to enhance the properties of polymers are silicon dioxide (SiO₂), titanium oxide (TiO₂), aluminium oxide (Al₂O₃), zinc oxide (ZnO), magnesium oxide (MgO)), nitrides (boron nitride (BN), aluminium nitride (AlN), silicon nitride (Si₄N₃)) and carbides (silicon carbide (SiC)). [1, 2, 4, 26].

4.2 Accounting for Linear Expansion Coefficients

Where cast metal elements are used, there is a manifestation of the effect of thermomechanical stresses associated with the emergence of compound deformations caused by temperature coefficient difference of linear expansion for electrode and cast insulation materials. Available data [23] illustrate electrical strength with electrode material grade. The use of metal electrodes cast into a sample, compared to electrodes made by metallization on a sample, reduces the electrical strength of epoxy insulation significantly.

During prolonged exposure to voltage, a compound's breakdown mechanism depends on the accumulation of mechanical and electrical micro-and macro-damage in insulation and on its development.

Under the exposure to high voltage, the material breakdown process generally begins in a local area with the highest electrical field strength, i.e., near electrodes with small curvature radii or near heterogeneities contained in the compound and distorting the electrical field. Such heterogeneities can be, for example, gas pores, filler accumulations, etc.

The CEI electrical strength increases slightly with increasing temperature up to the onset of thermal degradation [18]. This can be explained by the positive effect of internal thermomechanical stress decreases on electrical breakdown processes.

The electric strength of the LEI is most strongly reduced by gas inclusions - pores, cracks, delaminations at the border with metal elements, since partial discharges (PD) can occur in these inhomogeneities. Under the effect of PD, the following processes can emerge in the solid insulation of electrical conductors:

- Formation of gaseous ionization products, namely ozone, carbon oxides, nitrogen oxides, etc.;

- Chemical and structural breakdown of the dielectric under exposure to ionization products, such destruction being accompanied by chemical bond breakages, formation of new groups in polymer macromolecules, and also the formation of carbon, etc;

- Direct effect on dielectric by ion and electron bombardments, radiation generated at PD;

– Increase in the local electrical field strength and temperature in the PD zone.

Partial discharges generally do not induce the rapid breakdown of insulation gaps, the process of PD development is rather slow and depends on partial discharge intensity, therefore the PD effect is particularly strong under prolonged exposure to voltage (Figure 4).

However, in weakly heterogeneous electrical fields with high average breakdown strengths, there is a decrease in electrical strength of cast insulation in the presence of PD even under short-term voltage exposures, provided that partial discharge intensities exceed several picocoulons (Figure 7).



Fig. 7: Electrical strength of cast epoxy insulation in a weakly heterogeneous electrical field, with partial discharge intensities at a smooth rise of industrial frequency voltage [8]

Gas inclusions can appear in insulation during manufacturing due to technological process violations that emerge when shrinking cast masses and compounds and low-quality bonding between electrodes and dielectric.

Gas inclusions also emerge in operation due to cracking or delamination of insulation caused by high internal thermomechanical stresses.

Breakdown of solid insulation in electrical conductors, when exposed to partial discharges, is caused mainly by discharge energy release in a gas inclusion. The absolute value of energy dissipated in a discharge is typically low. However, it is transmitted to quite a small area of inclusion surface, where local temperature rises immediately.

This exposure entails the breakdown of a small volume of dielectric with the formation of byproducts, sometimes chemically active products. With multiple repeated partial discharges, the inclusion surface breaks down gradually, local depressions appear on it, and they grow over time to form narrow branched channels in the dielectric. Ultimately, the process ends with a complete breakdown of insulation.

High internal thermomechanical stresses cause a negative effect on the bonding between the compound and the metal electrodes, such stresses emerge due to compound shrinkage during curing, different linear expansion coefficients of the compound, and the cast reinforcement, and there are frequent attempts to compensate for such negative effect by selecting close linear expansion coefficients of dielectric and metal using special damping lavers on the interface between the compound cast reinforcement, developing and and applying special compounds and technologies of their production.

Table 2. Linear	expansion	coefficients of
differe	ent materia	ls

different materials			
Materials	Linear expansion coefficient, $10^{-6} \cdot °C^{-1}$		
Epoxy resin	50 to 60		
Epoxy resin + 200% (by weight) filler in the form of powdered quartz	25 to 30		
Aluminum	22.2		
Duralumin	23.5		
Brass	18.7		
Copper	16.6		

Cast iron	10.4 to 13.0
Porcelain	3.6 to 4.5

The table data shows that the difference between the temperature elongation of epoxy resin and other structural materials is extensive. The difference is decreased by adding inert filler such as dusty silica sand; this produces the epoxy compound required for casting. The use of current-carrying parts made from aluminum in cast-insulated devices is justified since linear expansion coefficients of the aluminum and epoxy compound are almost equal. The method of creating elastic liners between cast metal poured parts and the compound has also justified itself.

4.3 Degreasing and Chemical Activation of Surfaces

Increased epoxy compounds adhesion to cast metal parts can also be achieved by activating the surface layer of cast metal reinforcement, particularly by degreasing this surface.

Of all the theories of adhesion justification aimed at describing the causes of adhesion of dissimilar surfaces, the most common is the molecular theory of adhesion [27]. According to this theory, the adhesion of different surfaces for bodies is associated with the action of interatomic (chemical) bonds and (or)intermolecular (physical) forces. The latter, in turn, have an electrical nature of origin. Since adhesion occurs due to the presence of interatomic and intermolecular bonds, for a tight adhesion of surfaces (strong) there must be chemically active, polar, or polarized substances on both surfaces. Fats are not such materials, so it is necessary to perform degreasing, i.e. the process of removing various fatty films, etc.

5 Practical Experience for Coupling of Heterogeneous Surfaces

It should be noted that the quality of bonding between epoxy compound and cast metal electrodes can be evaluated by the value of the tensile load at failure. Where the bonding between electrodes and the compound is poor, tensile failure of a sample should be expected to happen in a way that the tear cross-section would accommodate almost the entire active surface of a metal electrode, and the loads at failure would be minimal. Conversely, the better the bonding, the smaller the percentage of metal electrode surface in the tear cross-section. With perfect bonding, the tear can only happen along the dielectric body.

As a practical experience, it was decided to study the quality of adhesion on the metal electrode surface with a compound in design samples, depending on various methods of surface activation.

The experimental work consisted of two parts:

- production of the samples themselves;

- conducting tests of the mechanical strength of samples.

The method of sample production was carried out as follows:

1. manufacture of aluminum metal elements;

2. the implementation of surface treatment of aluminum elements in various ways (mechanical treatment, degreasing, chemical activation (for example potassium dichromate));

3. applying a pre-coating insulation layer of 1-2 mm on the aluminum surface. This item is present only during the second experiment;

4. filling the structure with the main volume of the compound under vacuum (KF-1 and KE-3 compounds).

The test procedure was as follows. The M16 thread was cut into the embedded metal elements, where the bolts were inserted. A smooth mechanical tensile load was applied to the bolts at a speed of 20 kg/s until destruction with the help of a special breaking machine.

The completed studies of the quality of bonding between the surfaces of metal electrodes located in electrical pathways and the compound in structural samples (Figure 8) depending on different methods of surface activation and, respectively, on increasing adhesion: without special treatment, with alkali degreasing, and also with potassium dichromate treatment, showed that activation of electrode surfaces can significantly increase adhesion and degree of bonding between electrodes and the compound, namely with alkali treatment by about 40% and with potassium dichromate treatment by 88% (Figure 8).



Fig. 8: Mechanical strength of cast epoxy insulation samples under tensile load with different methods of electrode surfaces activation

The main reason for such adhesion is the force field of molecules located in the solid metal surface, such field pulling molecules located in close proximity to this surface of the liquid polymer during its curing. Actually, the effect of the field of molecules located in the compound extends to the depth of a single molecule. The contact layer is formed by surface polymer molecules, and they, in contrast to chaotic and disorderly arrangement in the thickness, acquire an oriented and ordered structure.

There were also studies to relieve internal mechanical stresses near electrodes by applying an intermediate layer of the compound to the surfaces of electrodes before the main casting (Figure 9).

The results obtained (Figure 9) show that this technological technique is one of the most effective ways of improving the bonding between electrodes and the compound since even if untreated electrodes are covered with a compound layer it gives a 54% increase in strength and a 126% increase with additional potassium dichromate treatment of electrodes (by 183% for the lowest values).



Fig. 9: Effect on the mechanical strength of cast epoxy insulation samples under the tensile load of compound layer precoat on electrode surfaces

The noted positive effect of applying a compound layer precoat and potassium dichromate treatment of electrodes is caused by two reasons: oxide film removal from electrode surfaces and decrease in internal thermomechanical stresses in the compound near metal electrodes, provided that they are covered with a thin compound layer.

From the results presented in Figures 8 and 9, the following conclusions can be drawn. Firstly, degreasing the surface with precoat increases the mechanical strength of the samples by about 1.5 times, and with chroma peak by about 2 times. Secondly, the application of an additional layer of insulation 1-2 mm thick on aluminum elements before the main filling with the compound contributes to the greater mechanical strength of the samples, i.e., more adhesion. However, the emergence of precoat requires solving the issues of compound autohesion in the technological process of manufacturing, i.e., ensuring high physical and chemical properties of the bonding between individual layers.

Internal thermomechanical stresses can also be decreased by increasing the compound plasticity near an electrode since the emergence of thermomechanical stresses in the compound is associated with shortening interatomic distances. Dielectric's elastic state is caused by an increase in the range of interatomic distance fluctuations.

The application of a semiconductive layer around the conductor is one of the design solutions aimed at preventing partial discharges as a result of insulation delamination from the conductor. However, even here the issues of good bonding between this layer and the compound are still relevant.

The value of the obtained experimental results in the study of various ways to improve the adhesion of metal elements with epoxy compounds is the fact that they were obtained on samples as close as possible to the design of real insulators (namely, support insulators of gas-filled high-voltage devices), characterized by large volumes of dielectric and metal elements, which is associated with significant internal thermomechanical stresses in this dielectric.

6 Conclusion

The results given in the paper confirm that the issue of improving the electrical strength of cast epoxy insulation is an important one. Also, they indicate the following points regarding this type of insulation:

- Volt-temporal dependences of electrical insulation strength can be described using the proposed ratios for average electrical field strength values, and also in small breakdown probabilities;

- Statistical specifics of electrical insulation strength must be accounted when calculating the latter based on Weibull's limit statistical law;

- Internal local thermomechanical stresses in dielectric have a crucial effect on the electrical strength of cast epoxy insulation, and this effect can be substantiated based on the thermofluctational theory of dielectrics breakdown;

- It is expedient to reduce internal local thermomechanical stresses and, consequently, increase the electrical strength via a proper selection insulation structure of and manufacturing technology: by optimizing fillers, selecting linear expansion coefficients of individual insulation components, activating the surfaces of cast metal parts, applying special damping layers during manufacturing.

- Gas inclusions must be prevented within insulation, both during manufacturing and in operation, since they decrease the electrical strength most dramatically. The correctness of conclusions made is confirmed not only by the analysis of available data, but also by own experimental studies performed by the authors and given in the article: taking into account the activation for electrode surfaces as a result of their treatment with solutions, and also application of damping layers to electrodes during their manufacturing.

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References:

- Saleem M.Z., Akbar M., Review of the Performance of High-Voltage Composite Insulators, *Polymers*, Vol.14, No.3 (431), 2022, pp. 1-17. https://doi.org/10.3390/polym14030431.
- [2] Pleşa I.; Noţingher P.V.; Schlögl S.; Sumereder C. Muhr M., Properties of Polymer Composites Used in High-Voltage Applications, *Polymers*, Vol. 8, 2016, pp.1-173. https://doi.org/10.3390/polym8050173.
- [3] Varivodov V.N., Kovalev D.I., Zhulikov S.S., Golubev D.V., Romanov V.A., Mirzabekyan G.Z., Technological Aspects of the Use of Cast Polymer Insulation for High-Voltage Switchgear and Busbars, *Power Technology and Engineering*, Vol. 54, 2021, pp. 915–922. doi: 10.1177/1050651999013002002.
- [4] Hari R., Mohana Rao. M, Characterization of nano-additive filled epoxy resin composites (ERC) for high voltage gas insulated switchgear (GIS) applications, *International Journal of Emerging Electric Power Systems*, Vol.23, No.1, 2022, pp. 47 - 57.
- [5] Jalakas T., Janson K., Molder H., Roasto I., High- voltage pulse transformer for IOT modulators, *IET Electric Power Applications*, Vol. 14, No.12, 2020, pp.2348-2354.
- [6] Varivodov V.N., Kovalev D.I., Krupenin N.V., Khrenov S.I., Permissible Electrical-Field Intensities in the Epoxy Cast Insulation of a 6 to 110 kV switchgear, *Russian Electrical Engineering*, Vol. 89, No. 5, 2018, pp. 294– 297.
- [7] Varivodov V.N., Electrical strength of cast epoxy insulation in quasi-homogeneous fields, *Applied Physics*, Vol. 5, 2001, pp. 34–40.
- [8] Varivodov V.N., Internal insulation in gasfilled high-voltage and ultrahigh-voltage

equipment, PhD dissertation, Dept. High voltage technique, Moscow, 2000.

- [9] C. Liu et al., Combined Electrical and Thermal Aging of Alumina Filled Epoxy Solid Insulators for GIS, 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 2019, pp. 1-4, doi: 10.1109/EEEIC.2019.8783950.
- [10] Andersen A., Dennison J., Mixed Weibull distribution model of DC dielectric breakdowns with dual defect modes, 2015 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), 2015, pp. 570-573, doi: 10.1109/CEIDP.2015.7352017.
- [11] GOST6433.3-71. Solid electrical insulating materials. Methods for evaluation of electrical strength at a.c. voltage at power (50 Hz) frequency and d. c. voltage. [Online]. Available:

https://docs.cntd.ru/document/1200011888.

- [12] Standard ASTM D149 20. Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials at Commercial Power Frequencies. [Online]. Available: https://webstore.ansi.org/standards/astm/astmd 14920.
- [13] Zhao L., A formula to calculate solid dielectric breakdown strength based on a model of electron impact ionization and multiplication, *AIP Advances*, Vol. 10, No. 2, 2020, pp. 025003-1 – 025003-9.
- [14] Cao L., Yuan Y., Li E., Zhang S. Relaxor regulation and improvement of energy storage properties of Sr2NaNb5O15-based tungsten bronze ceramics through B-site substitution. *Chemical Engineering Journal*, Vol. 421, 2021, pp. 1-12.
- [15] Gockenbach E., High Voltage Engineering. In: Papailiou, K.O. (eds) Springer Handbook of Power Systems. Springer Handbooks, 2021.
- [16] Raju G. G. Dielectrics in electric fields, second edition, *Dielectrics in electric fields, second edition*, 2016, pp. 1-752.
- [17] Li B., Salcedo-Galan F., Xidas P. I., Manias, E., Improving electrical breakdown strength of polymer nanocomposites by tailoring hybridfiller structure for high-voltage dielectric applications, ACS Applied Nano Materials, Vol. 1, No. 9, 2018, pp. 4401-4407. doi:10.1021/acsanm.8b01127.
- [18] Kartashov E. M., Thermal destruction of polymeric fibers in the theory of temporary

dependence of strength, Tonkie Khimicheskie Tekhnologii, Vol.16, No.6, 2021, pp. 526-540. doi:10.32362/2410-6593-2021-16-6-526-540.

- [19] Walker R. C., Hamedi H., Woodward W. H. H., Rajagopalan R., Lanagan M. Impacts of crosslinking and degassing on the conductivity, dielectric loss, and morphology of low-density polyethylene and crosslinked polyethylene, 2021, doi:10.1021/bk-2021-1375.ch011.
- [20] Edward M. Petrie, *Passive processing methods*, The World of Electroplating magazine, Vol. 3, No. 03, 2007, pp. 183-272.
- [21] Großmann S., High currents and contact technology, 2021. doi:10.1007/978-981-32-9938-2_4.
- [22] Serra A., Ramis, X., Fernandez- Francos X., Epoxy Sol-Gel Hybrid Thermosets, *THE Coatings*, Vol. 6, No. 8, 2016, pp. 1-19.
- [23] Varivodov V.N., Kovalev D.I., Golubev D.V., Mirzabekyan G.Z., Development of insulation systems for high-voltage busbars with solid insulation, Russian Electrical Engineering, Vol. 92, 2021, pp. 185–192.
- [24] Liang M., Wong K.L., Electrical Performance of Epoxy Resin Filled with Micro Particles and Nanoparticles, *Energy Procedia*, Vol. 110, 2017, pp. 162–167. doi: 0.1016/j.egypro.2017.03.122.
- [25] Sato J., Susumu K., Osamu S., Masaru M., Shimizu T., Homma M., Solid Insulated Switchgear and Investigation of its Mechanical and Electrical Reliability, *Electrical Engineering in Japan*, Vol. 174, no. 4, 2011, pp. 28–36.
- [26] Rajkonwar L., Ram Prasath R.A., D J., Roy N.K., Studies on Epoxy Based TiO2Nano-filler for High Voltage Application, 2018 International Conference on Power, Energy, Control and Transmission Systems (ICPECTS), 2018, pp. 128-132.
- [27] Bukhari M.D., Gohar G.A., Akhtar A., Ullah S., Akram M.B., Abid J., Raza H., Adhesion Theories and Effect of Surface Roughness on Energy Estimation and Wettability of Polymeric Composites Bonded Joints: A-Review. VW Applied Sciences, Vol. 2, No. 1, 2019, pp. 74-86.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

-Vladimir Varivodov carried out methodology development for article, participated in writing and conducting the research in Section 4.

-Dmitry Kovalev provisioned laboratory samples and carried out project administration.

-Dmitry Golubev has organized oversight for the research activity planning and execution and conducted the research in Section 4.

-Ekaterina Voronkova was responsible for data visualization, writing article, carried out conducting the research in Section 4.

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