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EFFICIENCY OF APPLICATION OF SEMICONDUCTIVE COATINGS FOR REGULATION OF ELECTRIC FIELD IN HIGH-VOLTAGE INSULATION OF ELECTRIC MACHINES

Introduction. Intensification of competition and the desire to reduce the cost of high-voltage electric machines due to a significant increase in the electrical and thermal loads of the electrical insulation system complicate the operation of anti-corona coatings on the insulation surface of the stator winding and increase the intensity of discharge processes, which significantly reduce the life of the insulation in case of failure of the coatings. Purpose. The analysis of the efficiency of alignment of the electric field along the insulation surface of the stator winding of high-voltage electric machines with semiconductor anti-corona coatings. Methodology. A method for calculating the electric potential distribution along the surface of the winding insulation during the use of semiconductive coatings providing alignment decrease the electric field and eliminating the appearance of moving discharges. The reliability of the calculations is confirmed by experimental studies of the potential distribution over the surface of the anti-corona semiconducting non-linear coating along the frontal part of the samples of the rod of the hydrogenerator for a linear voltage of 20 kV. Practical value. The proposed methodology for calculating the distribution of the electric field over the surface of the insulation and the anti-corona semiconductive coating can be applied to justify the length of the coating in the frontal part of high-voltage electrical machines depending on the electrophysical characteristics of the coating, electrical insulation, and thickness. The results of an experimental verification of the stability of the nonlinear properties of coatings during prolonged electrical and thermal aging of specially made coating samples are presented. References 14, figures 6.

Key words: **frontal part of the rod, external partial discharges, electric field, regulation of the electric field, semiconductive coating, surface resistivity, distribution of electric potential, stability of nonlinear properties, long-term electric and thermal aging**.

Представлена методика розрахунку розподілу електричного поля по поверхні ізоляції і протикоронного напівпровідного покриття в лобовій частині стрижня високовольтної електричної машини. Отримано в залежності від питомого поверхневого опору напівпровідного покриття розподіл електричного потенціалу по поверхні протикоронного покриття та ізоляції. Обґрунтовано діапазон значень питомого поверхневого опору протикоронного покриття для ефективного регулювання електричного поля. Достовірність розрахунків підтверджено експериментальними дослідженнями розподілу потенціалу по поверхні протикоронного напівпровідного нелінійного покриття уздовж лобової частини зразків стрижнів гідрогенератора на лінійну напругу 20 кВ. Представлено результати експериментальної перевірки стабільності нелінійних властивостей покриттів в процесі тривалого електричного і теплового старіння спеціально виготовлених зразків покриття. Ефективність регулювання електричного поля напівпровідними покриттями підтверджено результатами випробувань зразків стрижнів гідрогенератора СВ -1500 / 100-12 в початковому стані і після комплексного тривалого впливу електричного поля і температури. Бібл. 14, рис. 6.

Ключові слова: **лобова частина стрижня, зовнішні часткові розряди, електричне поле, регулювання електричного поля, протикоронне напівпровідне покриття, питомий поверхневий опір, розподіл електричного потенціалу, стабільність нелінійних властивостей, тривале електричне і теплове старіння.**

Представлена методика расчета распределения электрического поля по поверхности изоляции и противокоронного полупроводящего покрытия в лобовой части стержня высоковольтной электрической машины. Получено в зависимости от удельного поверхностного сопротивления полупроводящего покрытия распределение электрического потенциала по поверхности противокоронного покрытия и изоляции. Обоснован диапазон значений удельного поверхностного сопротивления противокоронного покрытия для эффективного регулирования электрического поля. Достоверность расчетов подтверждена экспериментальными исследованиями распределения потенциала по поверхности противокоронного полупроводящего нелинейного покрытия вдоль лобовой части образцов стрежней гидрогенератора на линейное напряжение 20 кВ. Представлены результаты экспериментальной проверки стабильности нелинейных свойств покрытий в процессе длительного электрического и теплового старения специально изготовленных образцов покрытия. Эффективность регулирования электрического поля полупроводящими покрытиями подтверждена результатами испытаний образцов стрежней гидрогенератора СВ 1500/100-12 в исходном состоянии и после комплексного длительного воздействия электрического поля и температуры **.** Библ. 14, рис. 6.

Ключевые слова: **лобовая часть стержня, внешние частичные разряды, электрическое поле, регулирование электрического поля, противокоронное полупроводящее покрытие, удельное поверхностное сопротивление, распределение электрического потенциала, стабильность нелинейных свойств, длительное электрическое и тепловое старение.**

Introduction. One of the main problems in the manufacture of high-voltage electric machines is the suppression of external partial discharges that occur in the slot part of the winding due to the potential difference between the insulation surface and the stator core and in the frontal part due to a sharp jump in the electric field at the exit of the winding from the slot [1-3].

The regulation of the electric field in the insulation of the stator winding, which suppresses partial discharges in the air gaps between the insulation surface and the slot walls and elimination of the sliding discharges along the insulation surface in the places where the windings exit the stator slot, consists in the use of conductive and semiconductive coatings. Intensification of competition and the desire to reduce the cost of high-voltage electric machines due to a significant increase in the electrical and thermal loads of the electrical insulation system complicate the operation of anti-corona coatings on the insulation surface of the stator winding and increase the intensity of discharge processes, which significantly reduce the life of the insulation in case of coating failure [4-9]. In connection with the foregoing, the need arises for the use of anti-corona coatings that provide effective regulation of the electric field during operation of high-voltage electric machines.

The goal of the paper is analysis of the efficiency of alignment of the electric field along the insulation surface of the stator winding of high-voltage electric machines with semiconductive anti-corona coatings.

Problem definition. Case insulation of the stator winding is the most loaded element, subjected to the simultaneous influence of an electric field, temperature and thermomechanical stresses. Particularly high requirements for modern insulation systems are imposed in connection with the design and manufacture of powerful air-cooled turbo-generators. The permissible working electric field strength of the case insulation (in the region of the flat side of the rod) reaches values (3-3.2) kV/mm for insulation made by vacuum-injection impregnation for conductors with optimized geometry (with rounded corners) [2, 3]. An increase in the requirements for the reliability of powerful electric machines has led to the need to use in the manufacture of stator case insulation of materials characterized by increased stability of physico-chemical and electrical insulation properties. Traditionally, combined mica tapes are used for this purpose, in which glass tapes are used as a substrate, and mica papers impregnated with epoxy resin are used as a dielectric barrier. The increase in the content of mica in mica paper provides a significant increase in long-term electrical insulation strength [10]. The level of electric field at which the electrical insulation of the slot of the rod works depends on the nominal voltage of the machine, the thickness of the insulation, and the configuration of the surface of the copper of the rod and the slot of the stator. As a rule, modern powerful turbogenerators have slots and rods of a rectangular shape. With this shape of the electrodes, the maximum values of the electric field strength [11] occur at the corners of the current-carrying rod (Fig. 1, curve 5: the equipotential surface is $\varphi = \pi$, the force line number is $\psi = 0$), and the insulation is extremely irregularly loaded over the slot volume. In the corner of the slot, i.e. for $\varphi = 0$ and $\psi = 0$, the electric field strength is 0 (Fig. 1, curve 3). The degree of alignment of the electric field in the stator slot is characterized by the coefficient of electric field non-uniformity K equal to the ratio of the maximum field strength $E_{\max}$ taking place in the slot to the uniform field strength E_{midl}, i.e. at a sufficient distance from the angle of the current-carrying rod (Fig. 1, curve 1: equipotential surface $\varphi = \pi/2$ and $\psi \to \infty$).

The slot part of the stator winding section is installed in the slot of the core freely, the existing irregularities and the spread in the dimensions of the slot of the core and section determine the presence of some air gap (not more than 1 mm) between the insulation surface and the core. A two-layer insulation system is formed: solid insulation – gaseous dielectric (air). Breakdown of the air interlayer (partial discharge), which is under conditions of a strong inhomogeneous electric field, will occur at a voltage lower than the working one [11-13].

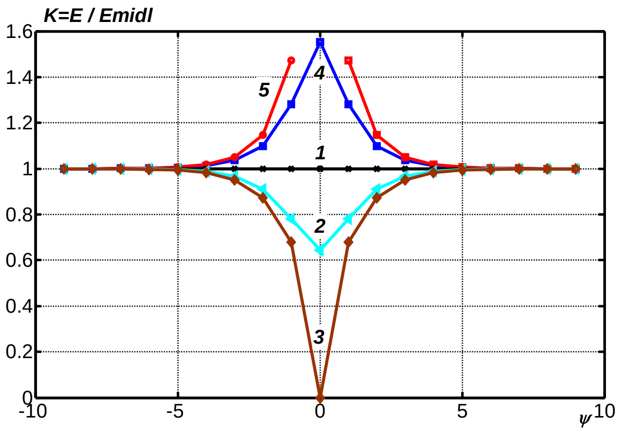

Fig. 1. The coefficient of non-uniformity of the electric field K in the slot of the stator winding of the turbogenerator for linear voltage of 20 kV:
curve 1 – $\varphi=\pi/2$ and $\psi\to\infty$;
curve 2 – $\varphi=\pi/4$ and $\psi=0$; curve 3 – $\varphi=0$ and $\psi=0$;
curve 4 – $\varphi=3/4\pi$ and $\psi=0$; curve 5 – $\varphi=\pi$ and $\psi=0$

A semiconductive coating electrically connected to the walls of the slot is applied over the insulation of the rod. Such a coating with a low value of specific surface resistance («*conductive*») provides contact at many points between the coating and the walls of the slot, that is, the entire surface of the slot part is grounded. As a result, the potential difference between the insulation surface and the slot wall is eliminated. This is usually graphite-based tape or varnish. On the one hand, the conductivity of the coating should be sufficient to eliminate partial discharges in the slot, which develop when a potential difference occurs between the insulation surface and the stator. On the other hand, it should not be less than a certain level at which the stator sheets are closed, which in turn leads to the appearance of eddy currents and an increase in losses. The specific surface resistance of the slot coating ρ_s lies in the range (10^2 – 10^4) Ω, which reduces the probability of breakdown of air gaps between the rod and the slot wall.

In the frontal parts, the rods with insulation are in a gas environment. Most of the voltage falls on the gas gaps. In this case, the component of the electric field strength along the surface becomes less than the critical intensity of the beginning of ionization of air or hydrogen [11-13]. The slot (conductive) coating extends beyond the slot to eliminate corona at the exit of the winding from the slot, where the electric field strength in the air is high enough for the development of discharge processes. In the absence of protective measures at the place where the rod exits from the slot, there is a sharp jump in the electric field strength, which can lead to the appearance of external edge discharges (corona and discharges along the surface of solid insulation) on the surface of the frontal part of the coil or rod of the electric machine. To eliminate the effect of corona, it is necessary to ensure a smooth distribution of the electric potential over the insulation surface of the frontal parts of the rods.

Regulation of the electric field in the frontal part of the insulation of the stator winding of high-voltage electric machines. An anti-corona coating which has large values of specific surface resistance (10^5-10^9) Ω is used in the frontal part [6-8]. In the frontal parts, a semiconductive layer is applied over a length of 20–25 cm. For this purpose, semiconductive coatings made on the basis of enamel are used [6-8], in which fillers are conductive powders: carbon black or graphite with a linear current-voltage characteristic. The dispersion of carbon black or graphite significantly affects the operational properties of anti-corona protection [9].

Most preferred are nonlinear coatings with a pronounced increasing dependence of the specific surface conductivity on the electric field strength (Fig. 2).

The coating creates a section of length l_s with specific surface resistance ρ_s (Fig. 3), and the surface resistance of the coating is much less than the surface insulation resistance ρ_{inss}. Because $\rho_s \ll \rho_{inss}$, then the component of the electric field strength E_{Os} along the insulation surface at the point O decreases. But at the end of the coating (at point K), a new region is formed with a sharply uniform field.

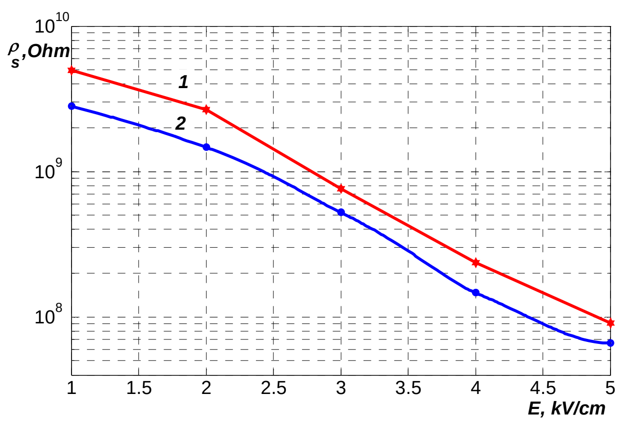

Fig. 2. Experimental dependence of the electric field strength of the rectified frequency of the specific surface resistance of the anti-corona coating based on a nonlinear compound (curve 1) and the coating in the form of a tape (curve 2)

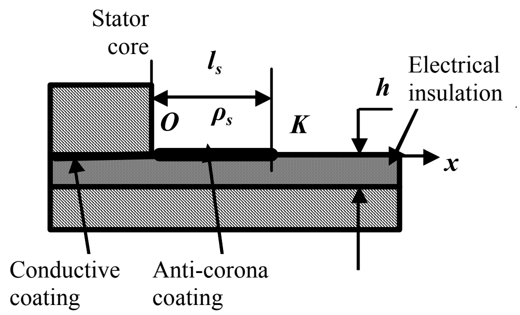

Fig. 3. Schematic representation of a fragment of the frontal Part of the rod with insulation and anti-corona coating

In the absence of a semiconductive coating, the electric field strength at point O

$$E_{oo} = U_o\sqrt{\omega\rho_{ins\,s}C_s} = U_o\sqrt{\omega\rho_{ins\,s}\,\varepsilon_0\varepsilon/h}\,, \qquad (1)$$

where U_o is the potential (voltage) at the point O; $\omega = 2\pi f$ is the circular frequency; $C_s = \varepsilon_0\varepsilon / h$ is the insulation capacitance of thickness h with dielectric permeability ε; $\varepsilon_0 = 8.85\cdot10^{-12}$ F/n is the electric constant.

In the presence of a semiconductive coating, the electric field becomes equal

$$E_{Os} = U_o\sqrt{\omega\rho_s\varepsilon_0\varepsilon/h}\,, \qquad (2)$$

i.e. coating provides a reduction of E_{oo} in $\sqrt{\rho_{ins\,s}/\rho_s}$ times.

Capacitive currents flowing through a semiconductive coating cause a voltage drop along the coating, resulting in E_K becomes less in comparison with E_{oo}, i.e. in the absence of coating. The electric field strength at the edge of the coating is determined by the expression

$$E_K = 2U_o\sqrt{\omega\rho_{inss}\varepsilon_0\varepsilon/h}\,\exp(-\sqrt{\omega\rho_s\varepsilon_0\varepsilon/2h}\cdot l_s)\,. \qquad (3)$$

By choosing the values of l_s and ρ_s, it is possible to reduce E_{oo} and E_K to acceptable levels at which there are no surface discharges.

The condition for choosing the values of the specific surface resistance ρ_s of the semiconductive coating is the inequality $E_{Os} \le E_{Od}$, which together with expression (1) for determining the electric field strength at the point O E_{oo} makes it possible to determine the upper boundary of the specific surface resistance of the semiconductive coating

$$\rho_s \le \frac{E_{Od}\;h}{\omega\varepsilon_0\varepsilon U_{so}^2}\,, \qquad (4)$$

where U_{so} is the calculated voltage value, E_{Od} is the permissible electric field strength at point O (in air, at the highest operating voltage of power frequency), determined, for example, on the basis of the Paschen empirical law for gaseous dielectrics [13, 14].

The choice of coating length l_s is determined from the condition

$$l_s \ge \sqrt{\frac{2h}{\omega\rho_s\varepsilon_0\varepsilon}}\,\ln\!\left(\frac{2U_{so}}{E_{Kd}}\sqrt{\frac{\omega\rho_{ins\,s}\varepsilon_0\varepsilon}{h}}\right). \qquad (5)$$

The permissible value of the electric field strength E_{Kd} at point K depends on the thickness of the insulation h, the electrical characteristics of the insulation and the semiconductive coating, respectively.

Figure 4 shows the influence of the specific surface resistance of the anti-corona coating ρ_s on the potential distribution over the semiconductive coating (curves 1, 2, and 3) and over the insulation surface (curves 1', 2', and 3') of the stator winding of the high-voltage electric machine on the linear voltage U_l =20 kV along the frontal part of the rods. Curves 1 and 1' correspond to the values of the specific surface resistance of the anti-corona coating ρ_s =5·10^6 Ω; curves 2 and 2' – ρ_s =5·10^7 Ω; curves 3 and 3' – ρ_s =5·10^8 Ω (Fig. 4). Higher values of the specific surface resistance of the semiconductive layers lead to lower voltages on the insulation of the frontal parts of the rods (compare curves 1' and 3' in the region of small l_s values). An increase in the specific surface resistance of the coating causes a decrease in the length of the semiconductive coating.

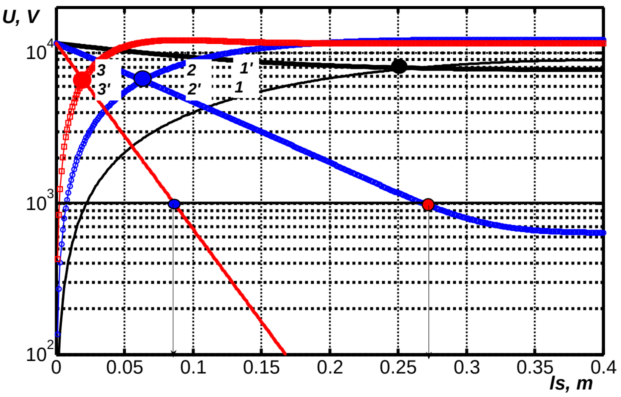

Fig. 4. Potential distribution over the surface of the anti-corona coating (curves 1, 2, and 3) and insulation (curves 1', 2', and 3'), respectively

An increase in ρ_s from 5·10^6 Ω to 5·10^8 Ω leads to the intersection of the potential distribution curves over the surface of the anti-corona coating and insulation, i.e. equality of potentials, with significantly smaller, more than 25 times, values of the distance l_s (compare curves 1, 1' and 3, 3' in Fig. 4). The length of the semiconductive coating, which ensures a decrease in potential at point K of no less than 10 times relative to the maximum value at point O, can be taken equal to 27.5 cm and 7 cm for coatings with specific surface resistance values of 5·10^7 Ω and 5·10^8 Ω, respectively (see curves 2' and 3' in Fig. 4). In this case, the voltage on the insulation surface does not exceed 1 kV. For a semiconductive coating with a specific surface resistance of 5·10^6 Ω, the electric field alignment efficiency is extremely low (see curve 1' in Fig. 4).

The correspondence between the calculated (curves 1 and 2) and experimental (points No. 3–6) results of the distribution of the electric potential over the surface of the anti-corona coating along the frontal part is shown in Fig. 5. In the samples of the rod of the hydrogenerator CB 1500/100-12, an anti-corona coating based on a nonlinear compound (symbols under No. 3, 4) and in the form of a tape (symbols under No. 5, 6) is used. The applied voltage of the rectified frequency corresponds to 10.5 kV (symbols under No. 3, 5 in Fig. 5) and 15.75 kV (symbols under No. 4, 6 in Fig. 5), respectively. The model dependencies of the potential distribution over a semiconductive coating (curves 1 and 2 in Fig. 5) for the stator winding of a high-voltage electric machine with linear voltage of 20 kV correspond to a specific surface resistance of 5·10^8 Ω (curve 1) and 5·10^7 Ω (curve 2), respectively.

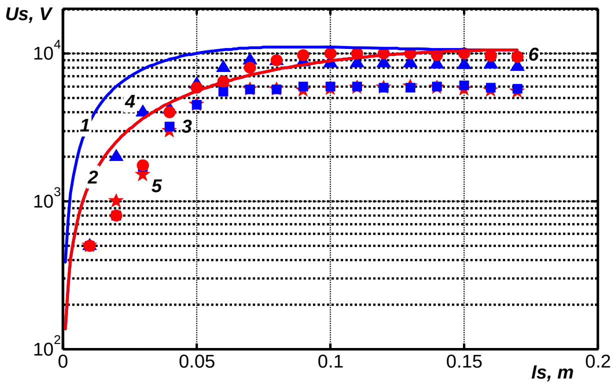

Fig. 5. On the reliability of the results of calculating the potential distribution over the surface of the anti-corona coating along the frontal part of the rods of a high-voltage electric machine

Stability of nonlinear properties of semiconductive anti-corona coatings during the process of electric and thermal aging. The stability verification of the nonlinear properties of the coatings was carried out according to the results of prolonged electrical and thermal aging of specially manufactured samples. Samples of 10 pieces for each type of coating were subjected to electric aging at electric field of 2.5 kV/cm of power frequency for 220 hours, followed by thermal aging at temperature of 175 °C for 100 hours. Electric aging was carried out in two cycles: the first was 60 hours, the second was 160 hours. In the initial state and after each cycle of electric and thermal aging, the measurements of the specific surface resistance were carried out at the rectified test voltage. Figure 6 shows a 3D diagram of the dynamics of changes in the specific surface resistance of nonlinear anti-corona coating samples during aging (ρ_{sa}) relative to the initial, before aging, state (ρ_s) depending on the electric field strength. The numbers in Fig. 6 relate to: anti-corona coating based on a nonlinear compound – 1, 2, 3; anti-corona nonlinear coating in the form of a tape in one layer in the half-overlap – 4, 5, 6 and in two layers in the half-overlap – 7, 8, 9 after the cycles of electrical and thermal aging, respectively.

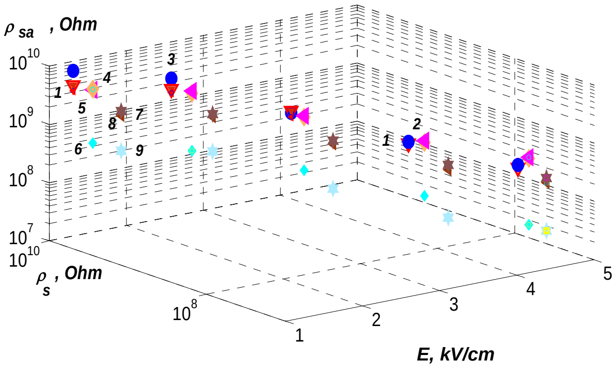

Fig. 6. Dynamics of changes in the specific surface resistance of anti-corona semiconductive coatings during the process of prolonged electrical and thermal aging of samples

For a nonlinear coating in the form of a compound, an increase in the specific surface resistance after aging cycles is observed, which is, probably, due to the additional polymerization of the compound under the influence of electric and thermal effects, which act as initiators of the polymerization process. For a nonlinear coating in the form of a tape after cycles of electric aging, an increase in the specific surface resistance relative to the initial state is also noted. After heat aging, there is a slight decrease in ρ_{si}. It is important that the nonlinearity of the specific surface resistance of the coatings is maintained in the entire range of the electric field strength. After thermal aging, the lower boundary of ρ_{si} corresponds to 10^7 Ω (see Fig. 6, No. 3, 6, 9), which indicates that the regulation of the electric field is sufficient (see Fig. 5, curves 1 and 2).

The stability of the properties of nonlinear anti-corona semiconductive coatings is confirmed by the test results of the samples of the rod of the CB 1500/100-12 hydrogenerator in the initial state and after the combined exposure to an electric field of power frequency voltage of $2.5 \cdot U_l/\sqrt{3}$ and temperature of 120 °C for 260 hours. In the initial state: by the distribution of electric potential along a nonlinear anti-corona coating along the length of the frontal part (see Fig. 3). After complex exposure: by visual absence of glow when applying test voltage exceeding the nominal voltage by 50%; by visual absence of sliding discharges when testing the insulation of the slot part of the rods with test voltage equal to $(3U_l/\sqrt{3})+3)$ kV; by appearance of the coating; by high values of insulation overlap voltage.

Conclusions. A technique is proposed for calculating the distribution of electric potential over the insulation surface along the frontal part of the rods of a high-voltage electric machine using semiconductive coatings that ensure equalization of the electric field strength and elimination of sliding discharges.

The distribution of electric potential over the surface of the anti-corona coating and insulation in the frontal part of the rod of the high-voltage electric machine is obtained with variations in the specific surface resistance of the semiconductive coating.

The proposed technique can be applied to justify the length of the coating in the frontal part of high-voltage electrical machines, depending on the electrophysical characteristics of the coating, electrical insulation and thickness.

The calculated data obtained are consistent with experimental studies of the potential distribution over the surface of the anti-corona semiconductive nonlinear coating along the frontal part of the samples of the hydrogenerator rods for linear voltage of 20 kV.

An experimental verification has been made of the stability of the nonlinear properties of specially made coating samples during long-term electrical and thermal aging, as well as of samples of CB 1500/100-12 hydrogenerator rods in the initial state and after complex exposure to electric field of 26.25 kV of power frequency and temperature of 120 °C for 260 hours.

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