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Intelligent Materials for the Power Sector (Overview)

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Abstract—The promising development of the smart electric power industry is based on the use of functional materials created based on the latest achievements in science and technology. The properties of intelligent materials change when exposed to any external factors. The ability of such materials to convert one type of energy into another and the ability to control this conversion make it possible to create various sensors and actuators for performing complex functions that are widely used in the electric power industry. This review article considers the use of superconductors to improve the characteristics of electrical equipment for energy purposes and shows the obvious advantages of high-temperature superconducting cable lines, as well as the high-temperature superconductivity of transformers and electrical machines. All the intelligent materials, the introduction of which into the composition of high-voltage insulation allows us to control its quality during operation, and materials that start the process of the self-healing of the insulation when microcracks appear, as well as the optimal microstructures of hard magnetic materials in various temperature modes, are presented.

Keywords: intelligent materials, high temperature superconductors, HTS cables, HTS transformers, HTS electrical machines, permanent magnets, high voltage insulation

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INTRODUCTION

The need for innovative and intellectual development of the country's electric power industry is determined by many objective conditions, socioeconomic factors, and evolutionary technological development of the power system. The concept of an intelligent energy system consists of creating a system-integrated and self-governing real-time system that has a single network infrastructure that technologically and informationally connects all the generating energy sources and all consumers. The technological equipment and means of automatic control required for a smart energy system began to be created in the mid-1970s. Today, an intelligent energy system is impossible without materials of the third generation, created based on the achievements of science-intensive technologies, the so-called smart or intelligent materials (IMs), the properties of which change under the influence of any external factors [1–6]. The main types of IMs are self-diagnosing IMs (passive constructions) and adaptive IMs (active constructions with additional devices—actuators). To achieve the best response to changing conditions, it is possible to optimize their properties by "learning." External factors that change the properties of materials can be mechanical stress, electric field, magnetic field, temperature, light, humidity, chemical properties of the environment, etc. Changes in the properties of IMs are reversible and multiple. Among the developed intelligent materials, we can note: alloys with a "shape memory," which, after deformation, restore their original shape when heated (the most famous alloy is nitinol), and self-healing materials, which can independently correct defects arising in them; self-lubricating materials, which reduce friction or wear, are applied in the form of coatings that have a hardness to reduce wear; and to reduce adhesion and friction, low surface energy. As a rule, these are composites with fillers made of metals, polymers, or ceramics and a matrix providing structural integrity; self-cleaning materials, repelling water and organic liquids; piezoelectrics that generate electricity when a mechanical load is applied (the most famous PZT material is lead titanate zirconate); photomechanical materials that change shape when exposed to light; magnetorheological fluids, which, when a magnetic field is applied, increase viscosity in the direction perpendicular to the direction of the field, and in the absence of a magnetic field, they are a suspension of randomly located magnetic microparticles (most often iron) in various oils; magnetostrictive materials that change their shape in a magnetic field, and when a mechanical load is applied, they change their magnetization (the most well-known material is terfenol-D); electrostrictive materials that change their shape in an electric field; electrochromic materials that change their optical properties under electrical influences (liquid crystal displays); pyroelectrics that generate electricity when the temperature changes; and smart gels capable of shrinking or swelling in comparison with their original dimensions by orders of magnitude (up to 1000 times).

The main feature of IMs is their ability to transform one type of energy into another. This transformation can be controlled, which determines the use of IMs for performing complex functions of sensors and actuators. The sensor converts the action into a signal, and the actuator converts the signal into action. Undoubtedly, such devices are widely used in the country's electric power industry. However, materials that ensure the creation of highly efficient equipment—cables, transformers, electrical machines, electrochemical converters, and energy storage devices [3, 7–11]—are a promising direction for energy and electrical engineering in the field of functional materials.

The aim of this study is to analyze the improvement of the characteristics of electrical equipment for power-generating purposes through the use of intelligent materials. High-temperature superconducting materials, intelligent magnetic materials, and insulating materials used in power engineering are considered.

RESEARCH METHODOLOGY

The research methodology is based on a systematic analysis of the real state and trends in the development of an intelligent electric power industry and the use of intelligent materials to improve the characteristics of electrical equipment for energy purposes. The analysis involved data from leading manufacturers and scientific publications in foreign and domestic journals. This made it possible to present in the article the most significant achievements in the creation of superconducting cables, HTSC transformers and electrical machines, as well as functional magnetic and insulating materials.

RESULTS AND DISCUSSION

High Temperature Superconducting Materials

The discovery in 1986 of the phenomenon of high-temperature superconductivity (HTSC), the appearance by the mid-1990s of affordable HTSC conductors, and the possibility of using cryogenic systems based on cheap liquid nitrogen intensified the research and development of electrical equipment based on them. At the present stage of development of the electric power industry, the use of HTSCs is one of the priority areas for the creation of energy-saving, environmentally friendly electrical equipment for energy purposes: superconducting AC and DC cables, transformers, DC and AC electrical machines, inductive energy storage devices, current limiters, frequency converters, rectifiers, inverters, circuit breakers, cryotronic converters, etc. [7–11]. The energy consumption in refrigerators for producing liquid nitrogen in the same volume as liquid helium turns out to be two orders of magnitude less. The technical and economic characteristics of superconducting electrical equipment in terms of their performance significantly exceed the characteristics of the traditional ones.

To date, a fairly large number of superconducting ceramics have been created, which contain rare earth elements and have a superconducting transition temperature in the temperature range from 86 to 135 K. The most common are yttrium ceramics $YBa_2Cu_3O_7$ (YBCO) with $T_c = 91$ K, bismuth ceramics $Bi_2Sr_2Ca_2$-Cu_3O (Bi-2223) with $T_c = 115$ K, and thallium ceramics TlBaCaCuO with $T_c = 119$ K.

To preserve the chemical structure of ceramics and, above all, to keep the number of oxygen atoms unchanged in it, protection from environmental influences is required, for which a protective coating is used. This coating also serves as a matrix. If the stabilizing coating is made of copper, then part of the oxygen atoms pass into the coating, which leads to the gradual disappearance of the superconducting state. In the case of protecting a superconductor with silver, the transition of oxygen atoms is excluded, as a result of which the structure of the superconductor is preserved, which ensures the invariability of its properties over time.

One of the significant disadvantages of HTSCs is their fragility. Their mechanical properties can be improved with additives. In the case of a strip superconductor, its mechanical strength can be increased by using a copper or steel strip foil (substrate).

Electrical products will require high-current superconductors; thus, the cable conductors or busbars must be round or rectangular in cross section and long. High-temperature conductors are made from metal oxide ceramic powder.

Today, the technology for the production of long-length wires of the first generation, 1G, (powder in a tube) is quite well developed. Hundreds of kilometers of wire is produced in the world, which are used to create superconducting electrical equipment: cables, current limiters, and magnets. However, more than two-thirds of 1G wires are pure silver, which excludes a significant reduction in their cost in the future (Fig. 1a).

The next drawback is the destruction of superconductivity in an external magnetic field. This limits the range of application of first-generation superconductors to devices with relatively weak working magnetic fields and makes it unpromising to manufacture products based on them such as generators, motors, and energy storage devices.

Attaining large values of the critical current densities and magnetic induction, as well as the highest critical temperature, is critically important, as is the case for metallic superconductors.

It should be noted that at a temperature of 77 K, the current density of the Bi-2223/Ag wire significantly decreases even with relatively low magnetic induction (0.5 T). At a temperature of 20 K, the cur-

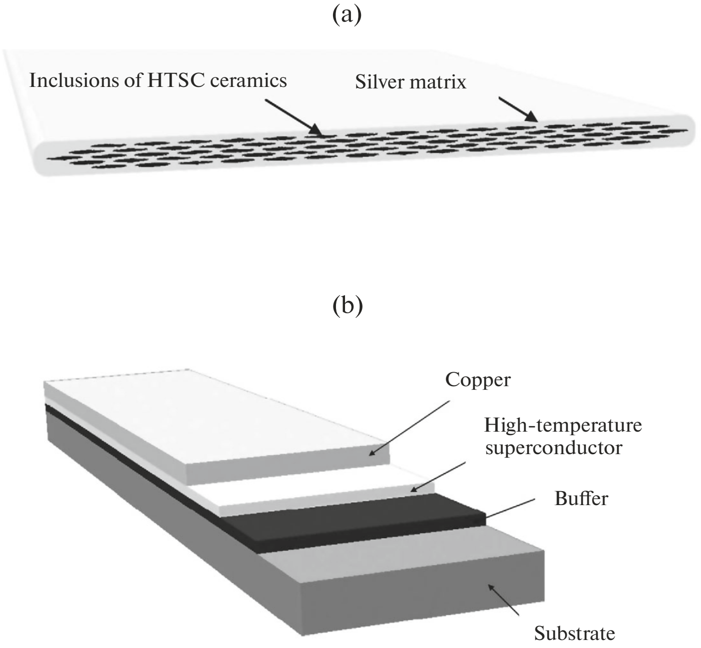

Fig. 1. Superconductors of the first (1G) (a) and second (2G) generation (b).

rent density changes little even at a magnetic induction of 6 T. This explains why the Intermagnetic General Corporation (United States) is developing a Bi-2223/Ag wire for the rotor of a 100 MBA superconducting turbine generator, 3000 m long, which will operate at a temperature of 20 K.

At the Bochvar High-Technology Scientific Research Institute of Inorganic Chemistry (HTS-RIIC), a Bi-2212/Ag wire 300 m long was created with the following data: cross-sectional area 0.25 × 4.4 mm^2, the number of superconducting cores or fibers is 361, the value of the critical current density of the wire is 240 A, the current density over the cross section of the superconducting part is 1800 A/mm, the temperature is 4.2 K, and the value of the magnetic induction is zero. At a temperature of 77 K, the critical current was 20 A and the current density was 150 A/mm^2.

Superconductors of the second generation 2G (YBCO), often referred to as "coated tapes," are currently the most promising direction in the development of technical superconductivity (Fig. 1b). The main fundamental advantage of Generation 2G is that they have the highest critical current density. Power equipment created based on them can have dimensions several times smaller than similar equipment of a traditional design, while having a higher power level and reduced energy losses. The cost of materials in a 2G wire is lower than the cost of materials in a 1G wire, and the allowable level of induction is higher. The main disadvantage of the 2G generation lies in the complex technology of manufacturing a wire material based on them and their high cost, which does not allow creating competitive industrial designs for mass use [12].

There are technologies for the manufacturing bulk superconductors based on HTSCs, the properties of which differ from film superconductors. Significant magnetic fields can be captured and "frozen in" in the HTSCs up to 10 T at 45 K, which is significantly higher than in conventional permanent magnets, and is a promising property for technical applications. However, the technology of structural materials based on bulk superconductors has received little attention so far in comparison with film technologies.

Superconducting Cables

The most effective device in the power industry, where the phenomenon of superconductivity is used, is a power superconducting cable (PSC). Low-temperature superconductivity could not ensure the economic feasibility of using a PSC due to the high cost of helium and cryogenic-vacuum equipment. The advantages of high-temperature superconducting cable lines are so obvious that work on their creation has been and is being carried out in many countries. In 2006, Sumimoto and Super Power put into operation a 350-meter long PSC in Albany (United States); a cable with an operating current of 800 A and a voltage of 34.5 kV. All three phases of the cable are located in one cryostat. In the same year, a triaxial cable with an operating current of 3000 A and a voltage of 13.2 kV was installed at the Bixby substation (Ohio, United

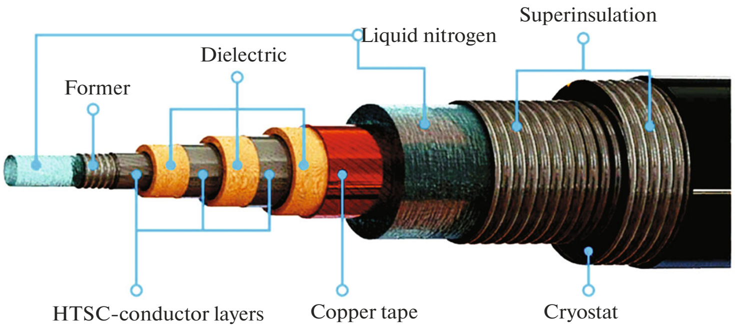

Fig. 2. Construction of one phase of a prototype of a three-phase HTSC power cable 200 m long.

States). The coaxial arrangement of the phases made it possible to reduce the consumption of the superconductor. One of the largest projects, a PSC 600 m long, with an operating current of 2400 A, a voltage of 139 kV, and transmitted power of 574 MVA, was implemented in 2008 on Long Island in New York. In Japan, in the power supply system of Greater Tokyo, a 66 kV, 200 MVA superconducting cable line was created; in South Korea, a superconducting ring in the power supply system of Seoul with a length of 20 km was created; in Germany, a line in the distribution network of Essen with an operating current of 2300 A and voltage of 10 kV was created; etc.

The current-carrying capacity of the PSC depends on the current-carrying capacity of the superconducting tapes and on the magnetic field in the product. In the cable, the magnetic field is parallel to the superconductor, the critical current is weakly dependent on the induction, and generation 1G superconductors can be used to manufacture the cable. However, a superconducting cable consists of dozens of superconducting tapes and cable design is a combined electrophysical, mechanical, and cryogenic challenge. The basic principles of creating HTSC cables were solved at the All-Russian Scientific Research Design and Technological Institute of the Cable Industry VNIIKP [12].

In 2007, work began on the creation of the first experimental-industrial superconducting cable 200 m long in Russia, with an operating current of 2500 A and a voltage of 70 kV. The parent organization of the project was Krzhizhanovsky Power Engineering Institute (ENIN) and the co-executors were VNIIKP, Moscow Aviation Institute (MAI), and OAO NTTs Elektroenergetiki. The design of one phase of a prototype of a three-phase HTSC power cable 200 m long [13] is shown in Fig. 2.

To reliably maintain the temperature level of the HTSC cable, cryo-supply and cryostatting systems are required. The cryogenic supply system includes flow paths of power devices, cryorefrigerators, cryopumps, heat exchangers, etc. The working medium is liquid nitrogen, liquid neon, and liquid hydrogen.

The problem of creating effective closed cryogenic supply systems for maintaining the thermal regime of extended cable lines has been solved. The cryo-supply system for extended HTSC cable lines is shown in Fig. 3 [13].

The use of HTSC cables not only reduces losses by reducing resistance, as well as the volume and weight of equipment, but can significantly improve the efficiency of the entire power system by simplifying its architecture. An HTSC cable line in the generator voltage can eliminate the need for step-up and step-down substations and high voltage overhead transmission lines. A good example is the project to improve the energy supply in the center of Amsterdam [14]. The advantages of the HTSC cable power transmission system are shown in Table 1 [12].

HTSC DC cables are of particular interest since the line resistance is practically zero. At the same time, the introduction of cables and other devices, the characteristics of which differ from the traditional ones, into the existing HTSC networks, will affect the integral characteristics of the network and require a systematic study.

Superconducting Transformers

The development of transformers using superconductivity began in Europe, Japan, and the United States in the 1960s. with the appearance of low-temperature superconductors (LTSCs) used for transformer windings. LTSCs required huge cryogenic systems to produce liquid helium, which made the project unprofitable.

Projects for the creation of HTSC transformers have been implemented in different countries since 1997 in prototypes of various designs and capacities [9, 15–19]. The main advantages of HTSC transformers due to the increase in the current density in the windings by several orders of magnitude compared to traditional ones are that (i) they reduce short-circuit losses by 90% and no-load losses by 80% (magnetic circuit made of amorphous steel); (ii) they offer the possibil-

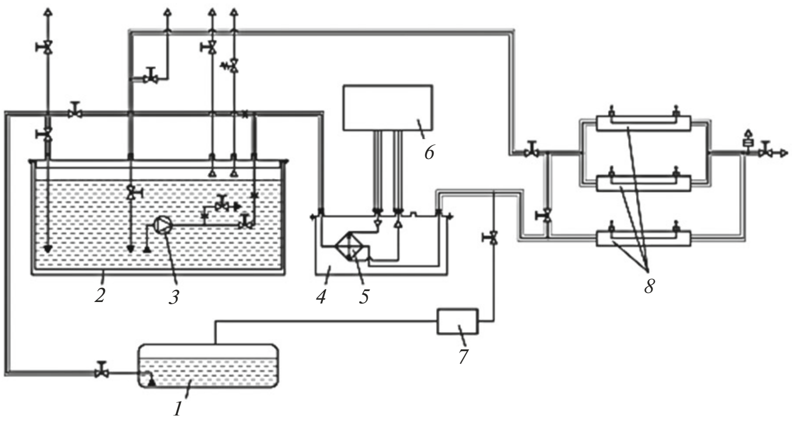

Fig. 3. Diagram of the cryogenic supply system for extended HTSC cables: (*1*) a container for storing liquid nitrogen; (*2*) working cryostat for consumable liquid nitrogen; (*3*) cryopump with HTSC drive; (*4*) cryostat of the heat exchanger; (*5*) heat exchanger; (*6*) cryorefrigerator; (*7*) a heat exchanger for heating gaseous nitrogen during auxiliary operations; (*8*) extended cryostats for maintaining the operating temperature of HTSC devices.

ity of limiting short-circuit currents; and (iii) they the weight and size by factors of 2 to 3.

At ENIN, various samples and laboratory models of superconducting rod and toroidal transformers with a pulsating magnetic field, as well as an electric machine type with a rotating magnetic field, have been developed, manufactured, and tested [20–22].

It is proposed to improve the energy and resource-saving indicators of HTSC power transformers by reducing the magnetic leakage field of the windings, achieved by the constructive implementation of the turns and layers. HTSC tape multicore wires of the first generation, where each individual core is located in its own localized magnetic field in its vicinity, and HTSC tape wire of the second generation, SS Amperium wire, laminated with stainless steel and insulated with a polyimide film, have been created.

For the first time in Russia, a prototype of a three-phase transformer with second-generation HTSC wire windings and an amorphous steel magnetic core with a power of 1 MVA, 10/0.4 kV was created [23]. Compared to a traditional transformer of the same power, short-circuit losses are reduced by a factor of about 27; and no-load losses, by a factor of 2.8.

For the first time in the practice of HTSC transformer construction, the latest materials and innovative technologies are used in one device: HTSC winding wire of the second generation, amorphous electrical steel, HTSC windings with a localized magnetic field, and a three-phase armored magnetic core with upper overlapping yokes (Fig. 4).

Superconducting Electrical Machines

Electric motors and generators with HTSC windings are being used in industrialized countries (United States, Germany, Japan, France, etc.) to drive propellers of marine vessels, devices for metal mixing in metallurgy, extruders for pulling metal pipes, and as wind generators. A marine superconducting synchronous electric motor with a capacity of 36.5 MW, 120^{-1} min was created in the United States; in Germany, a 4 MW HTSC shipboard electric motor and a 4 MVA HTSC generator were developed; and in 2008 Siemens implemented the first superconducting wind turbine 3.7 MW, 14 min^{-1}.

The use of a superconducting generator with a power of 10 MW and above gives a significant reduction in the mass of a wind turbine; however, due to the cost of a superconductor, a commercially viable option has not been unambiguously determined. Many firms for offshore wind farms prefer a gearless drive, in which a torque-to-weight ratio of a wind turbine of 25 kg/kNm has been achieved, and they are also looking for various ways to reduce its cost. European firms are carrying out intensive work on a 20 MW wind turbine project; and American firms, on a 50 MW wind

Table 1. Comparison of characteristics of power transmission systems

Parameter	Resistance, Ohm/km	Inductance, mH/km	Capacity, nF/km
HTSC cable	0.0001	0.06	200
Stitched cable polyethylene	0.03	0.36	257
Air line power transmission	0.08	1.26	8.8

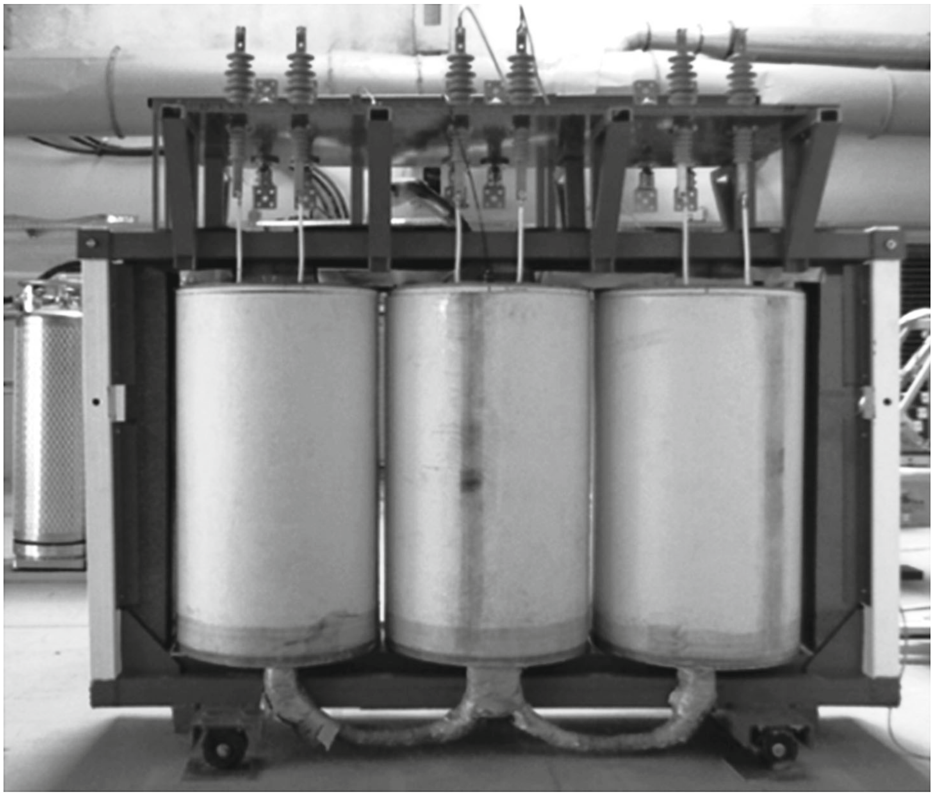

Fig. 4. Three-phase power distribution HTSC transformer 1 MVA, 10/0.4 kV.

turbine; they consider gearless superconducting synchronous generators to be promising [10, 11].

American Superconductor (AMSC) has developed a 10 MW Sea Titan wind turbine with a rotor diameter of 190 m and a gearless superconducting generator based on the second generation HTSC $ReBa_2Cu_3O_7$. The generator's diameter is 4.5–5.0 m, weight 150–180 t, efficiency 96%, and operating voltage 690 V [24, 25].

General Electric has developed a project for a 10 MW, 10 min^{-1}, direct drive wind turbine, the rotor of which is made based on a low-temperature NbTi superconductor, which is due to the presence of well-developed technologies for the production of both this material and the manufacture of windings based on it [26].

The projected cost of electricity generated by a superconducting wind turbine is 13–18% lower than that of the traditional version. The mass of the generator is 143 tons and the operating voltage is 3300 V.

Advance Magnetic Lab has developed a project for a fully superconducting 10 MW, 10 min^{-1}, wind turbine, with rotor and stator windings based on magnesium diboride [27].

In Russia, MAI is the leader in research on electrical machines with HTSCs and has created a series of jet motors with massive HTSC elements with a capacity of 1 to 500 kW, a 200 kW electric motor for transport, a 1.0 MVA contactless synchronous generator with claw-shaped poles and permanent magnets, etc. The achievements of the team are reflected in the monograph [28]. A synchronous generator with a capacity of $R = 1.0$ MW, voltage $U_f = 690$ V, and speed $n = 600$ min^{-1}, with an excitation winding made of HTSC tape of generation 2G on a salient-pole rotor and a multiplier based on a wave transmission with intermediate rolling bodies was created at MAI for wind energy. The classic copper stator winding is water cooled [29]. The general view of the generator is shown in Fig. 5. The stator bore's diameter is 800 mm, the active length to diameter ratio is $\lambda = 0.5$, and the air gap, including the rotating cryostat, is 10 mm.

To maintain the operating temperature of the rotor at a level of 65 to 75 K, a specially developed closed-loop cryo-supply system was used.

Bulk HTSC Elements

There are technologies for the manufacture of bulk superconductors based on HTSC, the properties of which differ from film superconductors. Significant magnetic fields can be captured and "frozen in" in HTSCs up to 10 T at 45 K, which is significantly higher than in conventional permanent magnets, and is a promising property for technical applications. However, the technology of structural materials based

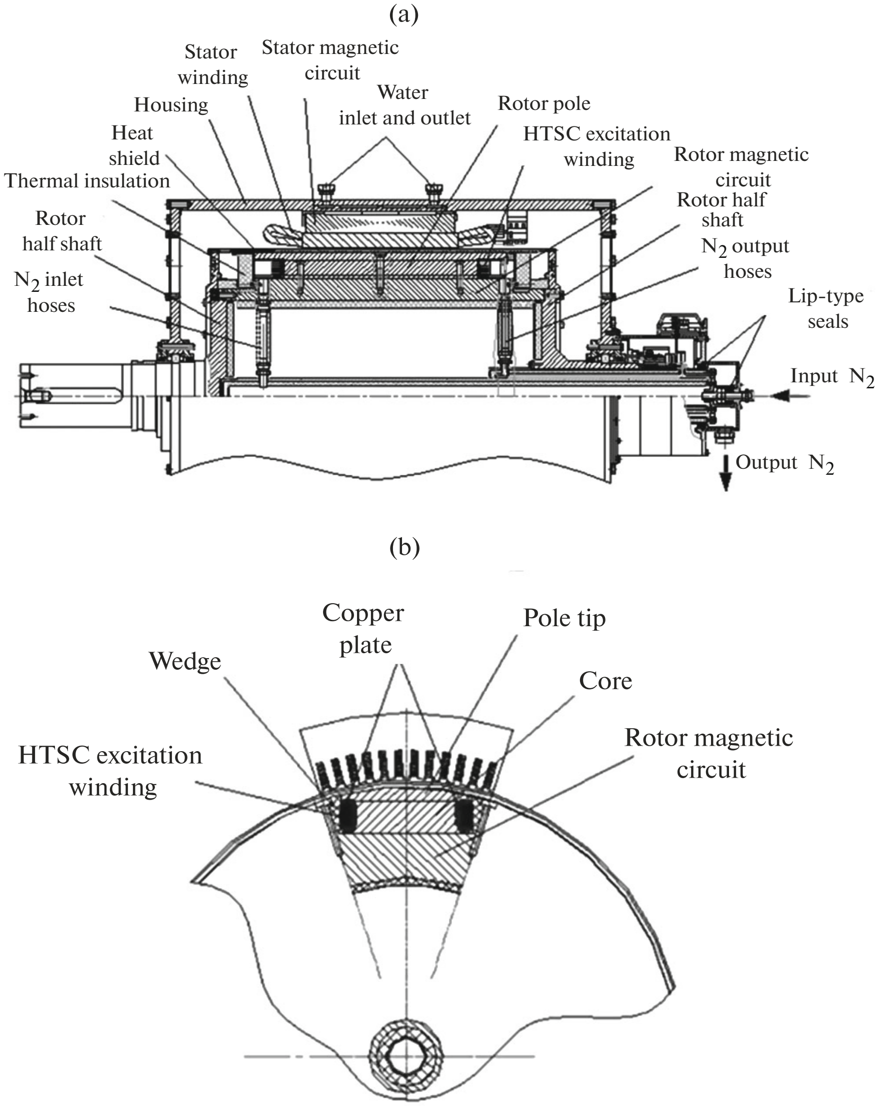

Fig. 5. General view of a prototype superconductor synchronous generator with a power of 2 MVA with a brush supply of current to the excitation winding: longitudinal section (a), cross section (b).

on bulk superconductors has received little attention so far in comparison with film technologies. The property of bulk superconductors to capture the magnetic flux during the transition to the superconducting state can be used as the base for the operation of many electromagnetic converters, in particular, the storage of electromagnetic energy.

A 5 MJ kinetic energy storage device on a magnetic suspension using volumetric HTSC elements includes a rotor, a magnetic thrust bearing based on annular permanent magnets, an ironless motor-generator with magnetoelectric excitation, and contactless HTSC bearings based on permanent magnets and volumetric HTSC elements. The rotor design includes a shaft, aluminum disc, steel tube, and carbon fiber shroud. The magnetic support consists of counter-magnetized ring permanent magnets. The support provides weight relief for the rotor. The motor-generator is an electric machine with an ironless stator and rotor, assembled according to the Halbach scheme of permanent magnets. Magnetic bearings consist of permanent magnets on the rotor and volumetric HTSC elements on the stator.

Magnetic Materials

It is known that only three elements from the periodic table are ferromagnetic at room temperature: iron (Fe), cobalt (Co), and nickel (Ni). The rare earth element gadolinium (Gd) becomes a magnet, but only at 8°C. It can be assumed that modern magnetic materials should change their properties in a wide range of temperatures [1]. Indeed, for an alloy based on rare earth metals with the chemical composition $Nd_2Fe_{14}B$

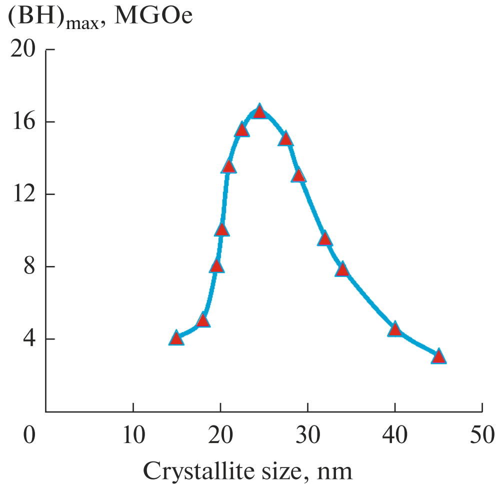

Fig. 6. Dependence of magnetic energy on crystallite size

(neodymium–iron–boron) at temperatures below 150 K, there is a zone in which the magnetic induction exceeds the value at room temperature, and a zone where the induction decreases sharply, and the processes are reversible.

The main advantages of this type of magnet: the high value of the energy product ($BH_{\max}$) is higher than the value of all known materials (up to 520 kJ/m^3); its ability to work without loss of magnetic characteristics in the temperature range –60 to + 240°C (Curie point +310°C); the absence of a rather expensive metal in the composition of the alloy, cobalt, also gives the magnets of this composition an advantage over the magnets from the SmCo (samarium–cobalt) alloy in terms of price and scale of production. The disadvantages of NdFeB magnets include their low corrosion resistance, which is eliminated by coating the magnets with protective layers of copper, zinc, nickel, and chromium.

High coercive rare earth alloy magnets are chosen for the excitation system of high energy density synchronous machines. Intensive research conducted to create the optimal, in terms of the magnetization reversal processes, the microstructure of a material for permanent magnets [30], and promising technologies for obtaining magnetically hard materials will undoubtedly lead to a qualitative increase in their characteristics.

As an illustration of these words, we can cite the dependence of the magnetic energy on the crystallite size, obtained by the employees of VNIINM: the maximum energy of the magnets of the NdFeB system is reached at a nanocrystallite size of 20 to 30 nm and has a pronounced maximum (Fig. 6).

Insulation Materials

The temperature drop across the thickness of the shell insulation, which can reach 30–37°C is of significant importance in the level of heating of the electric machines of limiting power with indirect cooling of the stator winding.

To maintain this value with increasing thermal loads, manufacturers of electrical equipment use materials for hull insulation with a high value of the operating electric field strength E (kV/mm) and increased thermal conductivity λ (W/m K). Together with this, the increase in the thermal conductivity of the sealing materials and anti-corona coatings included in the construction of groove insulation is of great importance.

Increasing the value of the working tension E allows us to reduce the thickness of the stator winding's housing insulation and, consequently, the temperature difference in it. Modern insulation materials based on preimpregnated (resin-rich technology) or nonimpregnated "dry" tapes (single VPI, and global VPI technologies based on the optimized structure) (Fig. 7) increase the thermal conductivity by 20–25% with the preservation of the dielectric properties of the housing insulation (λ = 0.33 W/m K) and allow designing a stator winding with an operating voltage in the range of 3.2 kV/mm. The introduction of fillers and nanofillers with increased thermal conductivity in the composition of dry or preimpregnated tapes increases the thermal conductivity of the tapes, but often leads to a decrease in their dielectric strength and an increase in their thickness. The working electric field strength for insulation of the housing made of such tapes is in the range of 2.3 to 2.6 kV/mm with a thermal conductivity of 0.3 to 0.55 W/m K [31].

A further increase in value E can lead to a decrease in the resource of the housing insulation both in the grooved part of the winding, and at the exit from the slot. The technological factor becomes especially significant when thinning the housing insulation. Thus, with a shell insulation thickness of 2.6 mm for machines with a stator operating voltage of 15.75 kV, in the case of a scratch 0.5 mm deep when laying the winding in the core grooves, the value of the operating voltage at the place of damage will change from 3.5 to 4.3 kV/mm. Such values are unacceptable for modern insulating materials, because they significantly reduce the life of the stator winding.

The technological factor can be excluded from consideration if the insulation material is given self-healing properties. Successful research on self-healing materials is being carried out in relation to metals, ceramics, and polymers. Specialists are aware of various strategies and approaches for their creation [1, 2]. A necessary condition for the self-healing of damage, as a rule, is the formation of the so-called mobile phase capable of "tightening" the damage. For auton-

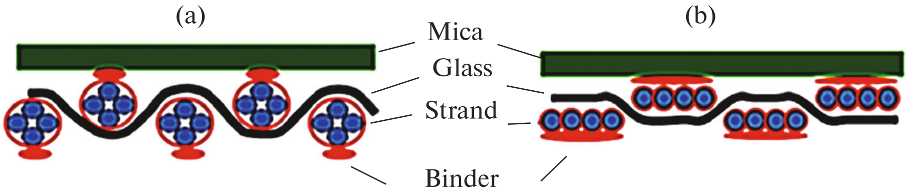

Fig. 7. Standard structure tape (a) and a tape with the optimized structure (b).

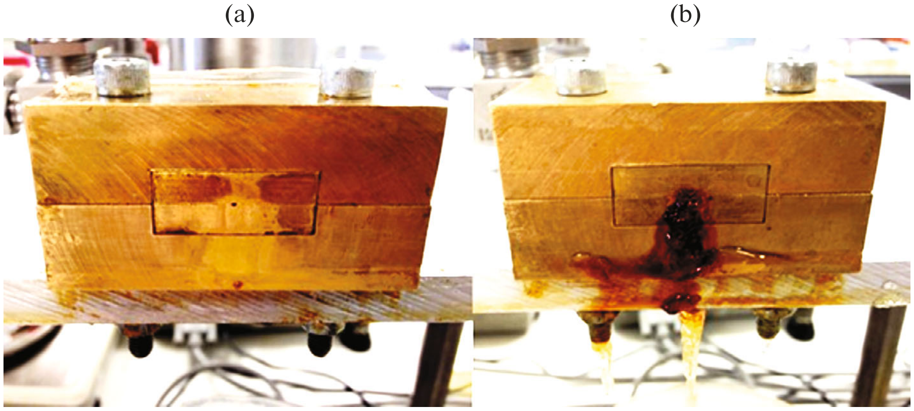

Fig. 8. Laboratory experiment with oil-filled cable: before leakage (a), after the leak (b).

omous self-healing materials, it is damage that is the impulse or signal for recovery.

Examples of materials that have demonstrated excellent potential in laboratory samples and will soon be in widespread use are given in [32]. In particular, for high-voltage submersible cables, the use of hydrophilic thermoplastic elastomers (h-TPEs) is proposed.

If the cable does not have polymer insulation, but is an oil-filled cable, then a self-repairing cable is offered. Studies on mixing insulating oils with drying oils have shown that drying oils can bind with intermolecular bonds in the presence of atmospheric oxygen, thus forming a preventive seal that prevents further leakage of the insulating oil (Fig. 8).

The appearance of microcracks in the material of electrical insulation is a harbinger of a catastrophic failure and a significant reduction in the life of the insulation. The development of self-healing thermosetting electrical insulation, designed to stop the mechanical deterioration of the material, is presented in [33]. Microcapsules filled with a monomer (healing agent) and a catalyst are added to the insulation material. When a microcrack propagates in the material, the microcapsule breaks, releasing a liquid reducing agent into the crack. The final step in the self-healing process is the polymerization of the monomer, which occurs upon contact with the catalyst added to the epoxy resin.

The second area of application of intelligent materials in insulation is the method of introducing "smart" fragments into the composition of polymer insulation, capable of giving information about the violation of the customer's insulation requirements.

In [34], the results of a study of a polymer material with additives of fluorophores that are sensitive to an electric field are presented. It is shown that the introduction of fluorescent solid pyrene at a concentration of 5.75% has a minimal effect on the electrical breakdown strength of the material and the loss tangent and, at the same time, provides good field-dependent fluorescence spectra. A method of introducing a fluarophore into a polymer, which ensures good sample uniformity, is described.

In [35], a study is described to determine the suitability of liquid crystals as the medium giving a visible response to an electric field in isolation. It has been shown that a liquid crystal device can be used to detect and report the presence of alternating and direct current, and that it is possible to encapsulate liquid crystal droplets in a receiving polymer and form a polymer dispersed liquid crystal (PDLC) system. The further work of the authors involves the study of PDLC as an intelligent material that responds to an electric field.

CONCLUSIONS

The prospect for the development of an intelligent electric power industry is determined primarily by functional materials created based on the achievements of science-intensive technologies: intelligent materials, the properties of which change under the influence of any external factors.

The ability of the IM to convert one type of energy into another and the ability to control this transformation made it possible to create various sensors and actuators for performing complex functions, which are widely used in the country's electric power industry.

The use of IM to improve the characteristics of electrical equipment for power engineering gives obvious advantages when creating high-temperature superconducting cable lines, reduces their weight and dimensions by factors of two to three for high-temperature superconducting transformers and electrical machines, and increases the efficiency of equipment by increasing the current density in the windings by several orders of magnitude compared to the traditional ones.

The intensive research conducted to create the optimal, in terms of the magnetization reversal processes, microstructure of the material for permanent magnets and promising technologies for obtaining magnetically hard materials will undo ubtedly lead to a qualitative increase in their characteristics.

The development of self-healing thermosetting electrical insulation in order to prevent mechanical deterioration of the material, and the introduction of "smart" fragments into the polymer insulation, capable of providing information about the violation of a customer's requirements for insulation, significantly increase the reliability of electrical equipment.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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