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The efficiency of the use of composite materials in electrotechnical equipment

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Abstract. The indicators of the efficiency of electrical installations are directly connected with the creating and using of new composite materials with the desired performance properties. The practical application of composite materials is one of the perspective scientific and technical directions, providing the increase of the efficiency of electrical installations due to the sealing of current parts by protecting them from the external medium. The technical characteristics of the composite material match to its structure and depend on the properties of the individual components. The verification of the compliance of material parameters is implemented by the methods of the computer analysis of a model of composite material in the form of the structure in which the individual elements have thermodynamic properties of the corresponding phase state. In the study the topology of individual elements in the material structure is defined by the conditional boundaries of the section within the studied composite. The efficiency of using the composite materials includes the raising of electrical safety, increasing the durability, reducing the costs of maintenance and repair and the extension of the scope of installations.

1. Introduction

The economic analysis of the efficiency of the Russian energy facilities shows that the energy per unit of the manufactured products is consumed on average by 2...4 times more than in the other industrialized countries. The indicators of Russian energy efficiency are lower than China's indicators 1.8 times, USA 2 times, Japan 6 times [1]. It is important to note that the possibility of a complex energy saving is primarily connected with minimizing the level of costs for its realization. The main reason of the current state of the low efficiency of electrical installations is the deterioration of the main power equipment, its level lags behind the foreign equipment by 30...40 years.

According to the expert estimations the costs for the implementation of energy saving technologies is almost by 4 times lower than the costs of production, distribution and transportation of the produced energy to the places of consumption. That is, in practice, in the difficult economic conditions there is a problem of increasing of energy saving and energy efficiency, but not increasing new powers which are ineffective due to the low level of the used technologies and outdated equipment.

2. Statement of the research problem

The analysis of the strategy of implementing energy efficiency programs shows that firstly we should implement technical measures not requiring a great investment. To such measures we relate the modernization of equipment, which has a maximum energy losses, for example, the complexes for transporting thermal energy their losses often exceed 50 %. This is confirmed by the comparison of different energy saving technologies, showing that the main attention should be focused on the problems of using all the types of energy with the minimal energy losses due to, firstly, the increasing of the efficiency and energy excellence of equipment for the generation and transportation of thermal energy.

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The reduction of losses in such equipment provides both only improving the operating characteristics (efficiency, power factor, dimensions and weight) and also the characteristics which are determined by the interaction of the technical objects and external environment such as the technosphere safety, system efficiency and compatibility. The increasing of the equipment energy efficiency is possible due to the improving individual elements, process or system modifications and choice of software and hardware management tools. We achieve a substantial result by improving the reliability of electrical devices too.

One of the perspective directions of increasing efficiency of energy devices is using the hermetic designs. The results of investigating the special hermetic electromechanical converters which we have nowadays, confirm the prospect of their using [2]. A typical example of such development is the hermetic AC electric drive of the compressor of 20 MW produced by Siemens to transport the associated gases from the great depths [3]. The device effectiveness is determined by the operating time not less than 20 thousand hours. It should be noted that in the heavy-load conditions the hermetic device is almost the only really workable variant of a drive device. Its feasibility is provided by the high reliability of the design. The scope of using the hermetic AC drives includes, as the already mentioned compressors and also the technological centrifuges, mixers, pumps and apparatus which should guarantee the total zero leakage of reactive and polluting components into the environment, the operation with flammable mediums, the operation at the high and low pressures and temperatures.

The increasing of the energy efficiency of technical systems using a hermetic equipment is also determined by the possibility of increasing electromagnetic loads due to the transition to the direct cooling of the elements.

The practical realization of such electrical installations is connected with the development and production of composite materials with the desired physical and chemical characteristics that is with one of perspective scientific and technical directions, affecting the strategic interests of all the industrialized countries. The improving efficiency of the electrical installation is provided by the hermetic sealing of the current parts due to their capsulation. The capsulation is that, for example, the insulation of the stator winding is protected from the external medium by a molded shell made of a composite material. This allows to provide a higher safety class of the installation, to increase the resource, to simplify the design, to increase its structural reliability, to reduce the cost of maintenance and repair, to extend the range of operating modes.

The technological basis of capsulation is the implement of special processes, providing the creation of composite materials with the desired performance properties. In this case the technological process significantly affects the physico-chemical characteristics of the composites dependent on the quantitative and qualitative composition of the elements forming the structure.

The integral characteristics of the composite material are determined by its structure and the properties of some components. In the absence of the exact mathematical model of the researched object, which is a composite material, the providing of the desired properties can be achieved with simulation methods. The simulation model can be built on the basis of the physical understanding about the researched object. The physical model of composite material is reduced to the highly dispersed structure in which some components are in the state of aggregation, at that the colloid particles have the thermodynamic properties of the corresponding phase state. The capsulated material is heterogeneous after the polymerization process. It is characterized by the relative insolubility of the components having the determined interfaces within the researched object. The definition of topology of individual elements in the material structure is connected with the solution of the Van der Waals equation, which allows to take into account the factors of influence of intermolecular action of the non-chemical origin.

It should be noted that the cost of the hermetic electrical installations is more than the cost of the similar standard equipment by 30 % however, this is not a determining factor in some cases because of the economic effect achieved by improving the reliability, security and durability of the installation.

The capsulation of installations by the composite materials significantly increases the maintenance intervals at the simultaneous increasing of the mean-time-between-failures. According to the statistics of the company HERMETIC-Pumpen GmbH the average mean-time-between-failures of the circulation pumps with screening motors is 7.5 years, with the traditional ones average time is 2 years.

The electrical installations using insulating composite materials are characterized by the higher electrical safety. The hermetical implementation of the output boxes, wire cable and other elements eliminates the access of gas and liquid and also prevents the emission of harmful substances into the atmosphere. It allows to use them in the food and medical industries. The capsulation allows to provide the required security when operating in the aggressive or toxic mediums. The using of composite materials increases the resistance of the installation to the mechanical effects and leads to the lower of the levels of self vibrations and noise. In addition, the hermetic installations are more compact that allows to place them in the hard-to-reach places. Thus the task of evaluating the effectiveness of using composite materials in the combined heat generating plants is the consideration of their design features at designing and developing recommendations for the practical implementation of this class of devices.

3. An example of the implementation

We consider the use of the composite material in the electromechanical converter of the alternating current (the asynchronous motor with a modified squirrel-cage rotor). The actuality of such a technical solution is connected with the possibility of using the frequency control allowing not only effectively to regulate the speed of rotation but also to provide the energy saving modes of operation due to the optimized algorithms of the electricity consumption using intelligent technologies (fuzzy logic, neural networks, neuro approaches).

The use of the composite as the material capsulating the stator windings allows to realize the modes of the generating and transporting thermal energy in the same device, it is the basis of creating a new class of devices – the combined heat generating converters [4-9].

One possible design of the stator of an electrical plant using two types of composite materials is shown in Figure1, where 1 is the antifriction material which provides the sliding of the hollow rotor and 2 is the material which insulates the stator winding.

Figure1. The example of using composite materials: 1 is the self-lubricating antifriction material; 2 is the insulating material.

Despite the structural similarity to the usual electric machines of the alternating current, these heat generating devices with the composite coating of the stator have a number of fundamental differences such as the presence of a motionless heating element fixed on the capsulated stator and a rotatable

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hollow non-magnetic rotor. The pressure blades are fixed inside this rotor. The necessity of using a motionless heating element connected with the fact that in the modes of the device close to the synchronous modes the amount of heat losses generated in the rotor is greatly reduced due to the convergence of the speeds of magnetic field rotation and the rotor. Therefore, to ensure the required heat output there is an additional source in the design of the device. The power dissipation of this source is slightly depends on the speed of the rotor [10].

The use of composite material allows to provide a low flow resistance due to the lack of a traditional shaft and bearings. It should be noted that in the absence of ferromagnetic elements in the inner bore of the stator, the heat generating device is characterized by a significant magnetizing current and the reactive power consumption causing significant heating of the composite material. The value of the heat load of the material depends on the dimensional relationships between the magnetic core and the air gap. Their values determine the hydraulic resistance of the flow part of the device. Since the value of the main magnetic flux determines the magnetic induction and the minimum width of the stator tooth, the thickness of the inner magnetic core is limited from the bottom. In particular, for the studied variant of the device with power 2.2 kW the width of the stator tooth is approximately equal to 4 mm but the reluctance is significantly reduced even when the thickness of element is 2 mm.

The axial length of the inner magnetic core is determined more difficult as it both changes the distribution of magnetic field in the inner area of the device and changes the process of heat transferring of an additional heat source due to the change of the hydraulic resistance. The results of the research showed that we can determine the relative range, in which we achieve the decreasing of the resistance of the magnetizing circuit without the significant deterioration of the heat transfer. This range is approximately the 0.25...0.70 of the air gap length.

In the analysis of electromagnetic processes determining the operating characteristics of the composite material the device can be represented in the form of a rotating AC converter with two secondary windings: motionless and moving hollow shells. For the description of electromagnetic processes at the constant distributions of magnetic field and power flows the real converter having a number of the turns of the primary winding w_1 and the secondary windings with w_2 and w_3 is replaced by the equivalent converter with the number of turns of the secondary windings equal to the number of turns of the primary winding. The impedances of the secondary windings are changed for the invariance of the active and reactive power components.

For the specified voltage the currents in all the electrical circuits are theoretically determined by their impedances. The primary winding includes the active r_1 and inductive x_{1L} resistances, the motionless secondary winding includes the reduced active r'_2, inductive x_{2L} and capacitive x_{2C} resistances, the rotating secondary winding includes the reduced active r_{3S}, inductive x_{3L} and capacitive x_{3C} resistances. However, in the real converters, the thickness of the walls of the hollow non-magnetic rotor is many times less than the depth of penetration of the electromagnetic field, therefore, we can assume that the inductive resistances of leakage of the hollow rotors x'_{2L}, x'_{3L} are small and the eddy currents are distributed throughout the thickness of the rotor walls almost uniformly at all the slides, so we can assume that the resistance r'_{3S} doesn’t depend on sliding. This allows us to find approximately a load component of the current consumption and the electromagnetic power transmitted from the stator and providing two processes – the heat of the heat carrier by the motionless element and the heat and transportation of the heat carrier by the rotating rotor [11].

The mechanical power of the device is determined by the power density perceived by the surface of the rotor as the product of the tangential stress on the tangential circumferential speed. It provides the pressure and performance. The heat power equal to the sum of all the heats provides the temperature of the heat carrier. It is obvious that it is necessary to define electric, magnetic and additional losses in the converter to define the thermal power.

The synthesis of the device and the frequency converter requires to take into account the nonuniform distribution of the current density over the cross section of the conductors of the primary winding due to the skin effect. Therefore, the determination of the electrical losses with the help active resistance obtained for the uniform distribution of the current density over the cross section that is only true for direct currents and currents of low frequency (several Hertz).

The nonuniform distribution of current depends on the value of the leakage field in the groove, its field lines are almost perpendicular to the axis of the groove, thereby the coupling of the field with the conductor elements located at the same height of the groove, defines the similar inductive resistances of such elements. At the same time, the inductive resistances of the elements located at the different height in the groove, will be different. The increase of the current density occurs as approaching to the surface of the groove, accordingly, the useful section is reduced and the active resistance increases. In practice for the quantitative evaluation we use the magnification ratio of the winding resistance due to the skin effect, which is dependent on the frequency of current and the geometry of the conductor.

The define of magnetic losses requires the consideration of technological factors, a type of magnetization reversal (pulsation or rotating of the field) and additional components. In practice we use the specific magnetic losses for the calculation, for example, the measured losses experimentally at the frequency of 50 Hz and magnetic induction of 1 Tesla. The recalculation to other frequencies and inductions requires the separation of hysteresis losses, proportional to the frequency, and the eddy-current losses currents depend on the square of frequency of the supply voltage.

The increase of the magnetic losses due to the reasons of the technological nature is taken into account by the empirical coefficients of the technological losses for the characteristic parts of the magnetic circuit. The total ratio of the technological losses for the yoke of the magnetic circuit is 1.3...1.6 and for teeth it is 1.7...1.8. The additional magnetic losses due to the non-sinusoidal from the higher harmonics are taken into account by the ratio of the added losses (1.2...1.3).

When we conducted the research we used the automated information-measuring complex based on a set of Labview virtual instruments, the system of T-FLEX CAD parametric design, the statistical software complex Statistica, CFD SolidWorks Flow Simulation, the software developed in the environment of Delphi and Elcut.

The main source of heating of the heat carrier is set by the value of electric losses in the additional heating element.The analytical study of electromagnetic fields taking into account their shape, the laws of the current distribution and the physical properties of the mediums suggests a number of assumptions. At the analysis of fields we consider only the first space harmonics of the magnetizing force; the value of the air gap is many times smaller than the external diameter; the current density is constant through the thickness of the rotor; the distribution of field intensity has only a normal component; the magnetic permeability of steel is infinite; the induction is outside the stator package is equal to zero. To summarize the fields in the current and current-free areas we introduce a vector potential. Let’s write Maxwell's equations, then Laplace's equation for current-free areas, and Poisson’s equation for the area of the eddy currents. To solve these equations we determine the vector potential, the field and density of the eddy current. The electric power produced in the heating element is determined by the real part of Poynting’s vector.

The definition of the additional losses is connected with the necessity of considering the influence of the higher harmonics of electromagnetic field and currents in the secondary circuits. The additional losses are taken place both in a motionless magnetic core and in low magnetic elements (the secondary windings, end caps, etc). Practically, these losses are estimated approximately due to their relatively small values, but mostly it is due to the high complexity of their exact calculation. The losses arising from the movement of the heated medium are divided into hydraulic and mechanical. The accurate determination of these losses is necessary to find the temperature of the composite material. At the engineering calculations these losses are accounted by the coefficients depending on the structural parameters and operational factors similar to the calculation of the pressure characteristics of fans, compressors or pumps. To check the obtained results and recommendations we use the package Comsol Multiphysics which is an interactive environment for modeling and calculation of the task reduced to the partial differential equations by the finite element method.

In calculating the magnetic field we use a two-dimensional model of the magnetic field of the alternating current. The problem is reduced to a differential equation in private derivatives relatively to the complex value of the z-component of the magnetic vector potential. This analysis confirms the possibility of using composite materials for electrical devices of heating and transport of the heat agent providing a fairly stable resulting temperature of the heated medium at the rated supply voltages, frequency and the given heat-transfer coefficient in the range of slips 0.4...0.9, which corresponds to the operation mode of the converter with the high resisting moment arising while the movement of the viscous working medium. As the estimation of effectiveness of using the composite materials in the research plant we selected the growth rate of the defect formation of the turn winding insulation of the capsulated stator depending on the constructive and operational parameters. The dependence of the growth rate of the defect formation (G_r) on the structural parameters (C_f is the coefficient of filling of the groove, l_{end} is the length of the end winding) is shown in Figure 2.

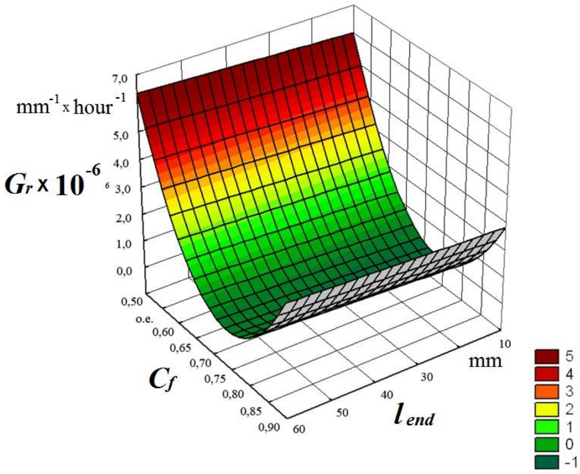

Figure 2. The dependence of the growth rate of the defect formation on the structural parameters

The comparative analysis of capsulated and traditional designs showed that the rate of defect formation in the designs made from the composite materials is less. Let's list the equity contribution of separate factors influencing on the plant reliability: the influence of the diameter of the winding wire is 3 %; the influence of the value of the end winding is 4 %; the vibration acceleration is 2 %; the influence of the fill factor of the groove is 6 %; the influence of the insulation quality of the is 10 %; the influence of the winding temperature is 75 %.

4. Conclusion

The efficiency of using the electrical equipment is directly determined both by the value of the losses in this equipment and also by their level of reliability. The problems of reliability are important especially in the autonomous complexes, therefore with improving the production, increasing requirements to the equipment reliability must be obligatory. The comparative analysis showed the obvious advantages of using the composite materials to ensure the requirements of safety and reliability. The use of electrical installations with the use of new composite materials allows to reduce the costs of repair and restoration and in general it can be considered as one of the measures to increase their efficiency when we modernize industrial and agricultural companies.

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