Analysis of electromagnetic processes in high-speed electrical machines with foil gas-dynamic bearings

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***Abstract*: Currently, one of the directions of electromechanical systems progress is the development of on the base of electric machines with ultra-high rotational speed (100000 and more rpm). The operating parts of these aggregates are turbine and/or compressor impellers, located on the same shaft (ie, without mechanical gear) with the inductor of the electric machine, so that these devices can be called “electrical turbo machines” (ETM). Such machines are the basis of prospective power stations with power from 1 to 400 kW for efficient low-pressure oil-free centrifugal compressors and blowers, vacuum pumps, refrigeration units, turbine generators and other devices. In this paper a number of specific problems of ultra-high speed ETM creation are described. Selection of the bearings type and selection of the electric machine type are provided. Influence of rectifier connection scheme on power losses in the machine is evaluated.**

***Index Terms* – ultra-high-speed electrical machines, foil-gas-dynamic bearings, permanent magnets, power loss, winding connection diagram, eddy currents, FEM.**

I. INTRODUCTION

It is known that the safe operation of high-speed machinery is largely determined by the choice of bearing assemblies. In ETM in addition to high shaft speeds bearings often operate under extremely difficult conditions: at varying loads, a wide range of temperatures, under the influence of impact forces and accelerations.

Traditional for electric machines ball bearings at high speeds have increased losses require special cooling and lubrication, which reduces the reliability and limits their operational life. In many cases, the use of lubricants in ETM is simply unacceptable, since there is a possibility of mixing of the lubricant and the working fluid.

In high-speed units the most promising is the use of non-contact bearings, the most widely used of which are gas-dynamic, gas-static and electromagnetic. These bearings have a lower stiffness than ball bearings, but have a number of advantages:

- low power losses due to friction;
- lack of complex and cumbersome oil lubrication system;
- possibility of operation over a wide range of temperatures and pressures;
- resource in the tens of thousands of hours and more;

Among electromagnetic bearings the most development nowadays received active magnetic bearings (AMB). Rotor suspension system with AMB includes bearings themselves embedded in the body of the machine, and an electronic control unit connected by wires to the windings of the electromagnets and sensors. AMB requires complicated and expensive control equipment, an external source of electricity, which increases the cost and reduces the efficiency and reliability of the entire system. Working temperature range of ATB often does not coincide with operating temperatures of ETM, which requires the installation of additional cooling devices. In addition, all current and future designs of support assemblies with ATB involve the use of additional safety bearings, mainly of ball bearings.

Gas-static bearings require increased precision manufacturing of working surfaces and are very sensitive to the cleanliness of the working fluid. The main disadvantage is the need to install an external source for the compression of the working gas and supplying it to the working area.

Unlike the gas-static, foil gas-dynamic bearings (FGB) are autonomous, their work do not require an external power source: compressed gas required for the operation of the gas-static supports or electricity, supplying electromagnetic bearings. In FGB supporting force is due to dynamic processes occurring during the rotation of the rotor, resulting in efficiency and simplicity of design. Mounting clearances in radial and axial FGB are relatively high, this allows to reduce the requirements of assembly accuracy, compensate for thermal deformation of ETM's components during operation, as well as lower requirements for bearing's working gas purity.

In general, the use of FGB in ETM allows to solve a number of pressing problems:

- provide the desired high speed of the rotor;
- ensure reliable operation of the ETM when exposed to significant vibration and shock loads in the presence of significant external heat gains;
- completely eliminate the contamination of the working fluid with oil vapors;
- reduce weight of the ETM due to a more compact design of the supporting unit;
- eliminate of the lubrication system and exclude the safety-bearings;
- increase the service life and simplified service of the ETM.

Currently gas-dynamic bearings are the main type of supports for high-speed ETM [1, 2].

I. Foil-Gas Bearings

The working surface of FGB is formed by a number of overlapping foils made of steel strip with improved elasticity. Anti-friction coating is applied on a working surface to the foils.

The main performance characteristics of FGB, which must be considered in the design of electric machine of the ETM are the following:

- load bearing capacity;
- frequency of ascent;
- damping capacity;
- operating temperature.

Load bearing capacity of FGB is provided in the design of the ETM due to the proper selection of geometric parameters (length, width, thickness, degree of overlap) and profile of the foils.

Frequency of ascent, i.e. the rotor speed at which a separating gas layer in FGB is formed, depends on the geometric parameters of foils and on the force pressing foils to the shaft at rest. Optimization of the frequency of ascent reduces dry friction torque when starting the ETM and wear of the antifriction coating on the foils and consequently increases working life of the bearings and the ETM.

Damping capacity of the FGB are due to their ability to dissipate the energy of the shaft vibrations due to friction between the foils and a body.

Operating temperature of the FGB is mainly limited by heat endurance of the antifriction coating of the foils.

Figure 1 shows the classical design of the radial FGB. In the bearing housing 1 two longitudinal grooves are made in which the foils 3, made of spring steel, are fixed via the shanks. Foils are partially overlapping each other forming a continuous series of wedge surfaces. Foils are preloaded on the shaft due to the fact that the radius of curvature of the foils before installation in the gap exceeds the radius of the shaft. When the shaft 4 is stationary, deformed during assembly foils, trying to straighten up, are pressed to the middle part of the shaft and hold it in the center of the bearing. Friction reducing coating is applied on the working surfaces of foils facing the shaft 4 in order to reduce the friction torque at rotor startup.

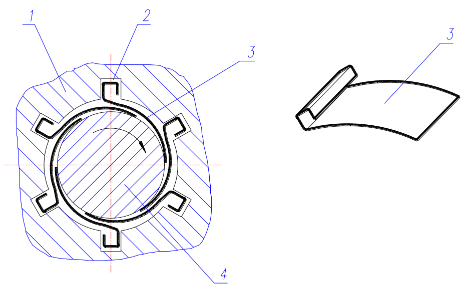


Fig. 1. Radial foil bearing.

Principle of operation of the FGB is based on the effect of the pressure increase in a multi wedge gap that arises in the relative movement of the surfaces. The rotating shaft entrains air in convergent areas between the shaft and foils, with increasing rotation frequency of the shaft air pressure in these zones increases, and finally becomes sufficient to separate the shaft from the foils. Separation of the shaft from the foils and formation of the carrying gas layer between them occurs at a frequency of the ascent, due to emergence of the hydrodynamic wedge. The resultant pressure exceeds the mass of the rotor on the bearing and the preload force of the foils on a trunnion. Linear speed of ascent depending on the geometry of the bearing and the rotor is 3-10 m/s.

The radial foil of thrust gas dynamic bearing is shown in Figure 2. Fig. 2a shows a view of thrust bearing, fig. 2b shows the board without carrying foils, fig. 2c shows skid spring element, fig. 2d shows fragment of saddle profile.

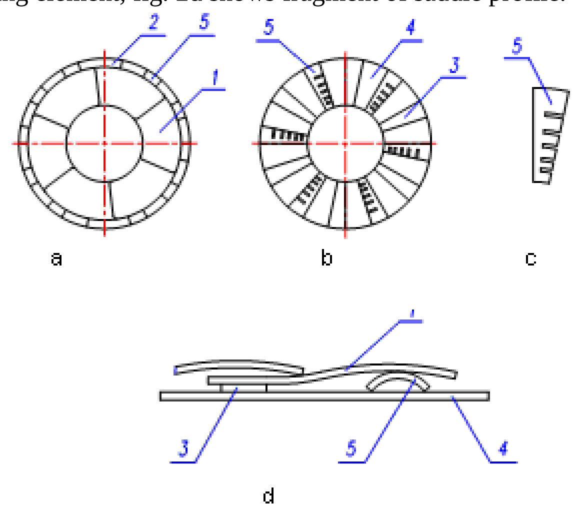


Fig. 2. Foil thrust bearing

Thrust bearing surface is formed by a series of shaped foils 1. Each foil has a cantilever portion 2 and with the slip segment 3 is attached to a ring board 4, by spot welding. The surface of each foil facing the heel is coated with antifriction coating. Working areas of the foils overlap and form a continuous series of wedge surfaces, through which at heel rotation high-pressure zones occur, providing a carrier gas layer. When loading the rotor with axial force, the heel of the carrier gas layer acts on the toe, elastic foils are distorted and rely on the skid springs 5. Each spring is formed as a sector having arcuate slots necessary to reduce the stiffness of the spring in the direction towards the center of the thrust bearing. Spring is profiled transversely to the radius, as shown in Fig. 2d. With further loading the thrust bearing foils and skid springs are deformed, thrust bearing stiffness increases, the bearing surface does not degenerate into a plane, but continues to maintain an optimum wedge shape, able to develop a large load carrying capacity.

Bearing capacity of the FGB depends on the profile of the gas layer formed according to the thickness, length and degree of overlapping foils, working air gap and mode of operation. A distinctive feature of the FGB is the ability to change the working gap profile according to operating mode. Suppleness and light weight of foils allow them to easily keep track of the rotor vibrations caused by imbalance or external disturbances. In case of convergence of the rotor with the foil pressure in the gas layer increases, so the foil is deformed. When the rotor moves away from the foil, the pressure in the gas layer decreases the foil draws near the rotor. The decreases of the tangential component of the gas layer reaction by foils self-alignment allows successfully suppressing the self-excited oscillations and significantly increase the speed of the rotor. The compliance of the foils allows the bearing to operate reliably in conditions of thermal deformation of the casing and in case of contamination of the working gaps.

Damping capacity in FGB occurs because of the friction between foils and the housing. Gas layers, located between the foils and the bearing housing, and hysteresis forces occurring during deformation of the foils create an additional damping effect. In case of shaft vibrations foils "monitor" these fluctuations, i.e. shaft together with the carrier gas precesses in the elastic layer of foils package.

Numerous areas of dry friction derived by the relative displacement of the foils in the process of deformation dissipate vibrational energy of the shaft, ensuring its stable rotation. Absence of mechanical contact between the shaft and the foils after the formation of the gas separation layer allows to receive a very high relative speed on the operating conditions, and to receive high resources. Degradation of anti-friction cover of bearings could happen only at start-up and power-down mode.

Theory of FGB operation could be found in the literature [3] and conference books on gas lubrication. However, it should be noted, that the creation of real FGB for ETM and determination of their performance is impossible without practical experience and experimental studies.

The wide raw of radial FGB is designed in MPEI it contains 14 bearings form 14 mm to 108 mm of shaft diameter. The smallest bearings have maximum rotational speed about 360000 rpm, and the biggest have rotational speed about 16000rpm.Carrying capacity of these bearings is between 0,2 to 38 kg. The model raw of thrust bearings contains 9 models with thrust diameters from 37 to 225 mm and with carrying capacity in range from 10 to 330kg.

It is obviously, that FGB could be used in ETMs of wide range of power and rotational frequency, however, authors experience shows that the reliability and efficiency of FGB are particularly limited by heat flow to them from the machine shaft. So it is important to minimize power losses in the rotor body of ETM to decrease this heat flow.

III. HIGH-SPEED ELECTRICAL MACHINES

It is known, that in the high-speed ETM with contactless bearing could be used only brushless electrical machines (EM). The most perspective of them are: asynchronous, switch-reluctance and synchronous with permanent magnet (PM) excitation.

For the first two types of machines is typical existence of reactive currents, which causes significant power losses directly in the rotor, and hence significant heat flow to the FGB through their shafts.

The other factor influencing on the choice of the EM type for high-speed applications is the specifics of their main dimensions determining - the diameter *D* and length *l* of the active part of the inductor. Main dimensions define the size and design of all the EM elements, its weight, energy, economic, operational and other characteristics. The main dimensions are related to its power P, rotation frequency of the rotor n and loads of electric and magnetic circuits (linear current density A and magnetic flux density in the air gap $B\delta$) by using known expression for Arnold machine constant [5], which results in equation:

$$D^2 l \equiv \frac{P}{nAB_\delta} \quad (1)$$

From (1) it is clear that an increase in the rotational speed n results in a proportional decrease in the active part of the EM volume, with all other actors being equal. In addition, this results in deterioration of cooling conditions of machines, which are defined by the area of the heat-leaking surfaces. Therefore, it is necessary to not only improve the efficiency of EM, but also take into account the power losses distribution in parts of high-speed and ultra-high-speed ETM during the design. In the "classical", ie low-speed, electrical machines, the major power losses appears in armature copper P_{cu} and iron loss from eddy current and hysteresis P_{fe}. In high EM the main losses are mechanical losses for air friction of the rotor P_{airfr} and losses in the bearings P_b. Losses P_b are defined by geometric dimensions and design of FGB, the parameters of the gas and the pressure in the gap and may be represented as a constant value for the selected FGB size, power and rotational frequency ETM. The situation is different with P_{airfr} losses, they dependent significantly from the geometric dimensions of the rotor [5], particularly on its diameter:

$$P_{airfr} = 1{,}69 \times 10^{-13} \times n^{2,7} \times p^{*0,7} \times (1 + 4{,}4\lambda) \times D^{4,4} \quad (2)$$

Where n – rotational speed of the rotor (rpm); p* - relative pressure of gas (p.u. for atmosphere pressure); *D* – rotor diameter (cm); $\lambda = l/D$ - relative rotor length, *l* - absolute rotor length (cm).

From the analysis of the expression (2) could be made the obvious conclusion that it is advisable to design high-speed EM with small-diameter long ($\lambda \geq 3 \div 4$) rotor to reduce power losses from the rotor air friction P_{airfr}. An excellent illustration for this could be shown the design of the rotor of microturbine power plants C-200 from Capstone [2], it is shown on Figure 3.

In addition to losses reduction "long" construction of ETM rotor reduces its inertia and linear speed on surface. First of it reduces the dynamic loads on the LGP, and the second – helps to reduce forces, applied to a rotor sleeve. λ is limited "from above", on the one hand, by the deterioration of the temperature mode of stator winding and technological difficulties of a “long” stator manufacturing, on the other hand, - by the rotor dynamics, what is particularly important for FGB operation. The LGP could operate only with hard rotors, with mechanical bending frequency at least for 30% higher, than ETM maximum rotational frequency.

Fig. 3. Microturbine power plant Capstone C-200.

It is shown on practice that the value $P_{airfr\ is}$ significantly affected by the shape and finish of the shaft surface - the power loss is significantly reduced, if the rotor has a smooth, polished surface.

Based on these facts it can be concluded that it is advisable to design ETM based on electrical machines with permanent magnet excitation. Indeed, theoretically this class of EM has the highest electromagnetic efficiency because they do not require extra energy to the excitation (energy of PM is used) and power factor of them is close to 1. The rotor of the EM can be easily made two-pole, "long" and smooth.

However, the usage of permanent magnets requires installation of the rotor sleeve, manufactured from strong material. Nowadays the most sleeves are made from metal. Due to this the additional analysis of power losses in the rotor of the eddy currents is required.

IV. TURBOGENERATOR SAMPLE RESEARCH

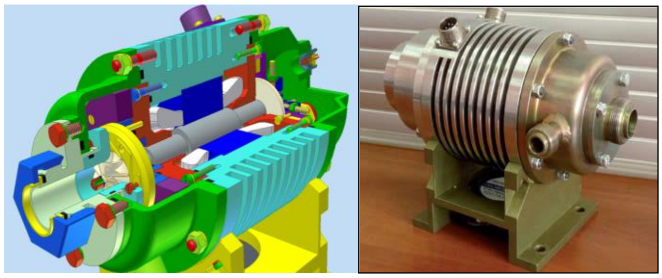
As an example of high-speed ETM could be presented project of turbogenerator for organic Renkine cycle power plant. Design project of this machine was settled using known method [4], with high speed machines features taken into account. Parameters of designed machine are given in table III.

TABLE III
FEATURES OF DESIGNED MACHINE

№	Parameter		value
1	Output power, W	P	1000
2	Nominal DC voltage, V	Ud	200
3	Stator Outer diameter, mm	Dout	65
4	Stator stack length, mm	L	39,5
5	Phase number, pcs	m	3
6	Stator teeth number	Z	12
7	Stator winding turn count	w	36
8	Stator Phase resistance, Ohm	Rs	0.28

The machine is equipped with foil gas dynamic bearings.

On the figure 4a sketch of designed machine is shown. And the photo of manufactured machine is shown on figure 4b.



a b

Fig. 4. Designed turbogenerator.

Operational modes were verified. It is important for understanding of calculation mistakes, which may occur due low quality of model parametrization. First the experiment of phase inductance measurment was done. During this experiment phases of machine were connected to DC voltage source for a short period of time. Phase current was observed and after that inductance was calculated due to electomagnetic induction law. Phase current was observed through digital oscilloscope. After that the same experiment was modelled using FEM. Two types of FEM models were researched 2D and 3D. The same calculations were done. Comparative results of these experiments are given in table IV.

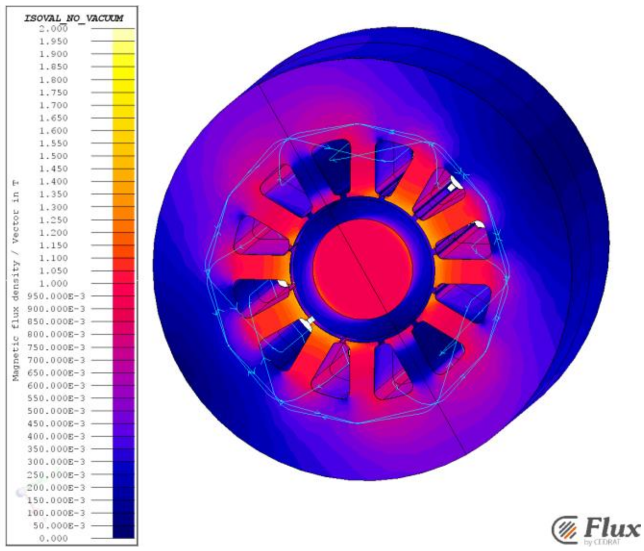


Fig. 5. FEM model of generator

TABLE IV
COMPARATIVE ANALYSIS OF MODEL AND REAL VALUES

№	Parameter	Experimental value	2D-FEM modeled value	3D-FEM modeled value
1	Phase inductance, uH	349	302	352
2	Linear (phase to phase) inductance, uH	842	593	848

As it is shown in table, differences between measured and modeled by 3D-FEM inductance values are quite small. However, the accuracy of 2D-FEM modelling is not so good. This happens because of two reasons. First: the rotor magnet length of studied ETM is less then stator length. Second: the inductances values are quite low and frontal-parts magnetic flux should be taken into account. Therefore, it could be said that 3D-FEM model is quite accurate.

At the next stage of the verification was done comparative analysis of machine variables at operating mode. The machine rotor was driven into rotation with turbine. Phases of the machine were connected to three-phase bridge rectifier, which was connected to load resistor. The same scheme was studied on the FEM-model. On the figure 6 are shown three oscillograms of phase voltages and one oscillogram of phase current. As it could be seen, the voltage curves are very distorted. The results of FEM-model calculation of the same operating mode are shown on figure 7. The accuracy of voltage levels calculation is about 98%, and the maximum inaccuracy in curve shapes does not exceed 5%.

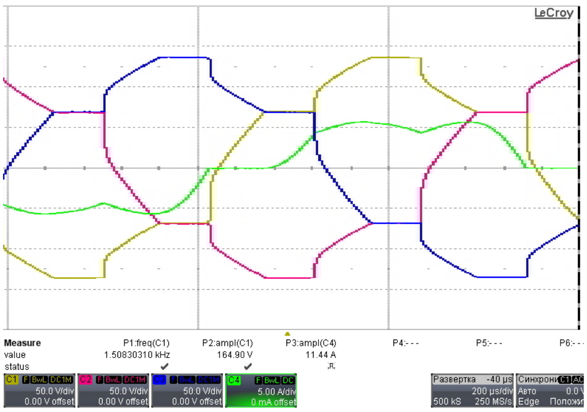


Fig. 6. Voltages and phase current at operating mode

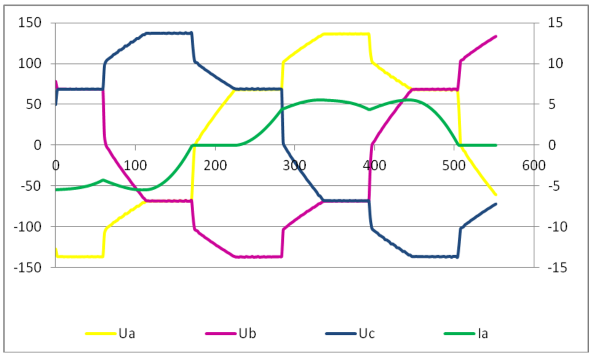


Fig. 7. Voltages and phase current, calculated by FEM

As the result of provided comparative analysis, we can say that designed model is quite accurate, and it takes into account the electromagnetic processes into designed machine.

V. Eddy-current analysis using FEM

As it was noted before, for regular foil bearings operation it is very important to minimize the heat flow from the rotor. This means that Joule losses in the rotor body should be minimized. Thereby it is very important to calculate the eddy-current losses into the rotor body at operating mode. However, it is very difficult to organize direct measurements of these losses, and indirect measurement is quite complicated due to whole machine losses analysis. It is not difficult to calculate stator iron and copper losses, but problems occurs when it is needed to calculate losses in foil bearings; it is caused that the height of gas layer cannot be measured. Ventilation losses could not be calculated with good accuracy due to unknown thermodynamic parameters of the air into machine.

Thereby the best method of rotor eddy-current losses calculation is using of FEM-model to analyze electromagnetic processes into machine rotor. Such research of designed generator was provided using verified FEM-model. On figure 8 it is shown the calculated eddy-currents density in the rotor surface. On figure 9 is shown the eddy-current density into the rotor body cut-plane.

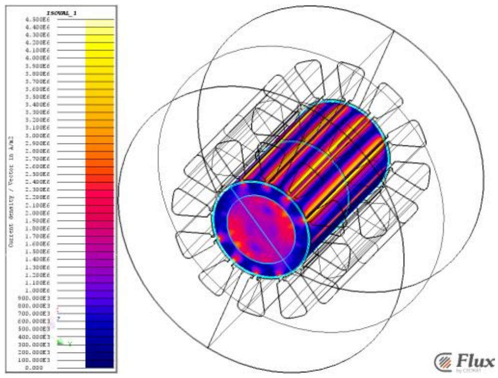


Fig. 8. Eddy-current density on rotor surface

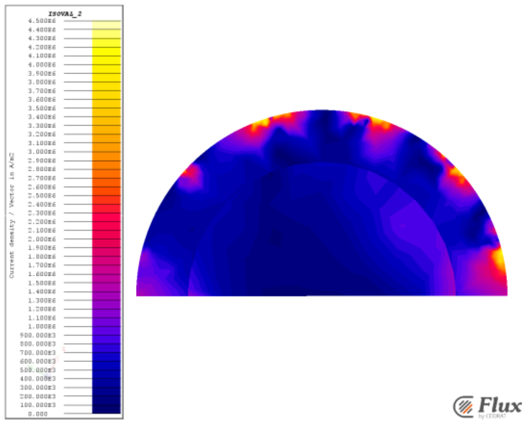


Fig. 9. Eddy-current density in the rotor body at cut-plane

It is known that rotor sleeve should have rather high electrical conductivity to protect magnet from eddy-currents, but increasing of conductivity results in rising of eddy-currents in the sleeve [5].

Analyzing figures 8 and 9 we can conclude that rotor sleeve material have enough electrical conductivity to protect magnet. Joule losses in magnet body are less than 1W.

Joule losses in rotor sleeve are about 16W, that is about 1,5% of nominal power of the machine. Therefore it is recommended to lower the eddy-currents in the rotor sleeve. It is not recommended to use sleeve material with lower electrical conductivity, because eddy currents in magnet could increase. And it could be harmful for magnetic properties of the magnet.

It is known from [6] that rotor eddy-current losses are affected by the number of phases in the machine and by the rectifier scheme. Next researches are provided for minimization of eddy-current losses in the rotor sleeve by using different winding schemes of machine.

For the research the FEM model was redesigned. Winding was changed to 6-phase scheme. The winding was formed as two independent three-phase Y-connected windings. Each of the three-phase windings was connected to three-phase bridge rectifier. Connection scheme is shown on fig 10.

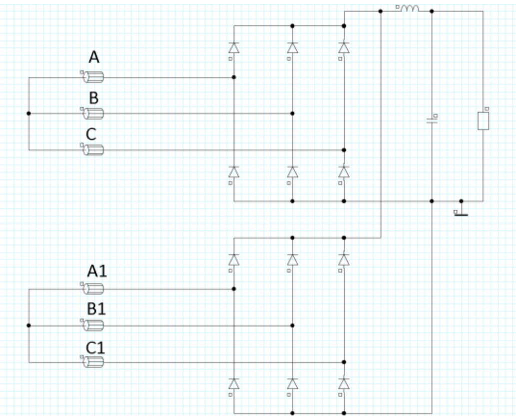


Fig. 10. Six-phase electrical machine with rectifiers

At operating mode with the same output power eddy-current losses in rotor sleeve decreased to 3.5W. That is much lower than in previous case.

For understanding of the reason of such power losses decrease it is important to analyze machine stator currents. On figures 11 and 12 are shown currents in machine windings for three-phase and for six phase implementation respectively.

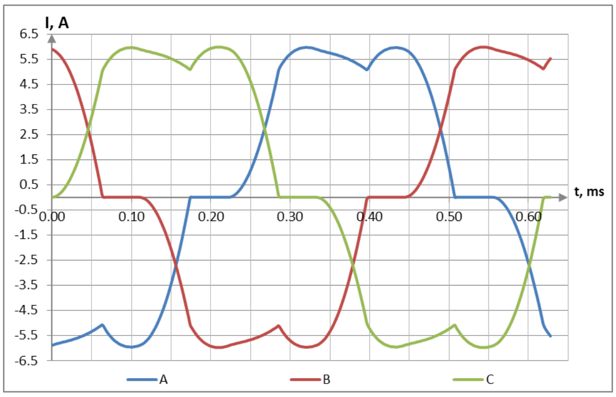


Fig. 11. Phase currents in three-phase machine

These currents could be transformed into rotor coordinate systems using Clarke and Park transformations. After that we could calculate magnitude of resulting current vector and its angle position according to rotor body. The results of this calculation is presented on figures 13 and 14.

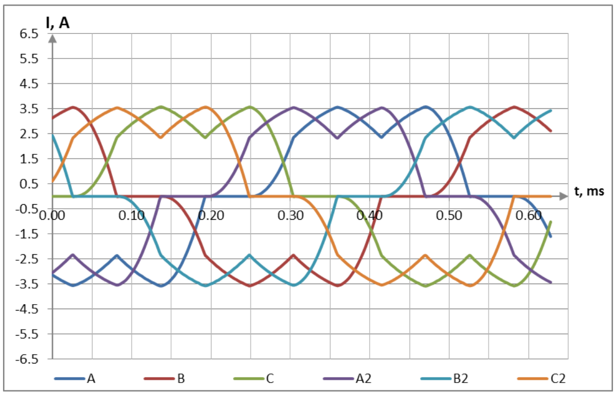


Fig. 12. Phase currents in six-phase machine

Relatively pulsation of current vector in three-phase scheme is about 25% from its mean value. And relatively pulsation in six-phase scheme is about 4%.

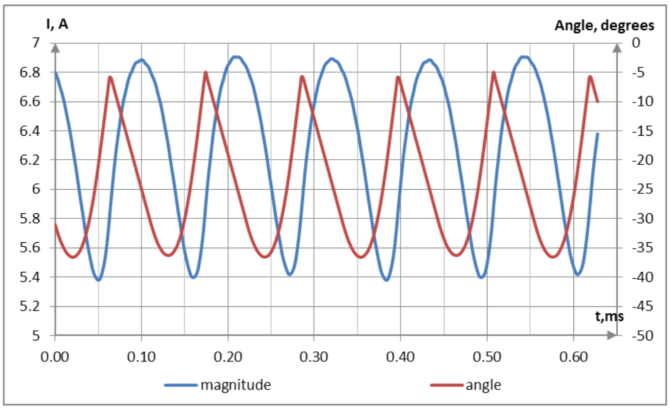


Fig. 13. Current magnitude and its rotational angle along rotor body in three-phase machine

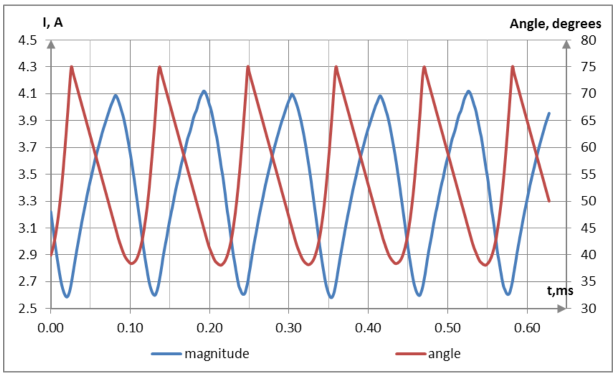


Fig. 14. Current magnitude and its rotational angle along rotor body in six-phase machine

The next statement we can conclude is that demagnetization (d-axis) current in six-phase scheme is higher than in three-phase scheme. This can be observed by higher mean value of current vector angle. This effect results in increase of total current magnitude, and as consequence in increasing of copper losses in the machine.

Due to this effect, it is not advisable to increase the amount of machine phases more than 6.

Conclusion

Most of modern power stations, low-pressure centrifugal compressors, blowers, vacuum pumps, refrigeration units, turbine generators and other devices are based on high-speed electrical machines.

Creations of these systems could be provided only by joint work of specialists in electro mechanics, power and information electronics and foil bearings. This union allows getting complex solving of problems in research, development and manufacturing of electric drives and power generation systems based on high-speed electrical machines.

Problems of design and calculation of foil bearings are solved nowadays, as well as the technological problems of foils coverage material selection.

Foil bearings are used in lots of high-speed electrical machines. These machines are implemented in high variety of operating power from 0,3 to 250 kW, and rotation speed up to 320000rpm, machines rotor mass can reach 60 kg.

Exploitation of these machines during ages has shown their environmental friendliness, high reliability and resource.

The analysis of high-speed machine which is done in the article has shown that the best implementation of low power generator is six-phase machine, connected to two three-phase rectifiers, which are connected parallel at output. Such implementation helps to decrease eddy-current losses in rotor body.

Acknowledgment

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