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Features of electromagnetic processes and force interactions in turbogenerators when consuming reactive power

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SUMMARY

Operation of a turbogenerator in the mode of reactive power consumption negatively affects its residual life. This conclusion is confirmed by the data of some experimental studies and statistical data on operating time to failure [1-8]. However, the known results of theoretical and experimental studies of physical processes in this mode are still insufficient to formulate reasonable criteria for selecting permissible modes of operation for different types of generators.

The implementation of the numerical analysis of a three-dimensional electromagnetic field in a turbogenerator is a difficult task for existing software computing systems [9-13]. In this work, for a detailed study of electromagnetic processes during the operation of powerful turbogenerators in various regimes, including consumption of reactive power, 3D model of turbogenerator is analyzed. Homemade software based on spatial integral equations is applied, which made it possible through the use of parallel computation processes to realize the calculation of the magnetic field in a complete three-dimensional formulation.

The paper presents the results of study of the electromagnetic field on the basis of the created 3D model of an air-cooled turbogenerator, which includes the main elements of its magnetic system. The constructed model makes it possible to determine the magnetic state of the stator and rotor steel and analyze the distribution of electromagnetic forces arising in the frontal parts at different power factors, as well as obtain data for the theoretical substantiation of the most dangerous zones for reactive power consumption when optimizing operating modes of turbogenerators.

On the basis of the obtained calculation results, conclusions are drawn about the most significant factors that worsen the operating conditions of generators when consuming reactive power. These include the electromagnetic forces acting on the stator windings at the point where they exit the slot. At the same time, no significant increase in the axial components of the magnetic induction was found when in modes with reactive power consumption, which could lead to additional heating of the end zones of the stator steel.

More accurate 3D models of turbogenerators can be used to create monitoring systems based on magnetic field sensors in the end zones [2,3,5,6]. The introduction of such monitoring techniques requires a preliminary analysis of electromagnetic fields to determine the optimal locations for sensors, their types and measurement ranges. The regime of reactive power consumption for turbogenerators is nominal, however, solving the problems of diagnostics of the state and predictive monitoring of the residual resource in these modes requires further deeper theoretical and experimental studies of the operation of turbogenerators.

KEYWORDS

Turbogenerator, PQ diagram, Reactive power consumption, Magnetic state of steel, Electromagnetic forces

OBJECT OF STUDY

Here we consider the magnetic system of an air-cooled turbogenerator with active power of 160 MW as an object of theoretical and computational studies.

Main parameters of the turbogenerator:

- apparent power, MVA - 188,2;
- power factor - 0,85;
- rated line voltage, KV - 15,75;
- rated current of the stator, KA - 6.91;
- frequency, Гц - 50 Гц;
- efficiency, % - 98,5;
- the number of pole pairs -1;
- rotational speed, rpm -3000;
- stator winding connection configuration – star connection.

At this stage, the aim was to calculate the distribution of the magnetic field in the limiting operating modes determined by recommendations of the manufacturer as a PQ diagram. Considered PQ diagram is shown in Fig. 1, from which 5 characteristic operating points were selected for analyzed. Points 1-3 correspond to the modes of consumption of significant reactive power, point 4 determines the mode of generating only active power and point 5 - the nominal operating mode of the generator with the delivery of reactive power to the network. The parameters of the selected modes are shown in Table I.

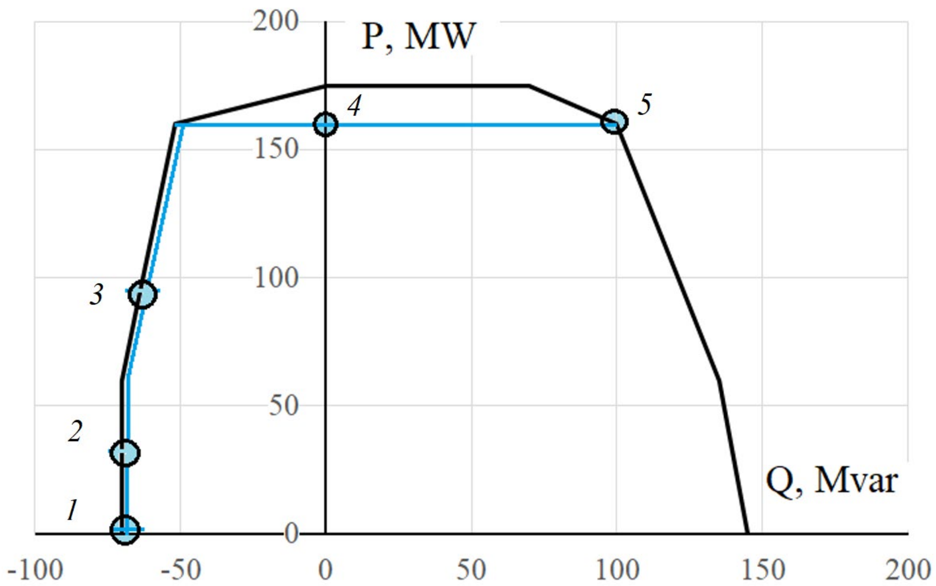


Fig. 1 – PQ diagram of generator with selected points for analysis

Table I - Parameters of the turbogenerator operating modes selected for analysis

Point number	P, MW	Q, MVar	φ, dergee	I, kA
1	0	-68	-90	2,493
2	32	-68	-64,8	2,755
3	96	-66	-34,5	4,2705
4	160	0	0	5,865
5	160	100	32,05	6,916

The plan of computational and theoretical research included the solution of the following tasks:

1) Compilation of models for a three-dimensional numerical calculation of the magnetic field in the main elements of the magnetic system of a turbogenerator without taking into account losses due to induced currents and magnetic hysteresis. Specific design features of the end zones of stator, flux shields, slitted teeth etc. are not represented in the model;

2) Carrying out calculations of the selected operating modes of the turbogenerator for comparison of the obtained results by the following parameters:

- the level of maximum magnetic saturation of the stator and rotor steel;
- maximum values of the axial component of the magnetization of the stator and rotor steel:
- distribution of forces acting on the stator winding in the slots and frontal parts.

MATHEMATICAL MODEL FOR CALCULATIONS

The calculation of a three-dimensional magnetic field in a turbogenerator using software based on the finite element method requires significant computing resources. To increase the performance of calculations, a specialized software complex was used, which is based on the method of integral equations of the magnetic field and provides high-performance calculations of three-dimensional magnetic systems using parallel computing processes. This software has been used for a long time at NRU MPEI for the design of electrical machines and other electromechanical and electromagnetic devices, as well as in the educational process. The reliability of the calculations using this software had been validated by numerous comparisons with experimental data, calculation data based on such well-known commercial programs as COMSOL and ANSYS.

The calculation of magnetic systems by the method of integral equations is divided into two independent parts: the calculation of unknown vector field sources and the calculation of the magnetic field parameters determined from the found sources.

The integral equation for the magnetic field strength created by the magnetized parts and the current in the windings has the following form

$$\mathbf{H} = -\frac{1}{4\pi}\left(\int_{V_{\text{п}}} \frac{\boldsymbol{J}\times\boldsymbol{r}}{r^3} dV + \int_{V_{\text{м}}} \frac{(\nabla\times\boldsymbol{M})\times\boldsymbol{r}}{r^3} dV - \int_{S_{\text{м}}} \frac{(\boldsymbol{n}\times\boldsymbol{M})\times\boldsymbol{r}}{r^3} dS\right), \quad (1)$$

where the vectors **H**, **M** and **J** are the magnetic field strength, magnetization and current density, respectively.

This formula allows to compose integral equations for magnetization, if we add to it the constitutive equation - the magnetic properties of materials. In the calculation algorithm of applied software, a model with a piecewise constant approximation of the magnetization vector over the volume is used, i.e. the volume of parts made of magnetic materials is divided into a large number of small elementary volumes, each of which is represented by a polyhedron and has a uniform magnetization. By placing the observation point sequentially at the midpoints of each elementary volume and writing down expression (1) a system of linear algebraic equations is compiled, connecting the unknown values of the magnetic field strength in elementary volumes with the sought values of the magnetization. As a matrix, it has the form

$$\boldsymbol{H} = \boldsymbol{AM} + \boldsymbol{H}_0, \tag{2}$$

where the multidimensional vectors **H**, **M** and $\mathbf{H_0}$ contain the components of the vectors of the magnetic field strength and magnetization in each elementary volume, $\mathbf{H_0}$ - the magnetic field strength of known sources. In the considered magnetic system of the generator, the known sources are currents in the windings.

When calculating the unknown distribution of magnetization vectors over elementary volumes, the magnetic characteristics of materials are added to the system of equations (2). For an isotropic soft magnetic material, the magnetic properties in any direction are determined by the dependence of the modulus of the magnetization vector on the modulus of the magnetic field strength *M (H)*. At each step *n* of the iterative solution, the components of the vector $\boldsymbol{M}^{*n}$, which simultaneously satisfy the indicated equations, are found by minimizing their residual (Fig. 2):

$$\Phi_k(H_k) = min|M_k^c(H_k) - M_k(H_k)|, \quad k = 1,2,...,N_1, \tag{3}$$

where $M_k^c(H_k)$ is the function of the modulus of magnetization of the *k* elementary volume, obtained from the solution of system (2); $M_k(H_k)$ – characteristic of material.

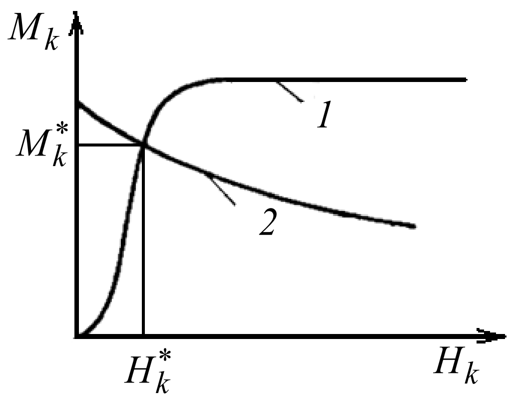


Fig. 2 - Determination of the residual function when calculating the magnetization of a part made of a magnetic material: 1 - characteristic of material; 2 - solution of the system of equations

The iterative process of solving a system of equations is built according to the scheme of simple-iteration method

$$\boldsymbol{M}^{n+1} = \boldsymbol{M}^n + \alpha(\boldsymbol{M}^{*n} - \boldsymbol{M}^n), \tag{4}$$

where $0 \le \alpha \le 1$ — iterative process parameter;

The conditions for achieving a solution with a given accuracy are made by comparing the magnetization values obtained at two adjacent iterations by the solution stabilization criterion

$$\Delta = \frac{\|\boldsymbol{M}^{n+1} - \boldsymbol{M}^n\|}{\|\boldsymbol{M}^{n+1}\|} < \varepsilon. \tag{5}$$

The value $\varepsilon > 0$ sets the accuracy of solving the system of equations.

The properties of parts of magnetic systems made of an anisotropic material are set in the coordinate system associated with the axes of anisotropy α, β, γ. The system of equations (2) is written in the axes of anisotropy and each axis is assigned its own magnetic characteristic.

Fig. 3 shows the model of the construction of the magnetic system of a turbogenerator, compiled for calculations. The model is built in 3D, including the end parts of the stator and rotor windings. It is assumed that the magnetic field distribution is symmetrical about the axial midpoint of the generator. The connection leads of the stator windings and difference between the connection end and the non-connection end of the generator are not taken into account. In the azimuth direction, the computational domain is complete and covers 360 °.

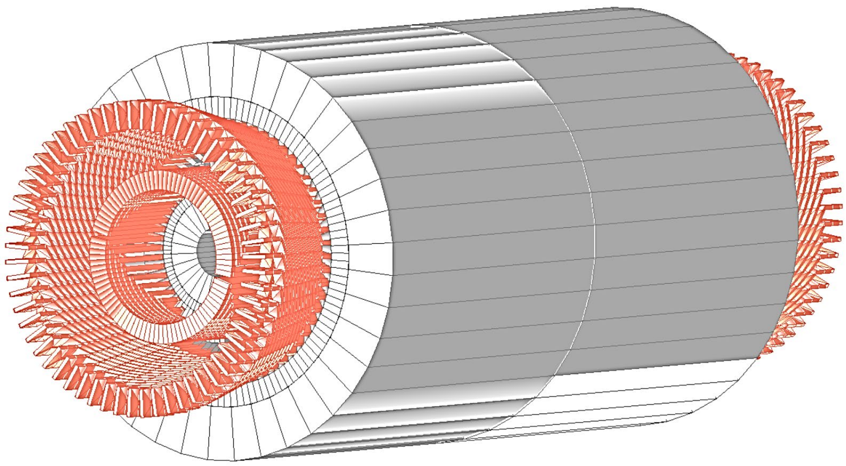
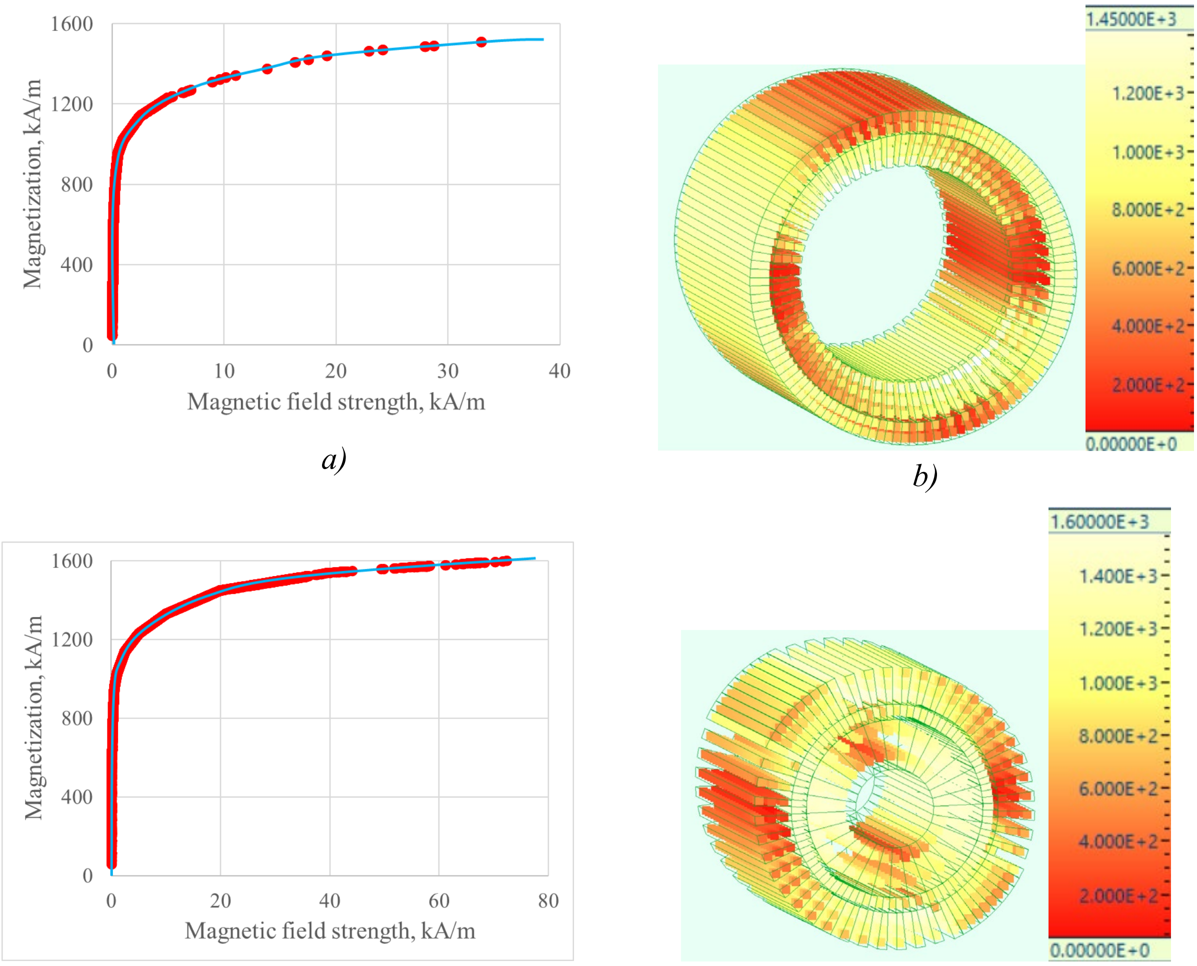


Fig. 3 - Model of the magnetic system of the turbogenerator

ANALYSIS OF THE MAGNETIC SATURATION OF STATOR AND ROTOR STEEL IN DIFFERENT OPERATION MODES OF TURBOGENERATOR

As a result of the calculations performed, we obtained the data characterizing the magnetic state of the material of the stator and rotor of the generator at the points selected for analysis, which are marked on the PQ diagram (Fig. 1). The relative position of the rotor poles and the stator rotating field for these points, as well as the stator phase currents *Iarm*, excitation currents *Iex*, load angles φ are given in Table II. In the considered modes, the relative position of the rotor poles and the rotating field of the stator varies in a wide range from 0 to 155 degrees, which should impact on the magnetic state of the steel stator and the rotor. However, limiting the stator and field currents in accordance with the power diagram significantly reduces the effect of changing the relative position of the poles. Fig. 4 shows the results of calculations of the modulus of magnetization of the rotor and stator steel in the nominal operating mode of the generator, which are marked on the magnetization curve of the material (red points on the magnetization curve in Fig.4 *a,c*). Fig.4 *b,d* show the distribution of magnetization in steel of the stator and rotor using color indication. The outer part of the stator is not shown in Fig.4*b*.

Fig. 5 shows the change in the maximum value of the axial component and modulus of the magnetic induction in rotor and stator steel for the selected 5 points on the PQ diagram. The zones with the maximum value of magntic induction are also marked there.



c) d)

Fig. 4 - The results of calculations of the module of magnetization of the rotor and stator steel in the nominal operating mode of the generator: *a*,*b* – stator; *c,d* – rotor

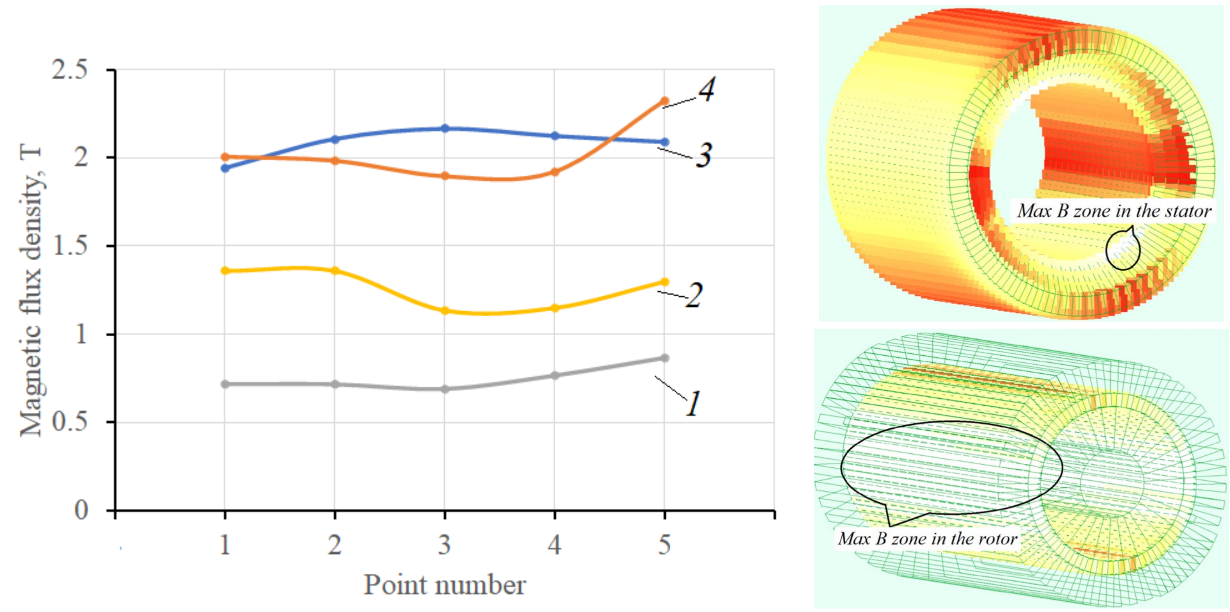
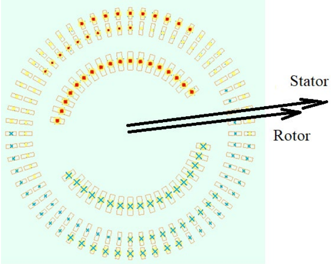
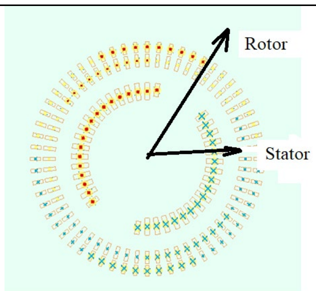
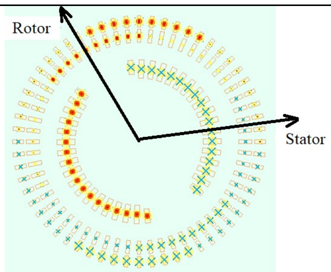
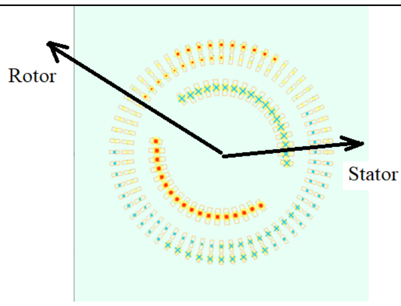
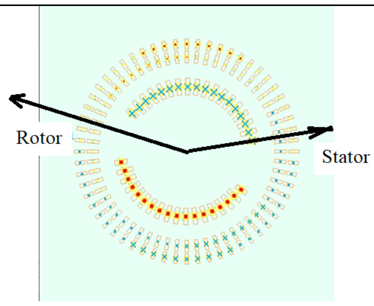


Fig. 5 - Maximum values of the magnetic induction of the rotor and stator steel for the selected 5 points on the PQ diagram: *1* - axial component of the magnetic induction at the

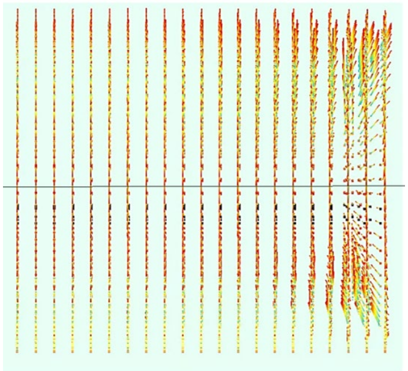
stator; *2* - axial component of the magnetic induction at the rotor; *3* - module of magnetic induction at the stator; *4* - the module of magnetic induction at the rotor

Table II - The results of calculating the parameters of the generator in the selected modes.

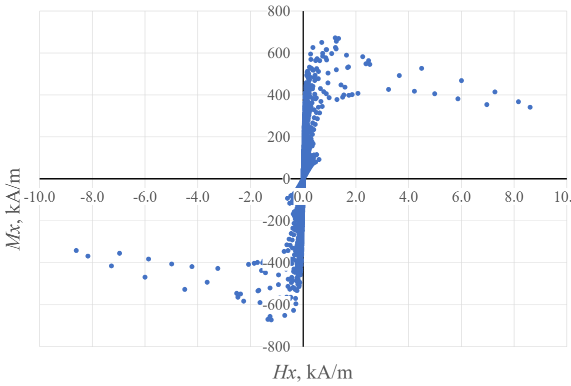
Point number	Relative position of the rotor poles and the rotating field of the stator	φ, deg	*Iarm*, kA	*Iex*, kA
1		-90	2,493	0,276 *In,ex*
2		-64,8	2,755	0,299 *In,ex*
3		-34,5	4,2705	0,447 *In,ex*
4		0	5,865	0,756 *In,ex*
5		32,05	6,916	1,0 *In,ex*

A significant increase in the saturation of steel in the modes of reactive power consumption (points 1-3) is not observed.

Analysis of the change in the axial component of the magnetic induction in end zone of the stator steel `in different operating modes of the generator is of great importance for assessing the energy losses for heating in this zone due to induced currents. The axial component of the magnetic induction in the steel of the rotor and stator takes place in all operating modes and should be minimized when optimizing the design of the magnetic system of the generator as a whole. A typical picture of the distribution of magnetization vectors in the end zone of the stator and the values of the axial component of the stator magnetization of the considered generator in the nominal operating mode (point 5) are shown in Fig. 6.



a)



b)

Fig. 6 - The distribution of the magnetization vectors in the end zone of the stator steel calculated in the nominal operating mode of the generator (½ part along the length of the generator is shown) - *a*; values of the axial component of stator magnetization – *b*

Variations of the axial component of the magnetic induction in the stator and rotor steel in different operating modes are shown in Fig. 5. The assumed increase in losses due to induced currents in the end parts of the stator caused by an increase in the axial components of the magnetic induction in the modes of reactive power consumption do not confirmed by the calculated data. This conclusion, of course, applies only to the considered modes of operation of the generator, when its apparent power is significantly limited in accordance with the recommendations of the manufacturer. To obtain more information about electromagnetic processes during the consumption of reactive power by the generator, including the effect of the axial component of magnetic induction on induced currents, thermal and mechanical phenomena in the end zone of the stator core, in the development of the above studies, it is necessary to perform calculations in the extended area of the power diagram. To confirm the results of the computational studies, it is planned to perform measurements of the magnetic field on an operating generator.

Calculations of the electromagnetic forces acting on the stator winding are performed as follows. Fig. 7 shows a part of the stator winding, isolated from the whole generator model, containing one bar and its frontal part. Four points are marked on the winding, at which the calculation of the specific electromagnetic forces in various operating modes was carried out. The first three points are located at the exit of the winding from the stator slot. Point 4 is located in the middle of the stator groove.

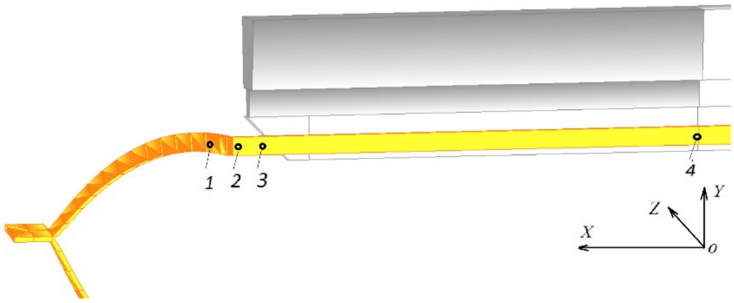


Fig. 7 - Part of the stator winding containing one bar and its frontal part with marked points for calculating the forces

The components of the electromagnetic forces are calculated in the coordinate system which is shown in Fig. 7. Results are presented in Fig 8, 9 in the form of hodographs described by the ends of the force vectors with an initial point at zero when the rotor is turned by 180°.

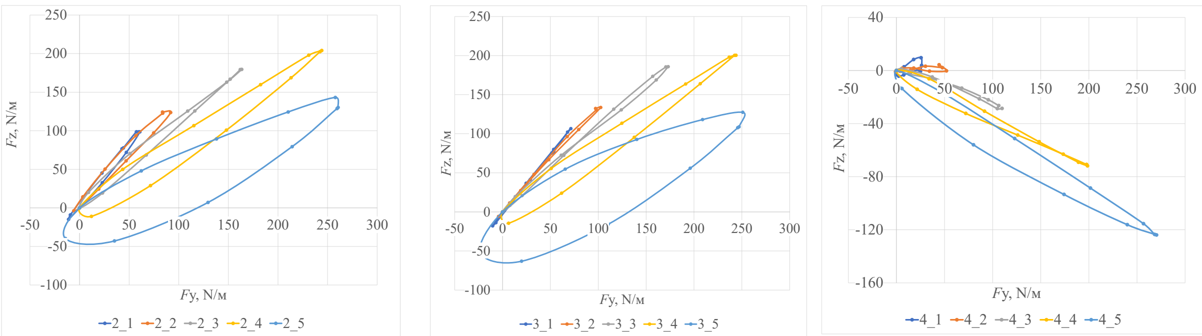
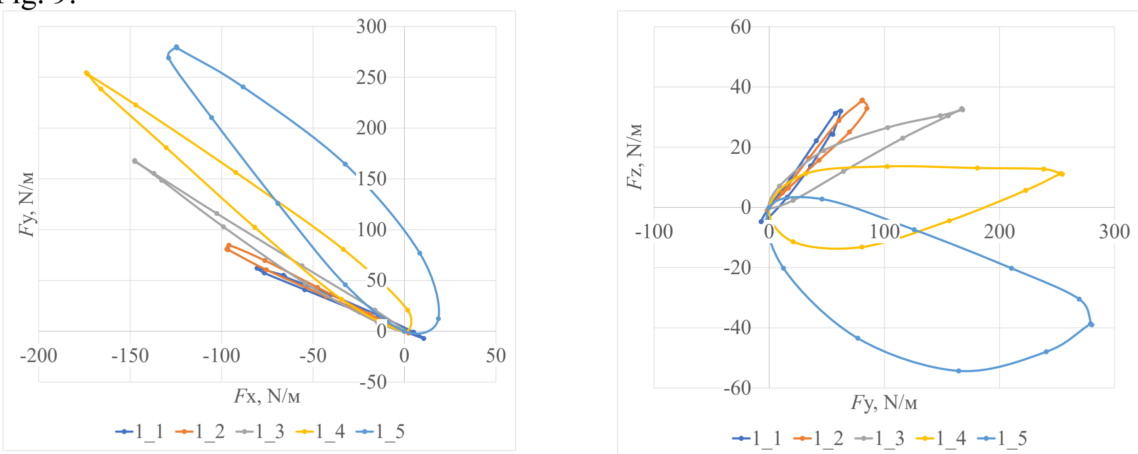


Fig. 8 - Hodographs of the electromagnetic force vector in the YZ plane: the first index of the hodograph designation is the number of a point on the stator winding (Fig. 7), the second index is the number of a point on the PQ diagram (Fig. 1)

At the first point on the stator winding, located on the frontal part, all three coordinate components of the forces take place. Their hodographs are shown in two planes XY and YZ in Fig. 9.



a) *b)*

Fig. 8 - Hodographs of the electromagnetic force vector for the first point on the stator winding (Fig. 7): *a* - in the XY plane; *b* - in the YZ plane. The first index is the number of a point on the stator winding, the second index is the point number on the PQ diagram (Fig. 1).

Analysis of the results of calculating the forces acting on the stator winding allows us to draw the following conclusions:

- despite the reduced values of stator currents and field current, the forces acting on the stator winding at the exit from the slot (points 1-3 in Fig. 7) are close in modulus to the values of forces in the nominal operating mode;
- in the mode of reactive power consumption (points 2, 3 in Fig. 1), the azimuthal components of the forces acting on the stator winding increase at the point where they exit from the groove.

CONCLUSION

The theoretical and computational studies of the electromagnetic field of various limiting modes of operation of a turbogenerator according to the PQ diagram are performed in a full three-dimensional formulation for the main structural elements of the magnetic system. The obained results show that in the mode of reactive power consumption there is no increase in the saturation of the stator steel and an no increase in the axial components of the magnetic induction compared to the nominal operating mode. Accordingly, the additional losses associated with an increase in the induced currents in the end parts of the stator due to the axial components of the alternating magnetic field are not confirmed by the calculation results. This conclusion applies only to the considered modes of operation of the generator, when its apparent power is significantly limited in accordance with the recommendations of the manufacturer (PQ diagram).

Studies of the electromagnetic forces acting on the stator winding in the zone of exit from the groove indicate an increase in the azimuthal components of the forces in the modes with reactive power consumption. An increase in azimuthal forces and their moments at the exit from the slots can cause additional deformations of the winding and a significant increase in azimuthal forces acting from the side of the winding on the end parts of the teeth and the stator magnetic core.

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