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PRACTICAL IMPLEMENTATION OF MULTIPARAMETRIC DESIGN OF FUNCTIONAL ELEMENTS OF A POWER MACHINE

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Abstract

The article performs multiparametric design of the stator core of the turbogenerator according to the criteria of electromagnetic and heat-ventilation load. The result of this design was the determination of the basic geometry of the stator core (inner diameter, outer diameter), the determination of the geometry of the tooth zone of the core (number of grooves, depth and width of the groove) and the determination of the cross-sectional area and the number of ventilation channels. The proposed toolkit allows you to determine both radial cooling channels and axial ones. The applied methodology can be used for different types of electric machine and almost all power classes (small machines, medium-sized machines and high-power machines).

Keywords: *electromechanical energy converter, multiparametric model, stator, turbogenerator, multiphysical processes*

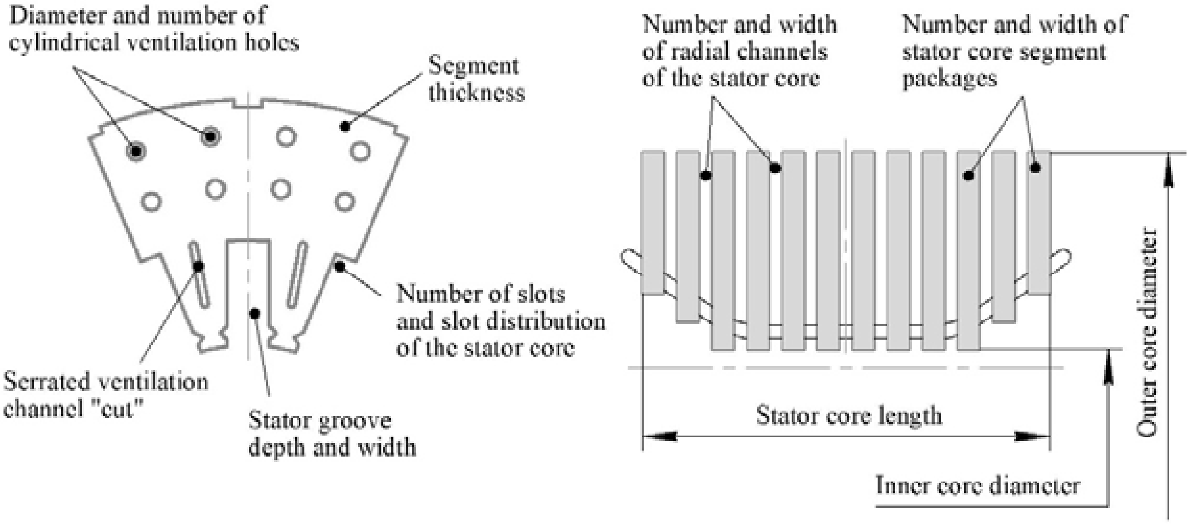
Introduction

The process of designing electromechanical energy converters is a complex and multifaceted task, which is limited on the one hand by the technical and methodological capabilities of the existing design tools, and on the other hand by the modern requirements of the market for electromechanical equipment, which include the requirements of manufacturability, safety, environmental friendliness and reasonable economy of the future unit. Currently, known design methods are based on a sequential organization of calculation stages, followed by the process of modeling individual phenomena and effects of the functioning of the electric machine and modeling, at the final stage, the future design of the electromechanical energy converter. This approach affects both the timing of design work and the quality of individual results obtained as a result of the design (Lei, G., Zhu, J., Guo, Y., Liu, C., & Ma, B., 2017; Omar, M.F.B., Sulaiman, E.B., Soomro, I.A. et al., 2023).

Research method

To perform multiparametric design of the turbogenerator stator, we will use the approach specified in (Hammza, T., Abas, E., & Hmoad, N., 2020). The objective function by which multiparametric design is performed is the total electric power of the turbogenerator (TG): $P_{em} = f\left(l_s; D_a; Q_{air}\right)$, where the variable is l_s – the length of the stator core, mm; the variable D_a – the outer diameter of the stator core, mm; and Q_{air} – the electric power consumption for cooling the TG. The development of the stator core usually comes down to determining the geometry of the core segment, its thickness, the grade of electrical steel and the assembly of radial packages of the stator core, in order to determine the axial length of the stator core. The general view of the stator segment is shown in Fig. 1.

Figure 1. *General view of the stator segment and stator core*



The process of performing multiparametric design of the stator core will be shown gradually from the point of view of the indicators determined by the calculation (Fig. 2).

Figure 2. *Graphical model for performing multiparametric design of the stator core*

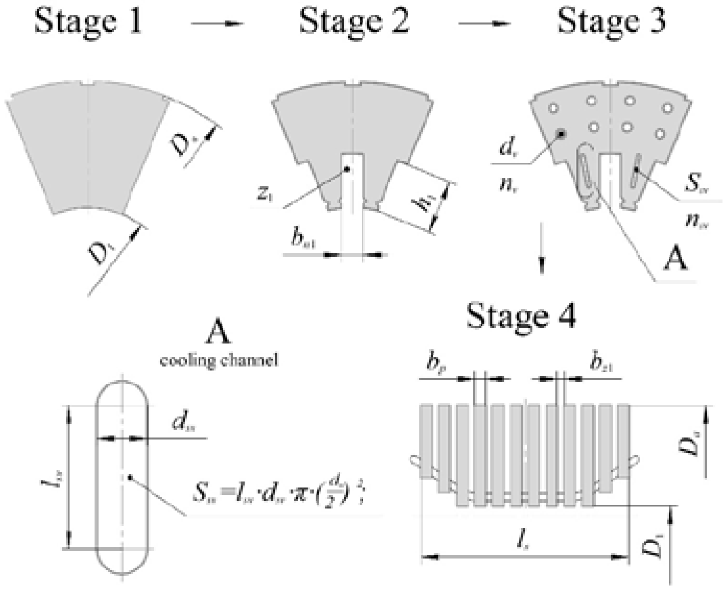


Figure 2 has the following explanation:

In the first stage, the overall dimensions of the core within the stator segment are determined – the outer diameter (D_a), the inner diameter, the so-called bore, (D_1) and the segment thickness (σ_s). In the second step, we determine the geometry of the tooth zone of the segment, namely: the number of grooves (z_1), the groove width (b_{n1}) and the groove depth (h_1). In the third stage, we determine the geometry of the ventilation channels: the number (d_v) and the diameter of the axial channels

(n_v), the number (n_{sv}) and the cross-section of the slot channel (S_{sv}). And at the final stage, the core is assembled from the segments, as a result of which the thickness of the radial package of the stator core (b_p), the width of the radial channel (b_{z1}) and the length of the stator core (l_s) are determined (Berestinov, A.A., Korobatov, D.V., Kulganatov, A.Z., 2023).

Mathematically, the general function of multiparametric design depending on the above-mentioned values has the following form:

$$P_{em}\left(l_s;D_a;Q_{air}\right)=\begin{cases} P_{em}=\dfrac{\pi}{4}\cdot l_s\cdot\left[\left(\dfrac{Q_{air}\cdot\left(2\cdot n_{st}-1\right)}{\upsilon_j\cdot n_{st}\cdot n_{n1}\cdot b_{z1}\cdot\pi}\right)-h_{n1}\right]; \\ P_{em}=\sqrt{3}\cdot\cos\phi\cdot\left(\dfrac{\Phi\cdot f_{w1}\cdot\omega_1\cdot D_1\cdot AS_1\cdot q_1\cdot p\cdot\pi}{0,26\cdot z_1\cdot\left(\dfrac{50}{f_n}\right)}\right). \end{cases} \tag{1}$$

where, υ_j – speed of cooling gas in ventilation channels, m/s; n_{st} – number of jets in the stator core ventilation scheme, pcs; f_n – frequency of electric current in the network, Hz; z_1 – number of stator slots, pcs.; a_1 – number of parallel branches of the stator winding; q_{a1} – number of slots per pole and phase; l_s – stator core length, mm; q_1 – number of slots per pole and phase; fw_1 – winding ratio of the stator winding, a.u.; ω_s – number of consecutive turns of the stator winding in the slots; AS_1 – linear load of the electric machine, A/mm; Φ – magnetic flux per stator pole, Vb; p – number of pairs of poles of an electric machine, pcs.; cos φ – power utilization factor, a.u.

Results

The result of the multiparametric calculation of the stator core geometry is given in Table 1, which shows a comparison of the electric power indicator obtained using multiparametric design and the power indicator from previously completed projects on the development of turbogenerators in Ukraine.

Table 1. *The result of multiparametric calculation of the geometry of the stator core of turbogenerators with a capacity of 100–1100 MW*

№	*Pem*	*Da*	*D₁*	*ls*	**Groove geometry**			**Geometry of ventilation ducts**				*P′em*
					z_1	bn_1	h_1	*dv*	*nv*	bz_1	*Ssv*	
1	**100**	2100	1090	4070	72	26,6	151	10	6	10	–	**98,3**
2	**200**	2515	1275	5000	60	38,6	250	12	10	5	–	**197,6**
3	**300**	2550	1275	4980	30	50,8	183	16	10	5	200	**296,9**
4	**500**	2760	1320	6200	48	37,0	245	20	12	4	210	**496,8**
5	**1100**	3300	1970	6440	60	41,5	239	20	16	4	280	**1095,7**

In addition to table 1, it should be noted that the TG with a capacity of 100 MW has purely hydrogen cooling, and in the remaining TGs the stator winding is cooled with water. From the table it follows that the results of multiparametric design quite qualitatively coincide with the results obtained independently, when designing by the classical iterative method (*P′em*). The percentage of error is from 0.39% to 1.7%. The largest percentage of error corresponds to the TG with a capacity of 100 MW, and the smallest – to the TG 1100 MW. The presence of "–" in the S_{sv} column indicates that the core cooling system does not have a "slit" type ventilation hole.

Based on the results of multiparametric design, a design of an electric machine stator for thermal and nuclear power plants was developed, which has improved characteristics of the pressing indicators of the end packages of the stator core, due to the installation of additional mechanical pressure devices, a patent for a utility model (patent No. 66717) was issued (Patent No. 66717 Ukraine, IPC (2006.01) H02K 1/16 Stator of an electric machine).

In addition, it is necessary to determine the flow rate of the cooling medium, which can be carried out based on the temperature of the medium, with a known value of the electrical losses being removed (Jasper Nonneman, Michel De Paepe, Ruud Sprangers, Ilya T'Jollyn, 2026):

$$Q_{qir} = \frac{P_{loss}}{t_m} \cdot C_P, \qquad (2)$$

where P_{loss} – heat losses, kW; t_m – temperature of the cooling medium, °C; C_p – specific volumetric heat capacity, J/m^3·C.

In electric machines with indirect and direct cooling of the windings, the temperature and flow rate of the cooling medium can differ significantly, for example, electric machines with direct cooling have an increased value of the medium temperature and a lower flow rate. In addition, in the structural parts of powerful electric machines, the flow rate of the cooled medium can be determined by the speed of its flow and the channel of the hydraulic channel:

$$Q_m = \upsilon_m \cdot S_{channel} \qquad (3)$$

where υ_m – the speed of the cooling medium in the channel, m/s; $S_{channel}$ – the channel cross-section, m^2.

In the global practice of designing cooling systems for powerful electric machines, when choosing a cooling medium, it is recommended to use the following provisions (Citation: Wang, Q., Wu, Y., Niu, S., Zhao, X., 2022; Usca-Gomez, H. G., Puma-Benavides, D. S., Zambrano-Leon, V. D., Castillo-Díaz, R., Quinga-Morales, M. I., Solís-Santamaria, J. M., & Llanes-Cedeño, E. A., 2025; Chen, S., Miao, C., Chen, X., Qian, W., & Chu, S., 2025).

1. In electric machines with indirect cooling of the stator and rotor windings, when using an air cooling medium, the value of the temperature heating in the stationary mode of operation of the machine is in the range of 25...30 °C., while it is necessary to take into account the heating of the air in the fan zone, which is 3...6 °C (when using an exhaust ventilation system – heating on the fan is turned off); when using a hydrogen cooling medium (with excess pressure), the value of the temperature heating can be taken as 20...25 °C.

2. In electric machines with indirect cooling of the stator winding and direct cooling of the rotor winding, the cooling agent is hydrogen (at an excess pressure of 0.3 MPa) and the recommended value of the total heating of hydrogen is 15...20 °C, while the heating in the rotor winding is 30...50 °C. Intensification of cooling, in this case, is carried out by increasing the excess pressure of hydrogen.

3. In electric machines with direct cooling of the rotor winding with hydrogen and direct cooling of the stator winding with distilled water, the total heating of hydrogen is 15...20 °C, and the heating of water in the stator winding fluctuates in the range of 15...30 °C.

For preliminary calculations of the flow rate of the medium being cooled, the above recommendations for determining the temperature of the agent (t_m) can be used.

From the expression (3) it follows that the flow rate of the cooling medium also depends on the thermophysical properties of the medium itself, including: specific heat capacity, density, kinematic viscosity, coefficient of volumetric expansion, coefficient of thermal conductivity, etc. The given physical properties are not constant and depend on the temperature and pressure of the cooling medium inside the electric machine.

For working design, it is advisable to use formulas for approximate calculation of the thermophysical properties of the most common agents, obtained by mathematical approximation methods based on experimental studies of the physical characteristics of the cooling medium. The determination of the thermophysical properties of the medium was carried out depending on its temperature (Ching-yu Yang. 2000).

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