Proposals for the Multiparametric Design Application in Electrical Mechanical Engineering

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Abstract. The aim of the work is to obtain practical results for the electrical machines multiparametric design application, to conduct a comparative analysis of the parametric and multiparametric design results of a turbogenerator and its elements when the load changes; to confirm the prospects the multiparametric design application. Currently, it is possible to use mathematical models when designing, and use parametric synthesis to optimize one specific parameter, which in certain cases turns out to be sufficient. The peculiarity of electric machines calculation and design is the necessity of simultaneous checking of all interrelated parameters (mechanical, electromagnetic, thermal) with any changes. The structure design with simultaneous control of several variables cannot be performed using one stage of parametric design; additional calculations are necessary. In this case, multi-parameter design is necessary, but it requires longer preparation for design work and higher qualifications of personnel. Therefore, it is necessary to understand in which cases it is advisable to switch from parametric to multiparametric design. The work goal set is achieved by comparing the results of a turbogenerator, stator core and busbar designing using parametric and multiparametric design. The most important is to obtain the results of comparison of a complex electromechanical system parametric and multiparametric design (turbogenerator, its individual unit and element), including when the parameters of various physical processes change, performing a comparison of the obtained results, confirming the feasibility of carrying out multiparametric design. The significance of the obtained results is that practical examples of the multiparameter modeling use are shown. Using multiparametric design, not only a busbar refined form with increased repair and operational reliability was obtained, but the proposed solution economic advantages were also indicated.
Keywords: turbogenerator, stator core, busbar, parametric and multiparametric design and modeling, electromagnetic, thermal and mechanical factors.

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Propuneri pentru aplicația de proiectare multiparametrică în inginerie electrică mecanică

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Rezumat. Scopul lucrării este de a obține rezultate practice ale utilizării proiectării multiparametrice pentru mașini electrice, de a efectua o analiză comparativă a rezultatelor proiectării parametrice și multiparametrice ale unui turbogenerator și ale elementelor sale individuale atunci când sarcina se modifică, care este însoțită de o modificare. în factori electromagnetici, termici și mecanici; pentru a confirma perspectivele și a determina limitele recomandării de utilizare a proiectării multiparametrice pentru mașini electrice. Prin urmare, este necesar să înțelegem în ce cazuri este recomandabil să treceți de la proiectarea parametrică la proiectarea multiparametrică. Scopul stabilit în lucrare este atins prin crearea de modele pentru sarcini de complexitate diferită (proiectarea unui turbogenerator, a unui miez de stator și a barei colectoare) folosind capabilitățile de proiectare parametrică și multiparametrică cu compararea ulterioară a rezultatelor obținute. Cel mai important lucru este obținerea rezultatelor comparației dintre proiectarea parametrică și multiparametrică compararea unui sistem electromecanic complex (turbogenerator, unitatea și elementul său individual), compararea rezultatelor obținute, confirmarea fezabilității realizării proiectării multiparametrice. Semnificația rezultatelor obținute este că sunt prezentate exemple practice de creare a unor modele multi-parametrice ale unui turbogenerator, miez de stator și un element separat (bară transportoare de curent). Folosind proiectarea multiparametrică, s-a obținut nu numai o formă rafinată a barei colectoare cu reparații și fiabilitate operațională sporite, ci au fost indicate și avantajele economice ale soluției propuse.
Cuvinte-cheie: turbogenerator, miez de stator, bare colectoare, proiectare si modelare parametrica si poliparametrica, factori electromagnetici, termici si mecanici.

Предложения по применению мультипараметрического проектирования в электромашиностроении

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Аннотация. Целью работы является получение практических результатов использования мультипараметрического проектирования для электрических машин, проведение сравнительного анализа результатов параметрического и мультипараметрического проектирования турбогенератора и его отдельных элементов при изменении нагрузки, что сопровождается изменением электромагнитных, тепловых и механических факторов; подтверждение перспективности и определение границ рекомендации использования мультипараметрического проектирования для электрических машин. Современное компьютерное обеспечение и разработанные программы сделали возможным на этапе проектирования создавать и использовать существующие математические модели, параметрический синтез для оптимизации одного конкретного параметра, что, в определённых случаях, является достаточным. Но особенностью расчета и проектирования электрических машин является необходимость одновременной проверки всех взаимосвязанных показателей (механических, электромагнитных и тепловых) при любых конструктивных изменениях. Проектирование будущей конструкции с изменениями и одновременным контролем нескольких переменных (регулируемых или нерегулируемых) не удается выполнить, используя один этап параметрического проектирования; необходимы дополнительные расчеты. В таком случае можно рекомендовать мультипараметрическое проектирование, что требует более длительной подготовки к проведению проектных работ, более мощного компьютерного обеспечения и более высокого уровня персонала. Поэтому необходимо понимать в каких случаях целесообразен переход от параметрического к мультипараметрическому проектированию. Поставленная в работе цель достигается созданием моделей для задач разной сложности (проектирование турбогенератора, сердечника статора и токопроводящей шины) с использованием возможностей параметрического и мультипараметрического проектирования с последующим сравнением полученных результатов. Наиболее важным является получение результатов сравнения параметрического и мультипараметрического проектирования сложной электромеханической системы (турбогенератора, его отдельного узла и элемента) в том числе, когда изменяются параметры различных физических процессов, выполнение сравнения полученных результатов, подтверждение целесообразности проведения именно мультипараметрического проектирования. Значимость полученных результатов состоит в том, что показаны практические примеры создания мультипараметрических моделей турбогенератора, сердечника статора и отдельного элемента (токопроводящей шины). С использованием мультипараметрического проектирования получена не только уточненная форма токоведущей шины с повышенной ремонтно-эксплуатационной надежностью, но указаны экономические преимущества предлагаемого решения.
Ключевые слова: турбогенератор, сердечник статора, токопроводящая шина, параметрическое и поли-параметрическое проектирование и моделирование, электромагнитные, тепловые и механические факторы.

INTRODUCTION

Currently, when designing new electrical equipment, the method of parametric modeling and design is usually used, which allows to significantly speed up the execution of design and pre-design work, compare different options, create new designs with better technical and economic indicators, and eliminate random errors in calculations and design that may appear due to the "human factor".

To carry out parametric modeling and design, various software environments are used (ANSYA, COMSOL Multiphysics, SolidWorks, MATLAB, T-FLEX CAD, CATIA, Autodesk, Altium Designer, OrCAD, etc.). Almost all of the listed programs use the finite element method and allow the creation of three-dimensional models with subsequent semi-automatic creation of two-dimensional models for the manufacture of parts and equipment units [1, 2].

It is also possible to perform dynamic calculations of parts in a stress-strain state, visualization and dynamics of changes in the structure as a whole, which allows one to choose the best design solution. By setting different conditions and entering different initial data, it is possible to search for the best solutions, accumulate statistical material, identify dependencies and patterns, and determine the directions of design. The mathematical apparatus of these programs is sufficient for almost all areas of technical design, including electrical mechanical engineering.

Parametric modeling can be divided into two types: 2D drawings/modeling and 3D modeling. In these cases, some, and sometimes several types of parameterizations are implemented simultaneously: tabular parameterization; hierarchical parameterization – parameterization based on the history of constructions and decisions taken); variational (or dimensional) parameterization; geometric parameterization (parametric modeling, in which the geometry of each object is recalculated depending on its position, parameters, variables and functions), [3, 4]. Parameterization has long been widely used in various industries: in the energy sector [1, 3-5], in construction [6–12], in the creation of measuring equipment [13–17], even in agriculture [18].

Traditional computer-aided design (CAD) techniques are "parametric," meaning that when designing a new product, one specific parameter can be changed depending on the task at hand: shape, size, etc. Even when using hybrid parametric modeling methods, it is possible to work only with parameters of the same type: for example, flat surfaces, surfaces of revolution, sections, etc.

This is not enough for complex equipment, such as electrical machines, in which every design change affects many parameters: thermal, mechanical and electromagnetic. Table 1 presents a list of parametric programs that are currently used in various industries.

Table 1

List of modern computer programs used in industry for parametric design

No	The program name	Parametric design implementation tools
1	ANSYS	– numerical calculation methods; – tabular parameterization; – hierarchical parameterization; – variational (dimensional) parameterization.
2	COMSOL Multiphysics	– numerical calculation methods; – tabular parameterization; – variational (dimensional) parameterization; – geometric parameterization.
3	T-Flex	
4	SolidWorks	
5	Creo Parametric	
6	KOMPAS 3D	– tabular parameterization; – geometric parameterization.
7	MATLAB	– numerical calculation methods; – tabular parameterization; – variational (dimensional) parameterization
8	FEMM	– numerical calculation methods; – tabular parameterization.

Currently, when designing electromechanical equipment (electric motors, generators), parametric synthesis and parametric optimization are quite widely and successfully used to solve certain issues:

- optimization of the traction and general industrial asynchronous motors tooth zone [19-25];
- determination of geometric dimensions and characteristics of special designs synchronous machines with excitation from permanent magnets [27-34];
- determination of turbogenerators some characteristics in special modes [13, 24, 35, 36-38].

A special feature of the electrical machines design, which must be taken into account in any design changes, is the deep connection of all parameters, characteristics and indicators: electromagnetic, mechanical and thermal.

It is also necessary to take into account the economic and environmental requirements for the new design. This significantly complicates the use of parametric design, requires additional calculations, and reduces the reliability of the results obtained. As a result, with each design change it is necessary to evaluate the possible range of changes in physical parameters and, most important, highly qualified designers are needed who can predict and foresee potential changes and take into account their mutual relationship.

This complicates the design, extends the time frame for implementing changes to the design, limits the number of options under consideration, and the ability (and desire) to seek better design solutions. For example, when modeling a new turbogenerator design with changing electromagnetic loads using the FEMM program, we obtain a new two-dimensional distribution of magnetic fields, [19]. But there is no information about changes in the thermal and mechanical state of the unit being modernized. It is necessary to make additional calculations each time.

Therefore, to design a new electrical machine, taking into account the possible change of several variables (regulated or unregulated), it is necessary to use multi-parameter design, which differs from conventional parametric design precisely by the ability to simultaneously analyze several parameters, taking into account their mutual influence [1, 4]. But multiparametric modeling requires more complex models, longer preparation times for design, and higher levels of personnel.

Therefore, simply establishing the feasibility of using multiparametric design for electrical machines is not enough. It is necessary to understand in which cases the transition from parametric design to multiparametric design is appropriate, and in which cases the use of parametric models is sufficient.

Purpose of the work: to conduct a comparative analysis of a turbogenerator the parametric and multiparametric design results, its individual unit and part (using the example of a stator core and a conductive busbar that connects the turbogenerator to a block transformer) when the electromagnetic load changes.

METHODS, RESULTS AND DISCUSSION

For the multiparametric design of a three-phase synchronous turbogenerator (TG), as the initial parameters and basic indicators of the model, we select the total power (P_S) and current density (j_S) in the stator winding:

$$j_s = \sqrt{\frac{\gamma \cdot C_p \cdot V_B \cdot \frac{q_k}{q_{cs}}}{l \cdot K_f}}, \qquad (1)$$

where γ – is the copper electrical conductivity, m/(Ohm mm^2);
C_p – is the copper specific heat capacity, (kW s)/(dm^3 °C);
V_B – is the speed of the cooling medium (hydrogen, water) movement in the hollow conductors of the stator winding (direct cooling), m/s;
l – is the length of the stator winding rod cooled section (part in groove), m;
q_k/q_{cs} – ratio of the cross-section of the cooling channels in the stator winding to the cross-section of copper in the stator winding, r.u.;
K_f – is the current displacement coefficient, which takes into account the saturation of the core magnetic circuit, r.u.

A mathematical model for carrying out multiparametric design of a turbogenerator can be defined as a multicomponent dependence:

$$P_S = f(U_N, a_s, a_{as}, j_s),$$

where U_N – is the stator winding rated linear voltage, V;

a_s – is the number of the stator winding parallel branches;

q_{as} – is the copper cross-section of the stator winding effective conductor, mm^2.

Moreover, each component can be represented by a dependent and independent function (adjustable or non-adjustable parameter).

Using (1), we write the turbogenerator active power value, kW:

$$P_S = \sqrt{3} \cdot U_N \cdot a_s \cdot a_{as} \cdot \sqrt{\frac{\gamma \cdot C_p \cdot V_B \cdot \frac{q_k}{q_{cs}}}{l \cdot K_f}} \cdot 10^{-3}.$$

The number and values of modeling components are determined by the requirements (constraints) of the future turbogenerator design. At the same time, we use the data and recommendations available from the manufacturer. So, the permissible current density in the stator winding largely depends on the turbogenerator cooling system: with indirect cooling of the stator winding, the current density is in the range of 3-4 A/mm^2; with direct cooling (channels through which hydrogen or water moves are laid into the grooves of the stator core)– the current density 6-11 A/mm^2 [13, 28].

For successful modeling it is necessary to know the data of the elements that are heat sources, i.e., the elements in which losses are released. Mechanical losses are constant losses, they depend only on the rotor speed, which does not change in almost any mode, and they can be taken into account separately.

The main sources of heat (losses) are the windings and the stator steel core. The value of these losses depends on the load value and the generator operating mode. It is also necessary to know the heat transfer coefficients of these materials and the cooling medium (air, water or hydrogen). For turbogenerator TGV-300-2U3 (data from the Electrotyazhmash plant, Kharkov, Ukraine):

- Q_{Fes}=100 W – is the magnetic losses in the stator core (per 1 package segment);
- $Q_{el_S} = 2650\ W$ – are the losses in the stator winding, which is located in the grooves of one segment;
- $\alpha_{H_2O} = 560$ – is the heat transfer coefficient of water during convective heat exchange through a metal wall and laminar flow, kW/(m^2 K);
- $\alpha_{H_2} = 55$ – is the heat transfer coefficient of hydrogen at a pressure of 1.1 atm (~111430 Pa), at a temperature of 100 °C (insulation heat resistance class *F*), kW/(m^2 K).

For a given value of the stator core outer diameter, we usually select the maximum possible number of slots (z_S).

Then $P_S = f(z_S)$ will be an independent function. The dependence $P_S = f(U_N)$ is also an independent function, because the voltage is determined by the connection diagram of the turbogenerator to the electrical network and its parameters [4].

The structural model for multiparameter modeling and design of a turbogenerator is shown in Fig. 1, (U_f – is the stator winding phase voltage, V).

When creating a turbogenerator multiparametric model, data on the geometry of the slots, the type of stator winding and the cooling system are used.

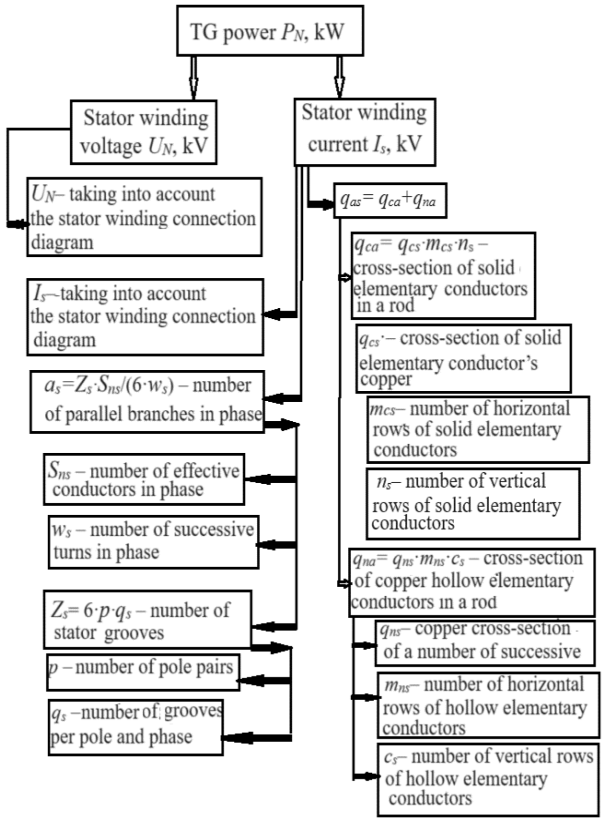
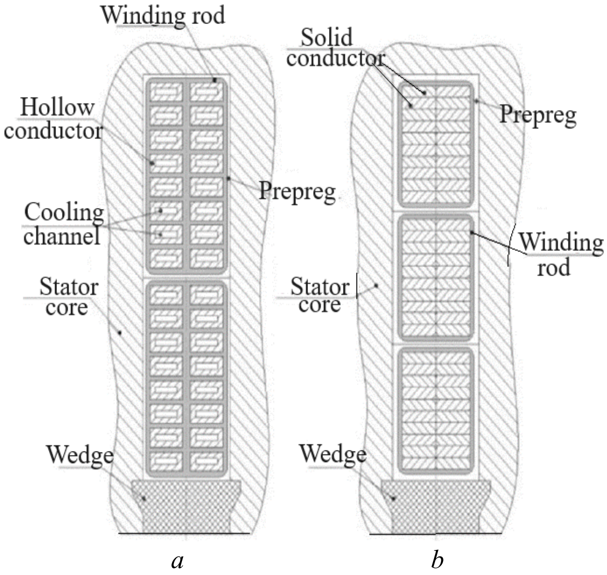


Fig. 1. Structural model for multiparametric design of three-phase turbogenerator

Fig. 2 shows stator grooves sketches with the winding. At the Fig. 2, *a* is a two-rod winding with direct hydrogen cooling and in Fig. 2, *b* is a three-rod winding with indirect cooling. Of all the turbogenerator parts and elements, the most loaded is the stator core. Its design is the most complex multicriteria task.

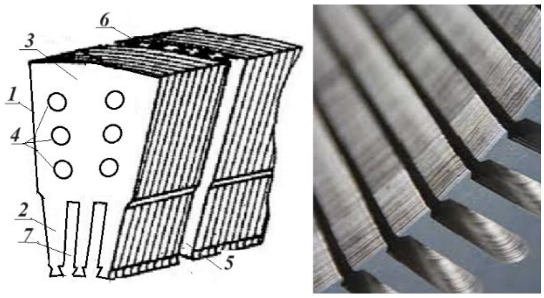
The stator core design is determined by the permissible values of the adjustable parameters: current density in the stator winding, stator winding nominal voltage, the turbogenerator nominal power, and depends on the non-adjustable parameters: on the cooling medium thermophysical properties (air, hydrogen, water), on the electrical properties of insulating materials, the magnetic circuit electromagnetic properties and the characteristics of the stator winding copper.



a – two-rod stator winding with direct cooling;
b – three-rod stator winding with indirect cooling

Fig. 2. Stator grooves sketches with the winding

The stator core consists of laminated packages pressed into the stator housing. Therefore, for its modeling and design, it is enough to determine the design of one core segment, Fig. 3.



1 – Stator core segment. 2 – Stator core tooth with slots for fastening the stator winding with wedges. 3 – Stator core back. 4 – Axial ventilation channels in the core back. 5 – Radial ventilation channels that separate the core segments. 6 – Spacers that provide the radial ventilation system. 7 – Stator core slot

Fig. 3. Segment of a laminated turbogenerator stator core

To create the stator segment multiparametric model we set by the turbogenerator power values and the values of stator winding current density; we select the direct cooling medium for the stator winding – hydrogen, the segment material – steel M250-50A (according to European Standard EN 10106-2016), the stator winding material – wire

PSD-1 according to TU 302.08.003, the insulation class for heat resistance is *F*.

For modeling, we use the values of the stator core outer and inner diameters, the groove depths, the number of grooves and stator winding parallel branches according to the manufacturer's data.

We build the stator core segment multiparametric model, taking into account the turbogenerator power and its thermal loads $P_S=f(\alpha_K, \alpha_S)$ where α_K – specific heat transfer coefficient, which takes into account heat transfer in the stator core segment tooth part, W/(°C mm^2); α_S – is the specific heat transfer coefficient in the back of the stator core, W/(°C mm^2).

$$\alpha_K = \frac{1+0.25\cdot V_K}{450}\cdot 1.3\cdot p_N^{0.8}, \quad (3)$$

where p_N – is the excess pressure of cooling gas (hydrogen), Pa;

V_K – is the cooling medium movement speed through the axial channels in the stator core tooths, m/s:

$$V_K = \frac{L\cdot 10^6}{\left(\frac{k_s}{2\cdot k_s - 1}\right)\cdot n_{rs}\cdot b_{rs}\left[\pi\cdot(D_S + h_{ns}) - Z_s\cdot b_{ns}\right]}, \quad (4)$$

where L – is the gas consumption in ventilation ducts, m^3.

We assume that the stator winding is cooled directly and the cooling medium is hydrogen. According to the standard data for the turbogenerators of the series under consideration, we use the standard performance of the built-in gas coolers in the housing of the TGV series turbogenerator;

k_s – is the gas jets number in the stator core cooling system;

n_{rs} – are the stator ventilation ducts number in the cooling system;

b_{rs} – is the width (diameter) of stator ventilation ducts, mm;

D_S – is the stator core internal diameter, mm;

h_{ns} – is the stator groove depth, mm;

b_{ns} – stator groove width, mm;

Z_S – is the stator grooves number.

Using (3) and (4), we obtain a multiparametric indicator of the stator core segment tooth zone heat transfer, which also depends on the electromagnetic characteristics of the TG:

$$\alpha_k = 1 + 0.25\cdot\left(\frac{L\cdot 10^6}{\left(\frac{k_s}{2\cdot k_s - 1}\right)\cdot n_{rs}\cdot b_{rs}\left[\pi\cdot(D_S + h_{ns}) - Q_K\cdot b_{ns}\right]}\right)\cdot\frac{1.3\cdot p_N^{0.8}}{450}; \quad (5)$$

where:

$$Q_K = \frac{6\cdot w_s\cdot P_{SN}\cdot b_{ns}\cdot 10^2}{\sqrt{3}\cdot U_N\cdot S_{ns}\cdot j_s\cdot q_{as}},$$

w_s – is the number of successive turns in phase;

P_{sN} – is the TG rated power, kW;

U_N – is the rated line voltage, V;

S_{ns} – is the effective number of conductors in the slot;

j_s – is the stator winding current density, A/mm^2;

q_{as} – is the copper cross-section of the stator winding effective conductor, mm^2.

Similarly, we determine the heat transfer coefficient of the stator core back, W/(°C mm^2):

$$\alpha_s = \frac{1+0.25\cdot V_s}{450}\cdot 1.3\cdot p_N^{0.8}, \quad (6)$$

where V_S – is the gas speed in the axial ventilation channel in the stator core back, m/s.

Then:

$$V_S = \frac{L\cdot 10^6}{\left(\frac{k_s}{2\cdot k_s - 1}\right)\cdot n_{rs}\cdot b_{rs}\cdot\pi\cdot(D_a + h_{as})},$$

D_a – is the stator core outer diameter, mm;

h_{as} – is the stator core back height, mm.

l_{ws} – is the stator winding turn length, mm;

L – is the stator core length, mm;

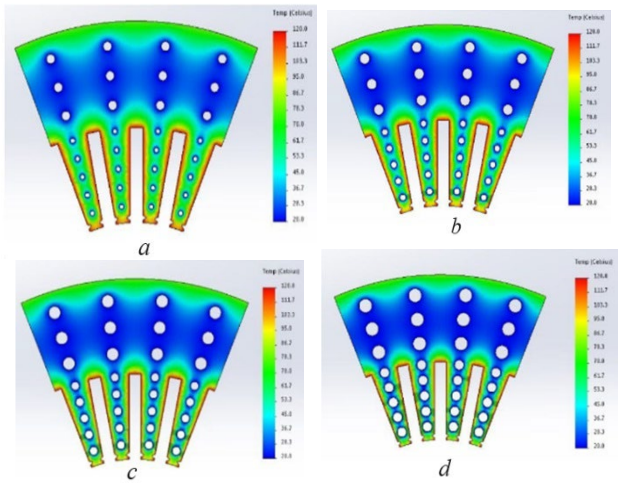
q_S – are the stator core slots number per pole and phase.

$$\alpha_S = 1 + 0.25 \cdot \left(\frac{L \cdot 10^6}{\left(\frac{k_s}{2 \cdot k_s - 1} \right) \cdot n_{rs} \cdot b_{rs} \cdot \pi \cdot Q_S} \right) \cdot \frac{1.3 \cdot p_N^{0.8}}{450}, \tag{7}$$

where:

$$Q_S = 0.2 \cdot \left(\frac{6 \cdot w_s \cdot P_{SN} \cdot 10^2}{\sqrt{3} \cdot U_N \cdot S_{ns} \cdot j_s \cdot q_{as} \cdot q_s} \right) + 2 \cdot h_{ns} + h_{as};$$

As a multiparametric modeling result, using (3) and (6), we obtained the stator segment geometry and determined the diameters of the axial ventilation channels, which can be recommended for turbogenerators of different powers (120 MW, 200 MW, 300 MW and 500 MW) provided that acceptable thermal characteristics for the selected heat resistance class of stator winding insulation (*F*) at rated load (Fig. 4).



a – 120 MW; *b* – 200 MW;
c – 300 MW; *d* – 500 MW.

Fig. 4. Temperature distribution in the turbogenerator stator core segment at different power values

Permissible temperatures in the core are ensured by changing the axial ventilation channels diameters. From Fig. 4 it can be seen that, thanks to the requirements laid down in the multiparametric model, recommended values for the axial ventilation channels diameters were obtained for various power values, that provide permissible temperature loads. A visual analysis of the recommendations received suggests the need to change the shape of the cooling channels in the turbogenerator stator tooth zone with a power of 500 MW, (Fig. 4, *d*).

To ensure the mechanical reliability of the toothed zone of a turbogenerator core with a power of 500 MW, it can be proposed to switch to cooling channels of the “notch” type. The proposed arrangement of channels of the “notch” type is vertical, along the tooth, maintaining the obtained value of the ventilation duct cross-sectional area, Fig. 5.

It is the easiest and fastest, i.e., expedient, to carry out multiparametric design for turbogenerator individual elements, for which the preparation of a design model is simple.

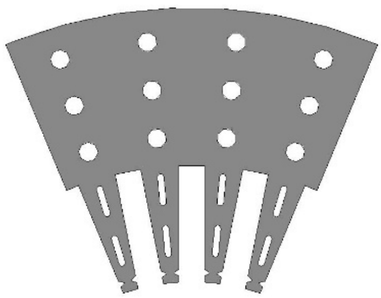


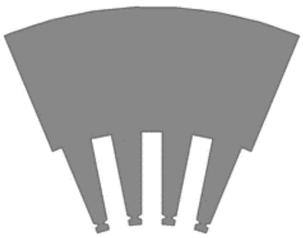
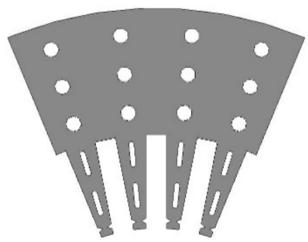
Fig. 5. Ventilation duct of the “notch” type, located along the tooth of the stator core

For example, let us consider and compare the results of parametric and multiparametric design of a turbogenerator busbar in the SolidWorks environment using the finite element method to specify the geometry of the busbar, the number and diameters of the holes for the connecting bolts. This will reduce the weight and dimensions of the busbar, and save materials for its manufacture.

To compare the results of modeling the stator segment using parametric multiparametric methods, we will compile Table 2.

Table 2

Comparison of calculation results using parametric and multiparametric modeling using the example of a separate turbogenerator unit (stator segment)

Characteristics of the indicator	Objective function	
	parametric modeling $P_s = f(S)$	the multiparametric modeling $P_s = f(S, \alpha)$
Is it possible to design with changes in other parameters (temperature, change in the materials from which the element is made, etc.)?	No	Yes. For example, it is possible to take into account the values of α_K and α_S in the objective function, which depend on the TG operating mode $P_s = f(S; \alpha_K; \alpha_S)$
Is it possible to automate the design of a part with complex geometry?	No	Yes
Do you need development of additional software, mathematical models and algorithms?	No	Yes
Are design work deadlines being reduced?	No	Yes, provided that there are calculation models, algorithms, etc.
The simulation result of the element that was chosen for the example (stator core segment)		

The ability of the electric machine magnetic core to operate with a nominal electromagnetic load with a sufficient level of cooling (heat removal) was taken as a sign of the results optimality of design and engineering work during the stator core segment development.

Connecting the busbar to the transformer and distribution board is the most important and labor-intensive process in the installation of the busbar.

This process that requires high precision, is carried out in a confined space and is carried out almost entirely by hand.

Transformer terminals have rather fragile insulators, therefore, when installing copper insulated busbars to the transformer terminals, a flexible bend of the busbar is usually provided, which dampens the vibration effects. It is recommended to connect the busbar and transformer with a flexible busbar to avoid an accident on the power line.

Flexible buses:

- dampen vibrations in the transformer terminals, which reduces the likelihood of damage to the contact connection;
- compensate for the difference in changes in the size of the transformer and busbar terminals during heating and cooling;
- allow you to compensate for technological inaccuracies in assembly (misalignment of the transformer and busbar terminals).

Reducing the cross-section and weight of a conductive busbar assembled from copper plates, which are connected with silver inserts, is economically feasible, since it reduces the consumption of copper and silver. A general view of the turbogenerator current-carrying busbar used in TGV series turbogenerators is shown in Fig. 6, where: l – is the busbar length, mm; h – is the busbar width, mm; b – is the busbar thickness, mm; d – is the diameter of the hole for connecting bolts, mm; n – is the number of holes.

To determine the best current-carrying busbar geometry, taking into account the turbogenerator power and its thermal loads, we will build a multiparametric model $j_s = f(S)$, where j_s – current density; S – area of the busbar middle section, mm^2, provided that the load is a constant value ($I_s = \text{const}$ – is the stator winding current).

In parametric and multiparametric design, the same goal was set: to determine the minimum permissible cross-sectional area of the current-carrying busbar for a given value of the electric current passing through the current-carrying busbar in the turbogenerator nominal operating mode; compare the results of two design options.

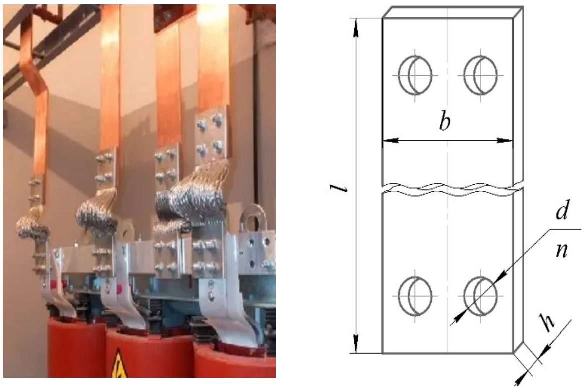


Fig. 6. Sketch of the TG current-carrying busbar, which is an element of the study

Let us write the magnetic field circulation equation (Maxwell's equation):

$$\mathrm{rot}H_m = j_s + \frac{\partial D_{el}}{\partial t}, \tag{8}$$

where H – is the magnetic field strength A/mm; j_S – is the electric current density in the busbar, A/mm^2; D_{el} – is the electrical induction, C/m^2.

In integral form we can write:

$$\oint \overrightarrow{H_m} \cdot d\vec{l} = I + \frac{\partial D_{el}}{\partial t} \cdot \int_S D_{el} \cdot dS. \tag{9}$$

The current density j_S, shape and cross-sectional area S are known, i.e., the value of the magnetic field is also known.

Let us apply the divergence operation to equation (6) and, taking into account Hooke's law, write the continuity equation for charge and current:

$$\oint_S j \cdot dS = -\frac{d}{dt} \cdot \int_V \rho \cdot dV, \tag{10}$$

where ρ – is the volume density of extraneous electric charge, C/mm^3; V – is the volume of current-carrying busbar, mm^3:

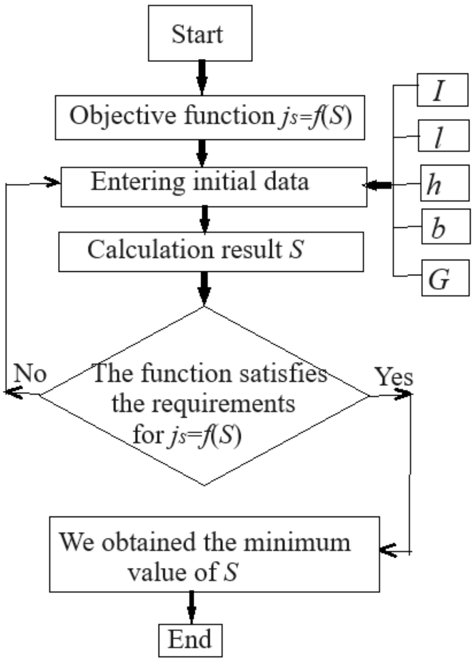
$$V = b \cdot h \cdot l,$$

S – is the current-carrying busbar cross-sectional area, mm^2. The cross-sectional area of a busbar that has been in operation for a long time must be determined from (10) due to the fact that the busbar will have defects: chips, tears, etc.

The right side of equation (10) shows the change in charge with time, which is located in volume V. When designing, we assume that the current-carrying busbar is new and has a rectangular shape in all planes. The area is determined only by the current I, which flows through the bus section S, and the given value of the current density j_S:

$$S = \frac{I}{j_s} = b \cdot h. \tag{11}$$

Fig. 7 shows an algorithm for determining the turbogenerator current-carrying busbar geometric parameters, subject to obtaining minimum dimensions and weight.



j_S – current density, A/mm^2; S – busbar cross-sectional area, mm^2; I – electric current, A; l – tire length, mm; b – busbar width, mm; h – busbar thickness, mm; G – the busbar material electrical conductivity, Ohm^{-1}

Fig. 7. Algorithm for parametric design of a current-carrying busbar

To assess mechanical reliability, we take into account the change in the electromechanical force N, which arises due to a change in the electromagnetic field when the generator operating current (load) changes. This force depends on the busbar mass and on the location where it is secured to the turbogenerator stator winding.

Let us decompose the force N into three axes – q_x, q_y and q_z, Fig. 8.

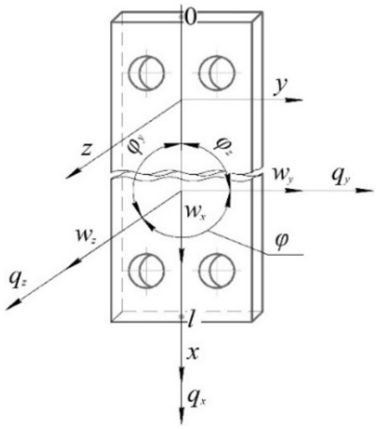


Fig. 8. Directions of electromechanical forces action along three axes

Possible movements of the busbar along the x, y, z axes from the action of this force N will be denoted by – w_x, w_y and w_z, and the angles of rotation of the busbar cross sections around the x, y, z axes – φ_x, φ_y, and φ_z, respectively.

The busbar cross sections rotation angles depend on the linear movements:

$$\varphi_y = \frac{dw_z}{dx}; \quad \varphi_z = \frac{dw_y}{dx}. \qquad (12)$$

The resulting deformation of the current-carrying busbar ε, the relative twist angle χ and the permissible curvature indices k_y and k_z depend on the linear displacements (w_x, w_y and w_z) under the action of the electromechanical force N:

$$\begin{gathered} \varepsilon = \frac{dw_x}{dx}; \quad \chi = \frac{d\varphi}{dx}; \\ k_y = -\frac{d^2 \cdot w_z}{dx^2}; \quad k_z = -\frac{d^2 \cdot w_z}{dx^2}. \end{gathered} \qquad (13)$$

Electromechanical force N, torque M and bending moments M_y and M_z (internal force factors are given to the busbar section center of mass) are equal to:

$$\begin{aligned} N &= E \cdot S \cdot (\varepsilon - \alpha \cdot t); \\ M &= K \cdot \chi; \\ M_y &= E \cdot i_y \cdot k_y; \\ M_z &= E \cdot i_z \cdot k_z; \end{aligned} \qquad (14)$$

where E – is the current-carrying busbar material elastic modulus, MPa; α – is the linear expansion temperature coefficient, 1/°C; t – is the current-carrying busbar temperature in the TG nominal operating mode, °C; K – is the current-carrying busbar stiffness coefficient when twisting it; reference value, which depends on the busbar material, N/m; i_y and i_z– are the busbar cross section moments of inertia, relative to the y and z axes, kg m^2.

Let us assume that the specific load q_x, q_y and q_z, the load from the busbar mass m, from the transverse forces Q_y, Q_z action on the current-carrying busbar act uniformly along its axes. Using Hooke's law, we write the busbar equilibrium equations:

$$\begin{cases} \dfrac{dN}{dx} + q_x = 0; & \dfrac{dM}{dx} + m = 0; \\ \dfrac{dQ_y}{dx} + q_y = 0; & \dfrac{dM_z}{dx} - Q_y = 0; \\ \dfrac{dQ_z}{dx} + q_z = 0; & \dfrac{dM_y}{dx} - Q_y = 0. \end{cases} \qquad (15)$$

Taking into account (13) and (14), system (15) can be represented:

$$\begin{gathered} \frac{d^2 w_x}{dx^2} = -\frac{q_x}{E \cdot S}; \quad \frac{d^2 \varphi}{d\varphi^2} = -\frac{m}{K}; \\ \frac{d^4 w_y}{dx^4} = \frac{q_y}{E \cdot i_z}; \quad \frac{d^4 w_z}{dx^4} = \frac{q_z}{E \cdot i_y}. \end{gathered} \qquad (16)$$

For a constant value of external loads along the current-carrying busbar length, we integrate equations (16) and obtain the following solution:

$$\begin{cases} w_x = A_1 \cdot x + A_2 - \dfrac{q_x \cdot x^2}{2 \cdot E \cdot S}; \\ w_y = C_1 \cdot \dfrac{x^3}{6} + C_2 \cdot \dfrac{x^2}{2} + C_3 \cdot x + C_4 + \dfrac{q_y \cdot x^4}{22 \cdot E \cdot i_z}; \\ w_z = D_1 \cdot \dfrac{x^3}{6} + D_2 \cdot \dfrac{x^2}{2} + D_3 \cdot x + D_4 + \dfrac{q_z \cdot x^4}{22 \cdot E \cdot i_y}. \end{cases}$$

$$\varphi = B_1 \cdot x + B_2 - \frac{m \cdot x^2}{2K}.$$

The integration constants A_i, B_i, C_i and D_i, are found from the boundary conditions at the busbars ends. For a busbar with a given length l, let us denote the offset of the busbar beginning as w_l; and the end of the busbar – w_0:

$$N = \frac{E \cdot S}{l} \cdot (w_l - w_0) \cdot \frac{x}{l} + \frac{q_x \cdot l^2}{2E \cdot S} \cdot \frac{x}{l} \cdot \left(1 - \frac{x}{l}\right). \quad (17)$$

According to data from the TG manufacturer (plant "Elektrotyazhmash", Kharkov, Ukraine), we use the ratios of the busbar's geometric parameters:

$$\begin{cases} b_1 = 5 \cdot d + [(n-1) \cdot 3.5 \cdot d], \\ l_h = 5 \cdot d. \end{cases} \quad (18)$$

where b_1 – is the current-carrying busbar width at the points of the stator winding connection to the block transformer terminals (beginning and end), mm; l_h – is the minimum permissible distance between the bolt holes centers to the busbar edge, mm.

Using (9) and (16), we will create an algorithm for a busbar multiparametric design for different operating modes (loads) in order to minimize its mass and metal consumption according to pre-established conditions for maintaining mechanical reliability, Fig. 9.

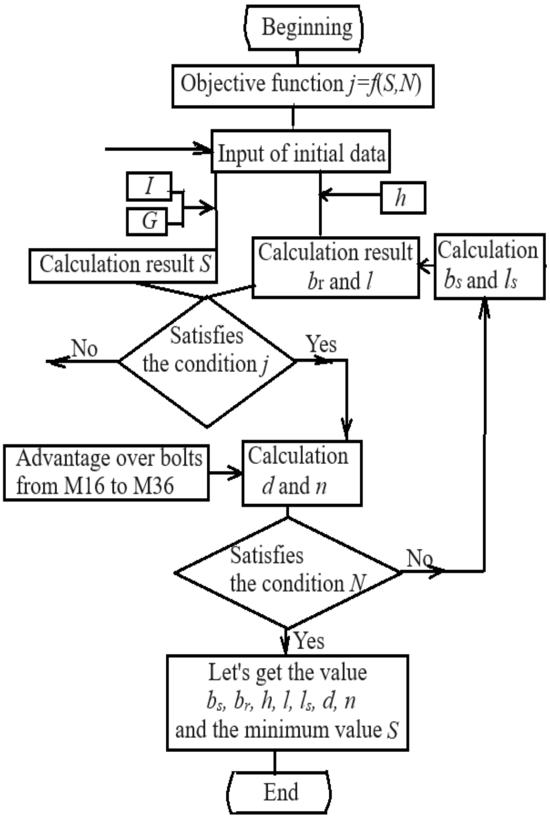


Fig. 9. Algorithm for implementing multiparametric design, using the example of a current-carrying busbar

When solving the problem, we considered load variation (current variation) in the range from 1000 to 6000 A. We also adopted the following data:

- permissible current density in the busbar 2.8 A/mm^2 (busbar air cooling);
- busbar material – copper grade M1 according to DSTU EN 13601-2010;
- busbar thickness $h = 6$ mm;
- number of holes across the busbar width equal $n = 2$;
- hole diameter $d = 18$ mm (for M16 connecting bolts);
- total busbar length $l = 450$ mm;
- the current-carrying busbar width in the central part $h_2 = 120$ mm; and width in the tail part $h_1 = 135$ mm;
- height of the busbar tail part $l_h = 90$ mm;
- the busbar cross-sectional area (along the central part) $S = 720$ mm^2.

The task of a current-carrying busbar multiparametric design was solved in the Object Pascal language.

The results of calculating the busbar geometry with a thickness of $h = 6$ mm when the load changes while reducing weight and size parameters and ensuring mechanical reliability are shown in Fig. 10 and in Table 3.

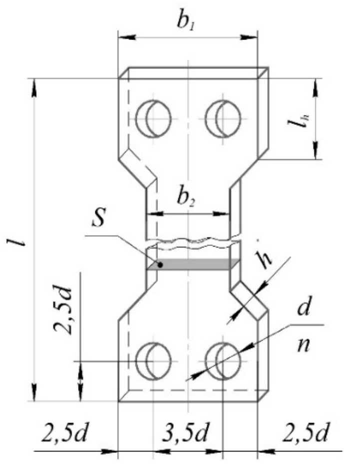


Fig. 10. The current-carrying busbar geometry, which was obtained from the results of multiparametric modeling

In Fig. 10 accepted designations:

b_1 – width of the tail part current-carrying busbar, mm;

b_2 – width of the current-carrying busbar main part, mm;

h – current-carrying busbar thickness, mm;

Table 3

Results of poly-parametric modeling of a conductive busbar with a thickness of $h = 6$ mm

Current strength, A	Cross-sectional area of the busbar (over the main part) S, mm^2		Width of the main part conductor busbar b_2, mm		Width of the tail section conductive busbar b_1, mm	Number of holes (for M16 bolt)
	calculation	accepted	calculation	accepted		
1000	357,14	360	59,52	60	90	1
2000	714,29	720	119,05	120	135	2
3000	1071,43	1080	178,57	180	180	3
4000	1428,57	1440	238,10	240	270	5
5000	1785,71	1800	297,62	300	315	6
6000	2142,86	2160	357,14	360	360	7

d – diameter of the hole for fastening bolts, mm;

n – number of holes;

l – current-carrying busbar length, mm.

A comparison of the calculation results for parametric and multiparametric design of the turbogenerator current-carrying busbar is shown in Fig. 11 and in Table 4.

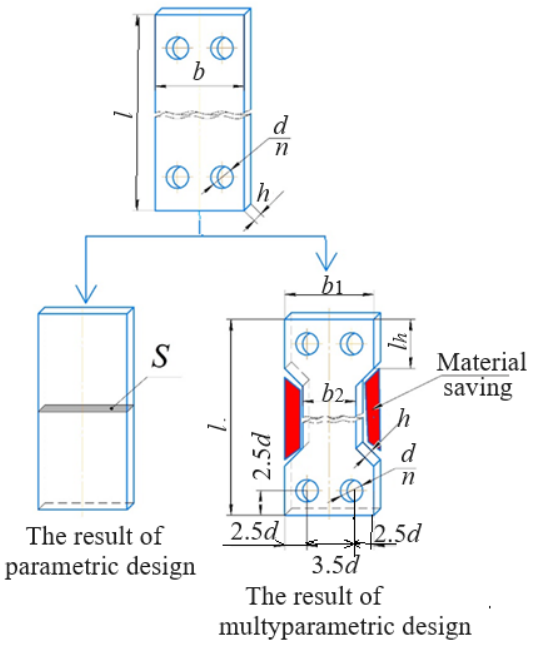


Fig. 11. Comparative results of a turbogenerator busbar parametric and multiparametric modeling in order to select the required section *S*

Conclusions

1. Parametric design is sufficient when it is necessary to analyze the change of one parameter (for example, electromagnetic load); and when there is no need to know the changes of other parameters (thermal and mechanical). When it is necessary to know and control such changes, additional calculations are carried out, which increases the design time and the accuracy design and calculation work, leading to the accumulation of inaccuracies.

2. The use of multiparametric design when it is necessary to control possible changes in several variables (electromagnetic, thermal and mechanical indicators), while simultaneously taking into account the mutual influence of each parameter change on other indicators with the establishment of restrictions for each parameter allows for a comparison of different options, facilitates the selection of the best solution, reduces the time of pre-design and design work for the new design of an electric machine (turbogenerator) development and reduces the time of its transfer to production. Similar results will be obtained when upgrading operating equipment; for example, when replacing the cooling of the internal volume of a turbogenerator with hydrogen for air.

3. The use of combinations of existing methods of multiparametric design and the development of private mathematical models for a single unit (or machine) allows for a significant improvement in the quality of the project being developed and a significant reduction in the time required for subsequent optimization and modernization of the electrical machine design.

4. The results of the stator core segment multiparametric design are shown with a change in the turbogenerator power, i.e., with a change in its thermal state and mechanical loads on individual elements. Without additional calculations, proposals were received on how, depending on the turbogenerator power, i.e., the value of the total current in the stator core slot, the geometric parameters of the core should be changed: the shape and dimensions of the slots and axial cooling

channels, the outer and inner diameters of the stator core.

Table 4

Comparison of the calculations results using parametric and multiparametric design on the turbogenerator separate node (current-conducting busbar) example

Index	parametric designing	multiparametric designing
Design goal: to minimize the parameter (busbar cross-section S)		
Objective function:	$j_s=f(S)$	$j_s=f(S,N)$
Is it possible to design with changes in other parameters (temperature; change in materials from which the element is made, etc.)?	No	Yes/ For example, in the objective function, take into account the temperature value t, which is determined by the load (TG operating mode) $j_s=f(S,N,t)$
Is it possible to automate the design of a part with complex geometry?	No	Yes
Do you need the development of additional software, mathematical models or algorithms?	No	Yes (after development of additional calculation models, algorithms, etc.), we need it
Are design work deadlines being reduced?	No	Yes (after development of additional calculation models, algorithms, etc.)

It is possible to change another indicator as an adjustable parameter, for example, a change in thermal characteristics. In this case, it is possible to simultaneously obtain the results of changes in geometric parameters, electromagnetic and mechanical characteristics at the specified limit values of these indicators.

5. Based on the conducted analysis of the prospects of using multiparametric design in the creation of electrical machines, it can be concluded that multiparametric design is necessary for the electrical machines design in which a change in one parameter significantly affects other indicators, the change of which, in turn, has clear permissible limits, which can also be determined during modeling. Multiparametric design requires more in-depth preparation of calculation models, the construction of more branched algorithms and the development of additional software. However, such design allows taking into account the technical capabilities of a particular enterprise, will increase the accuracy of execution and reduce the cost of design work.

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