Optimization of the Design and Parameters of Electromechanical Energy Converters Using Multiparametric Design Techniques

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Abstract. The aim of the work is to increase the accuracy of electromechanical equipment (turbogenerator) designing, selecting the optimal design and maximum permissible electromechanical loads in given dimensions by using the capabilities of multiparametric design, in particular, using the particle swarm method. Due to the refined calculations the presence of thermal and mechanical reserves, the possibility of using the turbogenerators existing cooling system when increasing their capacity have been proven. Multiparameter design using the particle swarm method makes it possible to search for the best solution in a multidimensional parameter space, where the "swarm particles" (possible solutions) gradually approach the optimal result while simultaneously maintaining all turbogenerator interrelated parameters within acceptable limits. The goal set is achieved by establishing the heat exchanger optimal operating parameters and turbogenerator cooling system other elements while increasing its power and maintaining all characteristics and indicators within the limits established for turbogenerators of similar power by the manufacturer. The most important result is the establishment possibility of using the factory cooling system when increasing the new turbogenerators power while maintaining the dimensions due to the identified thermal reserves in the base generator at refined multiparametric designing. The optimal geometry of the core and stator winding cooling channels and the internal layout of the heat exchanger elements have been established. The obtained results significance is that the proposed multiparametric designing methodology using the particle swarm method can be used for the optimal design of new electromechanical equipment or its modernization at power plant units.
Keywords: turbogenerator, optimal construction, increase in power, multiparametric designing, particle swarm method, modernization, cooling system; heat exchanger

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Optimizarea proiectării și parametrilor convertoarelor electromecanice de energie prin utilizarea tehnicilor de proiectare multiparametrică

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Rezumat. Scopul lucrării este de a crește precizia proiectării echipamentelor electromecanice (turbogeneratoare), selectând designul optim și sarcinile electromecanice maxime admisibile în dimensiuni date, utilizând capacitățile proiectării multiparametrice, în special metoda roiului de particule. Datorită calculelor rafinate, a fost demonstrată prezența rezervelor termice și mecanice, posibilitatea utilizării sistemului de răcire existent al turbogeneratoarelor la creșterea capacității acestora. Proiectarea multiparametrică utilizând metoda roiului de particule face posibilă căutarea celei mai bune soluții într-un spațiu de parametri multidimensional, unde „particulele roiului" (soluțiile posibile) se apropie treptat de rezultatul optim, menținând simultan toți parametrii corelați ai turbogeneratorului în limite acceptabile. Obiectivul stabilit este atins prin stabilirea parametrilor optimi de funcționare ai schimbătorului de căldură și a celorlalte elemente ale sistemului de răcire a turbogeneratorului, crescând în același timp puterea acestuia și menținând toate caracteristicile și indicatorii în limitele stabilite de producător pentru turbogeneratoare de putere similară. Cel mai important rezultat este stabilirea posibilității de utilizare a sistemului de răcire din fabrică la creșterea puterii noilor turbogeneratoare, menținând în același timp dimensiunile datorită rezervelor termice identificate în generatorul de bază la proiectarea multiparametrică rafinată. Au fost stabilite geometria optimă a canalelor de răcire ale miezului și înfășurării statorului, precum și dispunerea internă a elementelor schimbătorului de căldură. Semnificația rezultatelor obținute constă în faptul că metodologia de proiectare multiparametrică propusă, utilizând metoda roiului de particule, poate fi utilizată pentru proiectarea optimă a unor noi echipamente electromecanice sau pentru modernizarea acestora la unitățile centralelor electrice.
Cuvinte-cheie: turbogenerator, construcție optimă, creștere a puterii, proiectare multiparametrică, metoda roiului de particule, modernizare, sistem de răcire; schimbător de căldură.

Оптимизация конструкции и параметров электромеханических преобразователей энергии за счет возможностей мультипараметрического проектирования

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Аннотация. Целью работы является повышение точности проектирования электромеханического электрооборудования (турбогенераторов), выбор оптимальной конструкции и максимально допустимых электромеханических нагрузок в заданных габаритах за счет использования возможностей мультипараметрического проектирования, в частности, при использовании метода роя частиц. В работе за счет уточнённых расчетов доказана возможность использования существующей системы охлаждения турбогенераторов при повышении мощности новых машин с сохранением габаритов и при модернизации турбогенераторов, которые уже работают на электростанциях. Установлены запасы по тепловым характеристикам, которые позволяют выполнять такое увеличение мощности. Мультипараметрическое проектирование с использованием метода роя частиц делает возможным выполнять поиск наилучшего решения в многомерном пространстве параметров, где «частицы роя» (возможные решения) постепенно приближаются к оптимальному результату при одновременном поддержании всех взаимосвязанных параметров турбогенератора в допустимых пределах. Доказательством того, что поставленная в работе цель достигнута является определение оптимальных рабочих параметров теплообменника и других элементов системы охлаждения турбогенератора при повышении его мощности и условии сохранения всех характеристик, показателей и габаритов в пределах, установленных для турбогенераторов аналогичной мощности заводом-изготовителем. Наиболее важными результатами является получение данных о возможности использования заводской системы охлаждения при повышении мощности новых турбогенераторов с сохранением размеров за счет выявленных тепловых запасов в базовом генераторе при помощи уточненного мультипараметрического проектирования по методу роя частиц. Установлена оптимальная геометрия каналов охлаждения сердечника и обмотки статора, внутренняя компоновка элементов теплообменника. Значимость полученных результатов состоит в том, что предложенная методика мультипараметрического проектирования с использованием метода роя частиц может использоваться для оптимального проектирования нового электромеханического оборудования или проведения модернизации электрооборудования, уже работающего на электростанциях.

***Ключевые слова*:** турбогенератор, оптимальная конструкция, повышение мощности, мультипараметрическое проектирование, метод роя частиц, модернизация, система охлаждения; теплообменник.

INTRODUCTION

Turbogenerators (TGs) are the main and most complex equipment of both thermal (TPP) and nuclear (NPP) power plants.

This is the most expensive and complex equipment of any power plant; the manufacture of TG takes an average of 5-8 years.

Therefore, it is very important when designing new TGs or when modernizing them to optimize the design and electromagnetic parameters in comparison with the selected base TG.

Modern capabilities for refined calculations using numerical methods, computer software, and AI-assisted design tools for electromechanical equipment allow to more accurately perform the following tasks [1–4]:

- analyze complex physical processes and the mutual influence of design changes, load (current), electromagnetic fields, heat transfer, mechanical stresses, and vibrations – all of which are difficult or sometimes impossible to determine analytically; - optimize the TG and associated equipment designing; to select new materials, find the most effective solution in terms of reliability and cost;

- use electrical equipment virtual prototypes for testing, in cases where testing of real equipment, such as turbogenerators, on factory test benches or laboratory stands is impossible or very difficult.

Numerical design methods improve reliability. They provide forecasts of equipment condition during operation and identify possible overheating zones or defect formation. The most commonly used methods are finite element methods (FEM), boundary element methods (BEM), numerical integration, and optimization algorithms [5-8].

Research and development efforts aimed at optimizing the design of new equipment, including its individual components and assemblies, are being conducted in various countries [9-13].

In particular, when optimizing the design of electrical machines, parametric and multiparametric design is often used, which allows taking into account the relationship between geometric, electromagnetic, thermal and mechanical parameters. But almost all works consider low-power machines, machines of special designs and purposes [14-22]. The issues of optimizing the power plants electrical equipment, in particular, high-power turbogenerators, can be considered the most important, because modern civilization is completely dependent on the availability of electricity, on the possibility of an environmentally safe increase in its production.

TGs constantly operate with high electromagnetic, thermal and mechanical parameters, with overloads, and operate in transient modes. Therefore, optimization of their parameters and structural elements are a complex and mandatory condition for ensuring energy efficiency, reliability and durability of the entire power plant.

During major repairs or at the stage of modernization work, it is possible to optimize the design and parameters of turbogenerators that operate at power plants. Such modernization is possible provided that the potential for improving the thermal, electromagnetic, and mechanical parameters of the original design is identified.

A turbogenerator is a complex electromechanical system. Even minor changes in one parameter, such as electromagnetic load, affect other characteristics – thermal, aerodynamic or mechanical [23]. Therefore, with any change it is necessary to take into account the relationship and mutual influence of mechanical, thermal, electromagnetic parameters, conduct a complete recalculation of the TG, and determine that all parameters are within acceptable limits. Multiparametric modeling allows taking into account such mutual influence, ensures the search for an optimal solution while simultaneously maintaining interrelated parameters within acceptable limits [23, 24].

Multivariable analysis also enables consideration of the indirect effects of changes in one parameter on another. For example, the effect of additional heating due to increased losses with increasing the TG power. Additional deformations of structural elements may occur due to thermal expansion. Due to the thermal expansion, general stretching of the rotor and stator cores, movement of heated conductors relative to the cold walls of the slots, mechanical destruction, rupture of conductors and insulation of the stator winding are possible. Therefore, it is necessary to consider possible mechanical causes of insulation destruction, and not only defects due to thermal loads. Using multiparametric design, it is possible to obtain a forecast of the locations of formation of zones of increased mechanical stress, and to minimize failures due to material fatigue.

In general, digital tools (e.g., ANSYS, COMSOL) allow for the creation of multiphysics models that consider mechanical strength and thermal loading reserves of specific components. This enables electromagnetic parameters to be adjusted to increase TG output while keeping other indicators within allowable limits. Thus, multiparametric modeling is considered as the most suitable approach for modeling electromechanical energy converters (i.e., electric machines) [1].

Various methods are used in multiparametric design, including genetic algorithms, gradient methods, particle swarm optimization (PSO), and differential evolution. The choice of method significantly affects the optimality of the design outcome [24-28].

If only one optimal value exists for the parameter being analyzed, gradient methods like gradient descent or the Nelder–Mead algorithm can be effective. However, with many interrelated parameters (geometric, electromagnetic, thermal), mutual changes may lead the gradient algorithm to a local or suboptimal extremum rather than the global optimum. Moreover, gradient methods require differentiability of the objective function, which is not always possible in multiparametric design.

Method Particle Swarm Optimization (PSO) is a numerical optimization method that does not require knowing the gradient of the optimized function, making it promising for designing various electric machines, including TGs and large motors. Changes in one parameter (e.g., current, coolant temperature, mechanical load, or geometry of main or auxiliary components) affect a wide range of electromagnetic, thermal, and mechanical characteristics [24–28]. Therefore, for multiparametric design and modernization, the PSO method is considered the most effective, as it operates in multidimensional space and, unlike Newton's methods, does not require gradient calculations for each intermediate solution [8, 9, 26, 29].

It should be noted that simultaneously with the method PSO, the differential evolution method appeared, which, according to many researchers, is superior to the PSO method [11, 17]. But the calculations simplicity and high accuracy of results have led to the fact that optimization algorithms using the PSO method are used two to three times more often than differential evolution algorithms [15, 27, 28].

In PSO, agents (particles) move toward optimal solutions by sharing information with other parameters. Each particle stores the coordinates of the best solution it has found, which is crucial for systems with many interrelated parameters [4, 12, 30-33]. It is possible to search for the best solution in a multidimensional parameter space, where the “swarm particles” (possible solutions) gradually approach the optimal result while simultaneously maintaining all interconnected parameters of the turbogenerator within acceptable limits.

The aim of the work is to demonstrate the possibility of increasing the new turbogenerators power output within the dimensions of standard machines, as well as the potential for boosting the capacity of turbogenerators already in operation at power plants, while maintaining the existing cooling system design. This is achieved through refined calculations using the particle swarm optimization method in multiparametric design, which allows for identifying reserves in thermal and mechanical stresses. The example used involves optimizing the design and more accurately selecting parameters for a 500 MW turbogenerator along and its cooling system configuration refined.

METHODS, RESULTS AND DISCUSSION

The principle of a high-power electrical machine (turbogenerator) multiparametric designing with searching for the best solution in a multidimensional parameter space using the Particle Swarm Optimization (PSO) method is based on particles (possible solutions) gradually converging toward optimal solution. At the same time, "an ending the space" of all possible parameters for various elements and components of the turbogenerator is analyzed. This enables the design of new turbogenerators or partial modernization of those already operating at power plants [17, 21, 23]. The most relevant tasks for such design include:

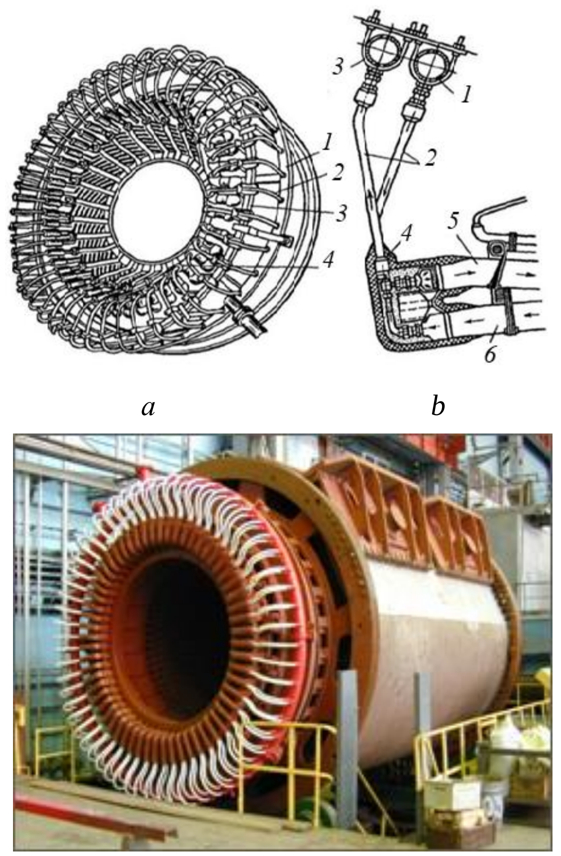
- determination of the optimal geometric dimensions of the magnetic circuit and air gap; selection of the winding type and parameters for given values of electromagnetic loads;
- minimizing losses in the generator, particularly reducing magnetic losses in the rotor core (the losses at eddy current and hysteresis);
- optimizing the turbogenerator's cooling system: defining the effective cross-section of heat-removal channels, their number, and spatial arrangement; determining the shape and number of fan blades; choosing the velocity and direction of cooling medium flows (hydrogen, air, water) to ensure the most uniform temperature distribution inside the generator;
- analysis of the condition and development of proposals for optimizing the design of individual elements and parts of the TG in order to reduce vibration;
- when optimizing the geometry of the TG individual units and parts, it is necessary to use the unification requirements and maintain the overall installation and connection dimensions of the basic TG.

The study compares the results of cooling system design for the TGV-500-2U3 turbogenerator (Kharkiv, Ukraine), as developed by the manufacturer, with those obtained using the particle swarm optimization (PSO) method in multiparametric designing. In the multiparametric approach, a search for thermal reserves of the base turbogenerator was conducted to explore the potential for increasing the power output of new turbogenerators or modernizing those currently in operation. A major design condition was to maintain the base turbogenerator overall dimensions, which would allow for preserving the standard foundations for installing TGs and turbines in the power plant machine halls, as well as enabling the use of auxiliary systems originally designed for the base TG [31-33].

A two-pole turbogenerator with a capacity of 500 MW (n_s=n_r=3000 rpm) has water-hydrogen cooling: the internal volume of the generator, the rotor, the stator core and frontal parts of stator windings, the shroud units, are cooled with hydrogen; and the stator windings are cooled with water, Fig. 1.

To find the optimal geometry of the heat exchanger and the parameters of the cooling medium (water/hydrogen) of the turbogenerator using the particle swarm optimal (PSO) method, we apply the following algorithm for performing calculations and optimizing solutions [16-21]:

1) creation of a "population”, “a swarm of particles" – compilation of a list of cooling channels possible designs and a range of possible values of change in the speed of movement of the cooling medium (water/hydrogen). The swarm simplest elements can be randomly determined at the initial stage of swarm creation without a specific criterion. At subsequent iterations, denoted by t=0; 1; 2;….T, PSO starts with a randomly generated swarm of n particles, which are d-dimensional.



a *b*

c

a – General view of the stator core with water supply and return hoses;
b – Diagram of hose connection with cold and heated water collectors;
c – Photo of the TG stator (white tubes – cold water supply and heated water return hoses)
1, 3 – Cold water collector (input to slot channels); 2 – Flexible PTFE hoses; 3 – Heated water collector (output from slot channels); 4 – Water-distribution nozzles; 5, 6 – Rod head assemblies

Fig. 1. Cooling water supply and return system for channels located in the stator core slots.

These "swarm particles" are vectors of real-valued positions representing initial (preliminary) solutions obtained by initializing each particle's position x_i^0 at iteration $t = 0$ to a random location in the search space. They are defined as:

$$x_i^0 = K(x_{\min}, x_{\max})^d, \qquad (1)$$

where d is the dimensionality of the search space or size of the problem being solved;
x_i is a particle with an initial position of vector x_i^0 with values chosen randomly from a uniformly distributed range $K(x_{\min}, x_{\max})^d$ with search space bounds x_{min} and x_{max}.

Typically, the position vector of the i-th particle at each subsequent iteration ($t \geq 0$) can be defined as:

$$x_i^t = \left(x_{i,1}^t,\, x_{i,2}^t,\, ...,\, x_{i,d}^t\right). \qquad (2)$$

The decision variables (i.e., the elements of the position vector) often correspond to physical parameters or components with natural limits. For instance, length, weight, and mass are examples where values must be non-negative. Thus, the range (x_{min}, x_{max}) should be set to independently constrain the value of each decision variable.

When determining the velocity of the cooling medium in heat exchanger channels, all particles are assumed to move in the search space at a step size sufficient to reflect particle knowledge and exchange information about promising regions in the search space, thus guiding the optimization process toward the most suitable areas. Similar to swarm creation, the velocity v_i of each particle can be defined as:

$$v_i^t = \left(v_{i,1}^t,\, v_{i,2}^t,\, ...,\, v_{i,d}^t\right), \qquad (3)$$

where v_i^t is the i-th particle velocity vector at the iteration t;
$v_{i,1}^t, v_{i,2}^t, ..., v_{i,d}^t$ – velocity parameters are randomly set (at the iteration $t = 0$) within an established range $(x_{i\min}, x_{i\max})$ or $(v_{i\min}, v_{i\max})$ so that particles stay within the defined search space;
v_{max} is the maximum allowed step size in any dimension [11];

2) Choosing initial parameters – selecting the cooling medium, shape, material, and geometric dimensions of the channels, and the heat transfer coefficient.

Usually, for multiparametric design, the most significant indicator of the equipment is selected, for which a mathematical model is created. For a turbogenerator, such an indicator can be an active power, which is determined by a large number of components, and on which many parameters and characteristics significantly depend [37-39].

Therefore, the active power of a turbogenerator can be defined as a multicomponent dependence:

$$P_S = f(U_N, a_s, q_{as}, j_s), \text{ W},$$

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

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

q_s – is the effective conductor stator winding copper cross-section, mm^2.

When designing, it is necessary to take into account that each component can be defined as a dependent and independent function.

This representation depends on whether the parameter under consideration is adjustable or non-adjustable, constant. For example, in our problem the geometric dimensions are assumed to be constant, i.e., this is a non-adjustable parameter.

Therefore, this parameter is a boundary value and is not included in the scope of an element optimization – particle swarm optimization (PSO).

Once the swarm is created and velocities are defined, each particle is checked for its initial individual best (optimal) position $f\left(p^0_{opt_i}\right)$ along with the initial global best position $f\left(g^0_{opt}\right)$. The numerical determination of these functions will be discussed below in equations (5) and (6). At the swarm creation stage, the individual best solution $p^0_{opt_i}$ *i*-th particle is set to its initial position x^0_i ;

3) Intermediate evaluation of the temperature of the most loaded TG components under new electric loss values (new load regime – different stator current value);

At the end of each iteration, the swarm particles are evaluated for their individual best positions pbest$_i$ and global best position gbest. It is assumed that each *i*-th particle has a unique fitness value $f\left(x^t_i\right)$ at the iteration *t*, calculated by evaluating the objective function. *PSO* stores the individual best solution (a candidate for the global best) that each particle has achieved up to iteration *t* as

$$p^t_{opt} = \left(p^t_{opt_1},\, p^t_{opt_2},\, ...,\, p^t_{opt_n}\right), \quad (4)$$

where p^t_{opt} – represents the individual best positions of all particles in the swarm at iteration *t*. Depending on whether the optimization task is a minimization or maximization, the individual best position $p^t_{opt_i}$, that the *i*-th particle achieved before iteration t is calculated as:

$$p^t_{opt_i} = x^l_i \left| f\left(x^l_i\right) = \min_{k=0,1,2,\ldots t}\left[f\left(x^k_i\right)\right]\right., \quad (5)$$

where *l* is the same index as the *k*-th iteration when the *i*-th particle found its best position before iteration *t*.

At the end of each iteration, all candidate solutions in p^t_{opt} are sorted, and the top-ranked solution is selected as the global (or neighborhood) best solution or position g^t_{opt}, visited by article *i*:

$$g^t_{opt} = p^t_{opt_m} \left| f\left(p^t_{opt_m}\right) = \min_{k=1,2,\ldots n}\left[f\left(p^t_{opt_i}\right)\right]\right., \quad (6)$$

where *m* is the same index as the *i*-th particle occupying the global best position among the swarm;

4) Updating the positions of “particles” (possible cooling channel designs) based on the obtained results [12, 20].

At each current iteration (say, indexed *t*+1), the velocity v_i of the *i*-th particle is first adjusted by steering its values positively or negatively depending on convergence trends. This pulls the particle toward positions in the search space known to be good from its own and other particles’ previous experience, [11, 26, 28].

In pursuit of the optimal solution, each swarm particle moves in each subsequent iteration $t \geq 0$ toward its previous individual position p^t_{opt} and the global best position g^t_{opt} in the swarm, by adding the velocity vector to its position from the previous iteration:

$$x^{t+1}_{i,j} = x^t_{i,j} + v^{t+1}_{i,j}, \quad (7)$$

where $v^0_{i,j} = 0$ – the velocity vector of the *i*-th particle at iteration *t* + 1 in the *j*-th dimension;

$$v^{t+1}_{i,j} = \omega \cdot v^t_{i,j} + c_1 \cdot r^{t+1}_{1_{i,j}} \cdot \left(p^t_{opt_i,j} - x^t_{i,j}\right) + \\ + c_2 \cdot r^{t+1}_{2_{i,j}} \cdot \left(g^t_{opt,j} - x^t_{i,j}\right), \quad (8)$$

where $\omega \cdot v^t_{i,j}$ – the inertia component. It determines the particle's flight direction, giving it momentum to move through the search space without abrupt directional changes, based on past flight history;

- $c_1 \cdot r^{t+1}_{1_{i,j}} \cdot \left(p^t_{opt_i,j} - x^t_{i,j}\right)$ is the cognitive component – the particle's memory of the previous individual best position where it had the best result;
- $c_2 \cdot r^{t+1}_{2_{i,j}} \cdot \left(g^t_{opt,j} - x^t_{i,j}\right)$ is the social component that determines the current

performance of the particle; it is associated with the best global solutions found in all iterations;

- $j \in 1, 2, ... d$ are the dimensions (or components) of the *i*-th particle;

- parameters c_1 and c_2 are acceleration coefficients. These are positive constants typically used to define the learning acceleration of the *i*-th particle toward p_{opt_i} and g_{opt} respectively [25, 27, 28];

5) the last stage obtains the optimal solution. In our study, this determines the most efficient configuration of the cooling system (heat exchanger).

At the end of each iteration p_{opt} and g_{opt} are evaluated using equations (5) and (6), respectively, which ultimately leads to obtaining the global best solution g_{opt}.

The main topologies used to describe the PSO process in the multiparametric design of electrical machines can be represented graphically as different configurations, i.e., sets of rules, tools, and technologies of the chosen method that enable more precise modeling of geometric and other relationships.

These topologies include fully connected, ring, von Neumann, star, random, and wheel topologies (Fig. 2) [34–36].

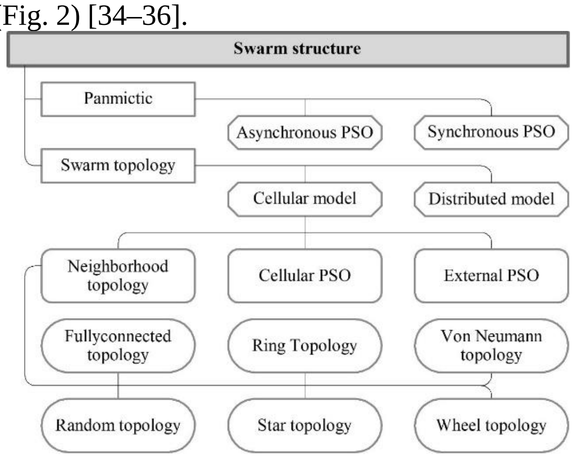


Fig. 2. Particle swarm topologies for solving multi-parameter design problems in electrical machines.

The neighborhood topology in the Particle Swarm Optimization (PSO) method defines how particles interact with each other and share information about the best-found solutions. This affects the convergence speed of the algorithm and its ability to find a global optimum. For optimizing the turbogenerator design using PSO, the most suitable neighborhood topology is a hybrid topology that combines global and local search. For global search, a fully connected topology ensures fast convergence but may get stuck in a local minimum. For the local search, a ring topology allows better exploration of the solution space but requires more iterations [35].

When creating the initial particle population during the multiparametric design of the 500 MW turbogenerator cooling system using the PSO method, the following elements of the turbogenerator cooling system are considered [27, 28]:

- the stator winding cooling channels (water);
- cooling channels for the stator core (axial-radial hydrogen cooling channels);
- heat exchanger parameters;
- parameters of centrifugal fans mounted on the rotor shaft;
- the air gap between the stator and rotor through which hydrogen is circulated by the fans.

Figure 3 depicts (where PSO algorithm flow for implementing multiparametric turbogenerator design is shown) the following notations are used:

S – number of possible solutions for a given swarm particle;

ΔP – total losses in the turbogenerator (electrical, magnetic, mechanical, and additional), removed by the cooling system, in Watts;

E_m – coefficient determined by the electromagnetic parameters of the turbogenerator: current strength and density in the stator and rotor windings, voltage, winding data of the stator, etc.;

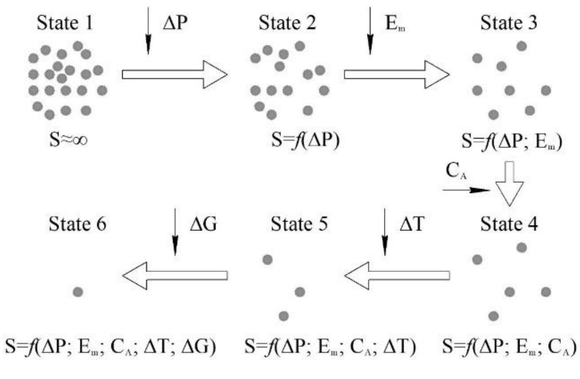


Fig. 3. PSO algorithm flow for implementing multiparametric design of a turbogenerator.

C_A – coefficient defining the allowable overall dimensions of the turbogenerator, including mounting and connecting dimensions, and data on materials used in machine unit structures. Effectively, this is the Arnold constant of the machine, linking various parameters of the machine (power, size, load), which helps determining the optimal machine size for a given power and rotational speed, as well as the effect of speed on dimensions and weight;

ΔT – temperature variation range, defined by permissible inlet temperatures of water and gas in the cooling system depending on the operating mode and insulation heat resistance class;

ΔG – combined characteristic of the blower fan on the turbogenerator shaft and the hydraulic resistance values within its cooling system nodes.

The transition from the first state (where $S \rightarrow \infty$) to the second state (where $S=f(\Delta P)$) is conventional parametric design, where the solution depends on a single variable (loss value). Transition from state 2 to 3 and all subsequent transitions are multiparametric, as the solution depends on two or more variables. Figure 3 shows that the PSO method sequentially searches for a solution while accounting for required additional data on the TG structure.

State 1 corresponds to the stage where, from the multitude of possible solutions (swarm particles), the losses ΔP to be removed by the cooling system are approximately determined.

State 2 is when the load on the cooling system is defined and the optimization of E_m parameters should proceed. At this stage, stator slot fill is specified, and magnetic circuit and rotor winding calculations are performed.

State 3 evaluates the overall machine dimensions and examines the possibility of maintaining the mounting and connecting dimensions, which is determined by the requirement to preserve existing foundations and auxiliary systems: oil supply systems to bearings and seals, water and hydrogen systems, electrical circuit connections, exciter connections, and finalization of the machine's electromagnetic parameters. The Arnold constant (C_A), can serve as a basic criterion, though not exclusively [16, 17, 23].

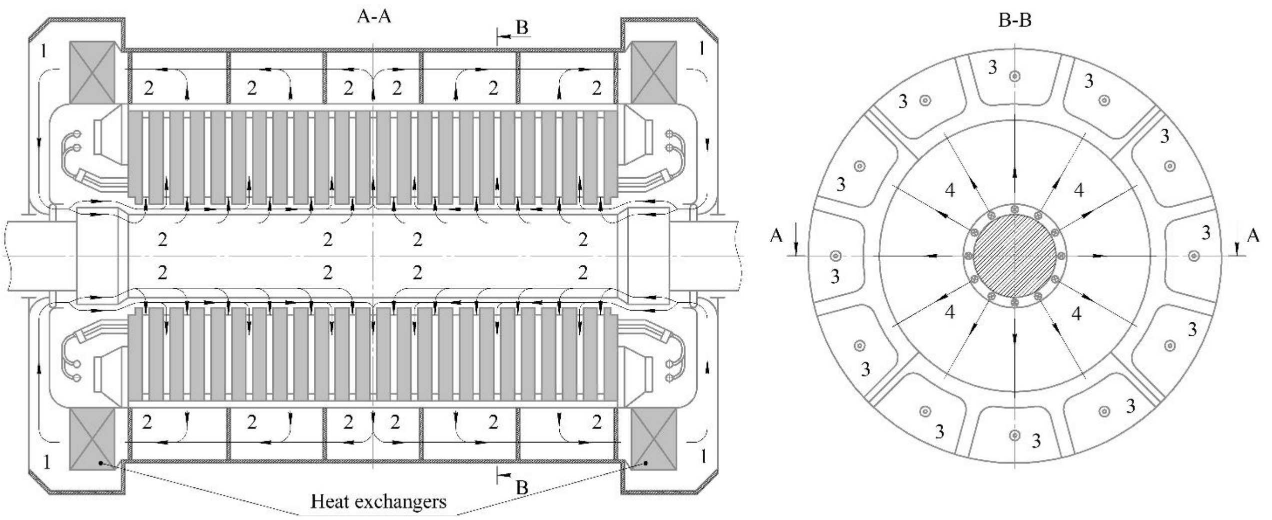
State 4 involves heat exchanger calculation (ΔT), determining water and gas temperatures at the inlet and outlet of the heat exchanger, and checking the thermal condition of the TG based on preset limits according to insulation heat resistance class and component temperatures [17, 21, 23, 37].

State 5 evaluates the hydraulic resistance of the cooling system elements (ΔG) and designs the centrifugal fan accordingly (impeller diameter, number of blades, working attack angle of the cooling element).

State 6 the final state, results in all swarm particles converging to a single “position,” which is the global solution – the optimal heat exchanger design for the TG, according to all optimization function criteria $S=f(\Delta P; E_m; C_A; \Delta T; \Delta G)$, [23, 28, 30].

As a result, one solution is chosen that maximally (or optimally) meets all constraint requirements for the TG processes. Main parameters are evaluated: electromagnetic, thermal, and mechanical. The requirement to maintain overall dimensions is checked; cooling system reserves are identified for a possible power increase of the TG [18, 22, 24, 26–28].

A calculation of the TGV-500-2U3 turbogenerator cooling system will be performed using the proposed algorithm. Figure 4 shows the basic diagram of the studied TG cooling system.



1 – cold gas; 2 – hot gas; 3 – gas moving through axial channels; 4 – gas moving through radial channels

Fig. 4. Schematic of the 500 MW turbogenerator cooling system with water-cooled stator windings and hydrogen-cooled rotor and stator core.

The channel geometry (d_g) for the stator winding can generally be calculated through the heat transfer coefficient. We assume that the channels of the heat exchange system are stationary and the hydrogen flow through them is forced. Then:

$$\alpha_{o.k} = \frac{Nu \cdot \lambda_k}{d_g}; \qquad (9)$$

where $\alpha_{o.k}$ – heat transfer coefficient of the k-th section of the stator winding cooling system channel, ºC/(Вт·м²);

$Nu = K \cdot \mathrm{Re}^m$ – Nusselt number, a dimensionless parameter representing the intensity of convective heat exchange relative to conductive heat transfer between the tube surface and the gas volume in the heat exchanger; K – coefficient depending on the flow type of the cooling medium (laminar or turbulent);

Re – eynolds number for water flow in the hollow conductors of the stator winding, dimensionless; m – exponent;

λ_k – thermal conductivity of the material of the hollow conductors in the k-th section of the stator winding cooling system, W/ºC·m;

d_g – hydraulic diameter of the cooling channel, m.

The axial cooling channels geometry in the stator core is related to the heat transfer coefficient as follow:

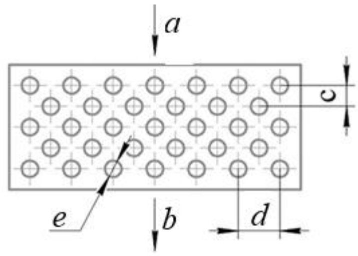
$$\alpha_{s.k} = K \cdot \left(\frac{\upsilon_k}{40}\right)^{0,8} \cdot \left(\frac{1}{d_g}\right)^{0,2} \cdot P_{air}^{0,8}; \quad (10)$$

where $\alpha_{s.k}$ – heat transfer coefficient from the steel surface of the k-th axial channel section of the stator to the hydrogen flow ejected from the air gap due to rotor rotation, ºC/(W·m²); P_{hyd} – pressure of the cooling hydrogen in the stator core axial channels, Pa; υ_k – the cooling medium (hydrogen) velocity in the k-th section of the stator core radial channels, m/s.

The geometry of the working section of the heat exchanger (with a staggered arrangement of cooling tubes) is related to the heat transfer coefficient, Fig. 5 [17, 29]:

$$\alpha_{t.k} = \frac{B \cdot \mathrm{Re}_k^n \cdot \mathrm{Pr}_k^{0,33} \cdot \left(\frac{\mathrm{Pr}_k}{\mathrm{Pr}_w}\right)^{0,25} \cdot \lambda_k}{d_g} \cdot c; \quad (11)$$

where $\alpha_{t.k}$ is the heat transfer coefficient for the k-th section of the cooling system in the heat exchange unit, ºC/(W·m²);



***a** – direction of hydrogen entry into the heat exchanger; **b** – direction of hydrogen exits from the heat exchanger; **c** – distance between tube rows; **d** – distance between tubes in a row; **e** – number and diameter of tubes in the heat exchanger.*

Fig. 5. Diagram of the staggered arrangement of cooling tubes in the heat exchanger.

Pr_k and Pr_w – Prandtl numbers for the gas medium and water, respectively, for the k-th section of the cooling system, dimensionless; c – finned surface area per linear meter of heat exchanger tube, m²;

B and n – empirical coefficients depending on the internal cross-section geometry of the heat exchanger. For a staggered tube arrangement: B=0.41, n=0.6.

Depending on the air gap size in the TG, the heat transfer coefficient can be defined as:

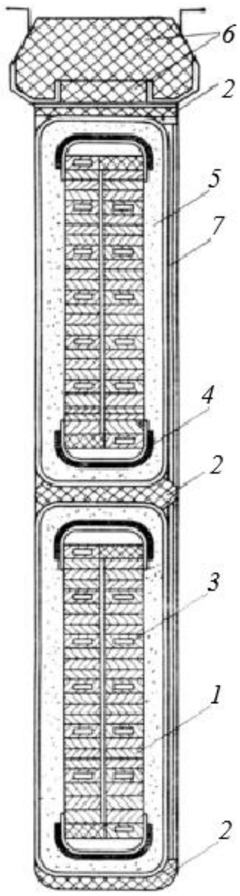
$$\alpha_{z.k} = \frac{1 + K \cdot \sqrt{\upsilon_r^2 + \upsilon_k^2}}{0,045} \cdot 1,3 \cdot P_{air}^{0,8}; \qquad (12)$$

where $\alpha_{z.k}$ – heat transfer coefficient for the k-th section of the cooling system in the heat exchange unit, ºC/W·m²; υ_k – velocity of the cooling medium in the k-th section of the air gap, m/s; υ_r – linear rotation speed at the outer radius of the rotor surface, m/s.

Let us introduce the initial parameters of the TGV-500-2U3 turbogenerator:

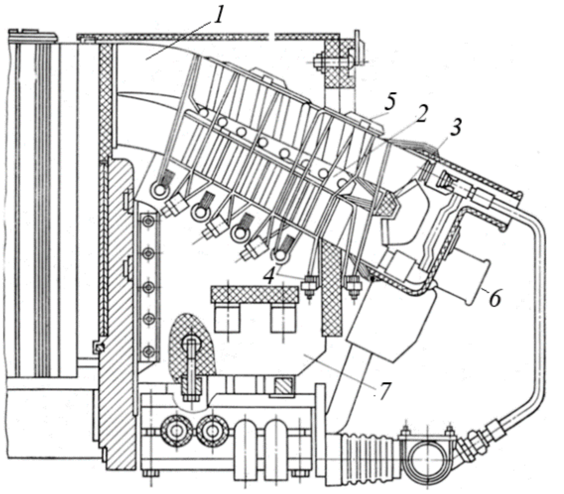
- total power 588 MVA, active power – 500 MW;
- two-pole TG (n_s=n_r=3000 rpm);
- stator winding is cooled by water, Fig. 6;
- stator and rotor cores, as well as rotor winding, are cooled by hydrogen;
- coolant in the heat exchanger tubes – water; in the heat exchanger shell – hydrogen.

The generator stator winding direct cooling is performed by circulating water (distillate) through hollow thin-walled steel channels made of non-magnetic steel, laid interspersed with solid elementary conductors.



1 – solid elementary conductor;
2 – insulating gasket;
3 – hollow elementary conductor with a steel channel for water passage;
4 – aluminum foil screen with an asbestos gasket installed underneath. The screen is used to equalize the potential across the width of the groove;
5 – general (housing) insulation of the upper or lower rod;
6 – groove wedge;
7 – side seal, gasket made of flat and corrugated fiberglass to dampen rod movements in the groove

Fig. 6. Cross-section of the TGV-500-2U3 stator slot.



1 – stator winding end parts; 2 – spacer shoe; 3 – prepreg plastic layers between winding layers; 4 – radial rods that form the end parts of the stator winding rods in the radial direction relative to the spacer shoe; 5 – tangential bandages with glass bandage tape bundles; 6 – heated water outlet into the drain manifold from the turbine side or cold-water inlet from the heat exchanger into the pressure manifold from the contact ring side; 7 – fiberglass bracket

Fig. 7. Sketch of the area of the stator winding frontal parts TGV-500-2U3 with water cooling.

The stator winding rods consist of solid elementary conductors, which are laid across the width of the slot in two rows and are transposed by 540° in the slot part.

The number ratio of solid conductors and hollow channels through which water flows is 1:3 for the upper conductors in the slot and 1:2 for the internal ones. These changes are achieved by transposing the stator winding in the axial direction.

Cooling water is supplied to the rods from a ring collector, most often located on the contact rings side. Water that has passed through the rods is accumulated in a collector located on the turbine side and is diverted from the collector to the heat exchanger.

All water channels in the stator slot are connected in parallel.

The pressure and drain manifolds of the TGV-500-2U3 turbogenerator are located at the ends of the stator. Water from the pressure manifold enters the rod heads through fluoroplastic hoses (see Fig. 1, white tubes) and is distributed in parallel along two electrically connected rods via a tubular tee, passes through them and enters the drain manifold, Fig. 7 [40].

The parameter calculations were performed for the TG's nominal operating mode.

A comparison of the 500 MW TG cooling system modeling results for optimal solution search, obtained by multi-parameter modeling using the particle swarm optimization algorithm in the MATLAB software package, and results based on the manufacturer's methodology (classical method), is presented in Table 1.

From Table 1, it follows that the calculation results obtained using both methods differ insignificantly, which supports the conclusion that the manufacturer's heat exchanger is optimal and that it is possible to retain the proven, field-tested heat exchanger design with unchanged overall dimensions during the modernization of the turbogenerator (TG) on power station units.

However, the results obtained using the PSO method revealed that the considered cooling system provides a slight thermal reserve for the TG under nominal load conditions:

• The number of hollow conductors in the stator core slot, through which water flows, can be reduced from 16 to 14, (see Fig. 6). This solution will allow for more solid copper conductors to be laid, increasing the slot fill factor, reducing the specific current density and electrical losses;

Table 1

Results of the comparative analysis of the cooling system modeling for a 500 MW turbogenerator, obtained using the multi-parameter modeling method via the particle swarm optimization (PSO) algorithm and by the manufacturer's classical methodology.

№	Parameter	Calculation Results		Notes
		PSO method	Classic method	
1	Geometry of stator winding cooling channel			
	Air channel in cross-section of elementary conductor	40 mm^2	40 mm^2	Copper tube 4×10×1 mm
	Number of hollow elementary conductors in the rod (in one layer of winding in the stator slot)	14 pcs	16 pcs	
	Stator slot depth	245 mm	250 mm	Recommended
	Stator slot width	37 mm	38 mm	Recommended
2	Shape and number of axial channels in stator back iron			
	Shape and number of axial channels in stator back iron	Ø 20 mm 190 pcs	Ø 20 mm 192 pcs	In segment stamp
	Shape and number of axial channels in tooth zone (rectangular punch)	6×35 mm 48 pcs	6×40 mm 48 pcs	In segment stamp
	Width and number of radial channels between stator core packs	4 mm 48 pcs	4 mm 48 pcs	
3	Geometry of the heat exchanger working section			
	Length of finned cooling tube	3200 mm	3260 mm	
	Outer and inner diameter of cooling tube	Ø19/17 mm	Ø 19/17 mm	Copper-nickel tube
	Distance between tubes in a row	46 mm	46 mm	
	Distance between tube rows	32 mm	32 mm	
4	Value of one-sided air gap	90 mm	90 mm	

• The stator slot depth and width can be reduced by 5 mm and 1 mm. Provided that the dimensions are maintained, this allows for a reduction in the induction value in the teeth and back of the stator core, and a reduction in the turbogenerator magnetic losses;

• The depth and width of the stator slot can be reduced by 5 mm and 1 mm. Provided that the dimensions are maintained, this allows for a reduction in the induction value in the stator core teeth and back, and a reduction in the magnetic losses of the turbogenerator;

• It is possible to reduce the axial channel diameter and their number in the stator core toothed zone. This solution increases the mechanical reliability of the stator teeth, which for the turbogenerator under consideration were made with rectangular notches, Fig. 8.

These reserves, identified using the more precise multi-parameter modeling method (PSO), have two practical applications:

The current density in the stator winding will not exceed acceptable levels due to the built-in reserve in the stator winding's cross-sectional area. The heat removal reserve will be ensured by two additional water flow channels in the stator slots and by the extra 60 mm length of the finned cooling tube.

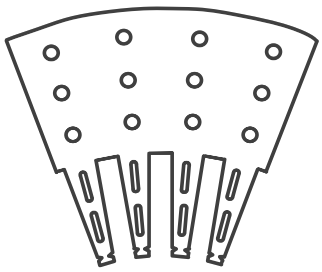


Fig. 8. Stator core segments with slots in the teeth and axial ventilation channels in the stator core back.

When designing new TGs, it becomes possible to reduce the mass and dimensional parameters of the TG design while maintaining power output, or to increase power output within the original baseline TG parameters.

Conclusions

1. The application of the PSO method in multiparameter design of electromechanical energy converters (turbogenerators) enables

simultaneous optimization of multiple parameters (electromagnetic, mechanical, and thermal), providing a comprehensive improvement in TG performance.

2. The PSO method does not require complex mathematical models and can be used for optimal modeling of the entire machine as well as its individual parts, units, or support systems such as cooling and working fluid supply systems, magnetic systems, and structural elements.

3. In multi-parameter TG design, the PSO algorithm allows simultaneous use of CFD calculations (Computational Fluid Dynamics, software-based flow modeling that improves accuracy by accounting for turbulence effects) and the finite element method. It is compatible with the MatLab software suite and SolidWorks CAD software. These capabilities allow refinement of the optimal search results, which is especially important for the equipment like TGs, where statistical analysis is limited due to the small number of identical electrical machines.

4. Conducting the PSO modeling for the considered turbogenerator TGV-500-2U3, manufactured by the «Electrotyazhmash» plant (Kharkov, Ukraine) allowed us to determine that there are small reserves in terms of thermal parameters. Determining such reserves will allow some changes to be made to the design of new turbogenerators, increasing their capacity practically without changing the design, and therefore eliminating the need to purchase new technological equipment, which is necessary in war conditions. Determining reserves based on thermal characteristics for turbogenerators at power plants makes it possible to switch from overload mode to overload mode if it is necessary to maintain network parameters.

Determining reserves based on thermal characteristics for the TGs at power plants makes it possible to switch them to overload mode if it is necessary to maintain network parameters.

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