SECTION 4. ELECTRICAL ENGINEERING

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4.1 The heat processes in a powerful turbogenerator

Today, numerical methods are increasingly used for the solution of scientific and engineering problems. There is a variety of commercial computer programs based on the finite element method (FEM) used for this purpose. The FEM is a numerical approach, by which the general differential equations describing a certain physical phenomena in a structure can be solved in an approximate manner. These equations are assumed to hold over a certain region of the structure, which can be one-, two- or three-dimensional. In fact, the region is divided into smaller parts, so-called finite elements, and the approximation is then carried out over each element. This approximation, usually a polynomial, is actually some kind of interpolation over the element, and it is assumed that the variable is known at certain points within the element, called nodal points. The precise manner, in which the variable changes between its values at the nodal points, is expressed by the specific approximation that may be linear, quadratic, cubic, etc. The coefficients of the polynomials are chosen in such a way that a variational principle is approximately satisfied. Having determined the behaviour of all elements, they are then patched together, using some specific rules, to form the entire region. The collection of all elements is called a finite element mesh.

The emergence of FEM took place in the early 1960’s and since then its use has spread to virtually all fields of engineering. The first applications on electrical machine problems were presented in the early 1970’s. In the 1980’s the research on numerical field computation methods expanded rapidly, and there are nowadays a variety of convenient simulation software for computer calculations and design of electromechanical energy converters, in particular powerful turbogenerators. The most well-known complexes are FEMLAB, ANSYS, MAXWEL and COMSOL Multiphysics. The COMSOL Multiphysics software [100] deserves special attention, because used today in many universities of the world, as well as professional researchers of various fields.

1. The most significant highlights of COMSOL Multiphysics are

- predefined physics and user-defined equations;
- high-performance numerical algorithms and postprocessing capabilities;
- application specific add-on products for chemical engineering, heat transfer, structural mechanics, electromagnetics and fluid flow;
- bidirectional interface with MATLAB;
- bidirectional interface with Simulink;
- ability to enrich models with custom user interfaces and compile them into stand-alone applications;
- ability to solve multiphysical problems and the complex (interrelated) mathematical models.

Also an important advantage of COMSOL Multiphysics is the simplicity of interface in a coefficient form enables simulation of physical processes without focusing directly on the differential equations solution and finding time for variation calculations (experiments).

Researchers use the COMSOL Multiphysics software to simulate designs, devices and processes in all fields of engineering, manufacturing and scientific work. The simulation platform brings fully coupled multiphysics and single-physics modeling capabilities, model management, as well user-friendly tools for building simulation applications.

Researcher can add any combination of add-on products from the COMSOL product suite to the COMSOL Multiphysics software platform. Doing so gives researcher access to specialized features to suit his particular modeling needs in a user interface that always looks the same, regardless of engineering field or physics phenomena. Add-on modules provide specialized functionality for electromagnetics, structural mechanics, acoustics, fluid flow, heat transfer and chemical engineering. Interfacing products are available for computer-aided design (CAD) and other third-party software. COMSOL Multiphysics is integrated with MATLAB and lets researcher generate a MATLAB file version of a simulation built with COMSOL Multiphysics. Researcher can modify the model MATLAB file, extend it with MATLAB code and run it from MATLAB. COMSOL Multiphysics is integrated with Simulink and lets researcher cosimulate using functional mock-up unit files for use in a Simulink diagram, export state-space models from COMSOL to Simulink or pass sweep and curve data for use by interpolation tables in Simulink. Researcher can also synchronize Microsoft Excel spreadsheet data with the parameters define in the COMSOL Multiphysics environment. All third-party software are: MATLAB, Simulink, Excel, CAD Import Module, Design Module, Electronic CAD (ECAD) Import Module, SOLIDWORKS Inventor, AutoCAD, Revit, Parametric Technology Corporation PTC Creo Parametric, Solid Edge, File Import for CATIA V5. All add-on products from the product suite connect seamlessly with COMSOL Multiphysics for a modeling workflow that remains the same regardless of what researchers are modeling.

The COMSOL Multiphysics simulation environment facilitates all steps in the modeling process – defining geometry, specifying physics, meshing, solving and then postprocessing the results. Optionally, by adding a tailored graphical user interface to a model, researcher can turn it into an application that is usable by anyone, regardless of modeling experience. Those applications can be deployed over the web using COMSOL Server, or compiled with COMSOL Compiler to run stand-alone. Model setup is quick, thanks to a number of predefined modeling interfaces for applications ranging from fluid flow and heat transfer to structural mechanics and electromagnetic analyses. Material properties, source terms and boundary conditions can all be arbitrary functions of the dependent variables.

Predefined multiphysics-application templates solve many common problem types. Researcher has the option of choosing different physics from the Multiphysics Menu and defining the interdependencies himself. Or researcher can specify his own partial differential equations and couple them with other equations and physics.

Modeling is useful together with experiments for optimizing processes and devices quicker, also often more efficiently and accurately than running experimental methods or testing prototypes alone. By developing experimentally validated models for analyses, researcher can gain a deeper understanding of the design or process because researcher can study it in a more convenient manner than in the laboratory.

Multiphysics is often a necessity for accurately modeling the design or process. As a user of COMSOL Multiphysics, researcher is free from the restrictive nature generally associated with simulation software and has complete control over all aspects of his model. Researcher can be creative in a way that is impossible, or a lot harder, with traditional approaches, thanks to the ability to couple any number of physics phenomena together. For even further customization, input user-defined physics descriptions, with associated equations and expressions, directly in the user interface.

Modeling with COMSOL Multiphysics provides accurate results. Accurate multiphysics models consider a wide range of possible operating conditions and physical effects. This makes it possible to use models for understanding, designing, optimizing processes and devices for realistic operating conditions.

COMSOL Multiphysics includes the Model Builder, Application Builder and Model Manager.

Modeling with COMSOL Multiphysics means being able to move between simulating electromagnetics, structural mechanics, acoustics, fluid flow, heat transfer and chemical reaction phenomena in one software environment. Researcher can also combine physics phenomena from these areas in a single model. The Model Builder in COMSOL Multiphysics provides researcher with a complete simulation environment and a consistent modeling workflow from start to finish, regardless of the type of design or process researcher wish to analyze and develop. The Model Builder contains all the functionality and operations for building, solving, visualizing and evaluating models. The Model Builder includes all of the steps in the modeling workflow – from defining geometries, material properties and the physics that describe specific phenomena to performing computations and evaluating the results.

The Application Builder gives researcher the tools to build his own simulation apps. When a model is developed, can be used the Application Builder to turn it into a simulation application with a dedicated user interface that can be used by engineers and scientists who are not experts in simulation software. In many organizations, a small group of numerical simulation experts services a much larger group of people working in product development, manufacturing, or as researchers studying physics phenomena and processes. To make it possible for this small group to service the much larger group, the COMSOL Multiphysics software contains functionality for building simulation applications. The Application Builder is included in COMSOL Multiphysics and allows simulation experts to create intuitive and very specific user interfaces for their otherwise general computational models – ready-to-use custom apps. Applications can be tested and run through COMSOL Multiphysics, also deployed with the addition of the COMSOL Server or COMSOL Compiler products. Both products allow researcher to share finished applications with his design teams, manufacturing departments, process operators, test laboratories, customers and clients worldwide.

To help keep models and applications organized, the COMSOL Multiphysics platform also includes the Model Manager, which is a tool for simulation management that provides version control and efficient storage. The Model Manager streamlines modeling and simulation work. This includes ways to collaborate and centrally organize models with version control that systematically tracks changes and updates to models. The Model Manager is accessible directly from the COMSOL Multiphysics user interface and allows researcher to use a local database or connect to a remote server database. There are options for efficiently storing models with only relevant data of drafts and revisions, as well as auxiliary data such as CAD, mesh and experimental data. Finding models and apps in the Model Manager is aided by user-defined tags for organizing the files and the ability to search for certain features or parameters. Researcher can control access to models with user groups and permissions.

There are different modules in COMSOL Multiphysics that solves certain sets of differential equations.

Analyzing electromagnetic systems and processes that encompass the static and low-frequency ranges requires a powerful simulation tool. With the AC/DC (alternating current / direct current) Module, researcher can run stationary, frequency-domain and time-domain analyses, as well as small-signal analysis. In the time and frequency domains, researcher can also account for capacitive effects.

Under static and low-frequency conditions, also when magnetic fields are negligible, modeling electric currents is sufficient for accurate results. The computations, based on Ohm's law, are made very efficient by solving for the electric potential. Based on the resulting potential field, a number of quantities can be calculated: resistance, conductance, electric field, current density and power dissipation.

The AC/DC Module add-on to the COMSOL Multiphysics platform provides researcher with a wide range of modeling features and numerical methods for investigating electromagnetic fields and electromagnetic interference (EMI) / electromagnetic compatibility (EMC) by solving Maxwell's equations. In general, the electromagnetic field is defined by Maxwell's equations, which are a rather simple formulation of the field problem, but they are difficult to solve, especially in electrical machines. This is due to the complicated geometry, the time-dependency of the magnetic field and the non-linearities because of the iron magnetic saturation. Furthermore, the equations of the magnetic field are coupled with the windings electric circuit equations and the rotor motion.

Researcher can compute magnetostatic fields, parasitic inductances, also forces on coils, conductors and magnets. A variety of formulations are available depending on if currents, magnetic materials or both are present.

For the most general case, where there is both current flow and magnetic materials present, a vector-field formulation allows for electric potential and input currents to be defined, also computes current density distribution, magnetic fields, magnetic forces, power dissipation and mutual inductances.

Coils can be modeled either explicitly, computing the exact current distribution within each wire, or in a homogenized sense, which is very efficient for coils with many turns. Complex coil shapes are automatically handled by computing the coil current distributions.

When modeling cables, wires, coils, solenoids and other inductive devices, the magnetic field is generated by electric currents flowing in conductive materials. Generally speaking, for time-varying fields with significant induction effects, there is a bidirectional coupling between electric and magnetic fields. In these cases, a vector-field formulation is needed, typically when the skin depth is of the order of the device size, but the wavelength is much larger.

Frequency-domain, small-signal analysis, time-domain modeling are supported in two- and three-dimensional. A specialized formulation is available that is particularly suitable for time-domain magnetic modeling of materials with a strongly nonlinear E-J (electric field intensity – current density) characteristic, such as superconductors.

Built-in functionality for rotating machinery makes it easy to model motors and generators. In any model that is used for simulating electromagnetic motion, researcher can examine the rigid or flexible body dynamics under the influence of magnetic forces, torques, induced currents, mechanical load and spring configurations.

The AC/DC Module provides built-in user interfaces for each of the electromagnetics areas listed above, as well as variations for specific modeling purposes. These interfaces each define sets of domain equations, boundary conditions, initial conditions, predefined meshes, predefined studies with solver settings for steady and transient analyses, as well as predefined plots and derived values. There are also features that connect the different interfaces, to easily model them together, which can be convenient for inductors, coils and motors.

Researcher can choose from a large material database that includes ferromagnetic materials, ferrimagnetic materials, B-H (magnetic flux density – magnetic field intensity) curves and H-B curves. Materials can be spatially varying, anisotropic, time-varying, lossy, complex-valued and discontinuous. It is easy to expand the scope of a simulation with little additional work. Researcher can define his own materials using mathematical expressions, lookup tables or combinations of both. Full anisotropic hysteresis is supported by means of the Jiles–Atherton material model for quasistatic parametric modeling and full transient analysis. Researcher can even compile his own material model in C-code and link to it as an external material.

2. Modeling losses in the laminated iron cores and yokes of motors and transformers is important for predicting their efficiency. In particular, for laminated iron (electrical steel), empirical electromagnetic loss models are important since macroscale Joule heating or induction heating is not able to fully describe the effect causing the losses. At the same time, modeling the laminates individually is often impractical. The AC/DC Module includes several well-known empirical loss calculation models, which give very good loss estimates for only a fraction of the computational effort that a high-fidelity model would take. This includes the effects of magnetic hysteresis and eddy currents, as well as other phenomena that contribute to the losses.

For accurate modeling of unbounded or large domains, infinite elements are available for both electric and magnetic fields. For electrostatics and magnetostatics simulation, boundary element method (BEM) is available as an alternative method for modeling large or infinite regions. Additionally, researcher can combine BEM with the FEM-based physics interfaces to perform hybrid FEM–BEM simulations.

For modeling very thin structures, researcher can use shell formulations that are available for DC, electrostatics, magnetostatics and induction simulations. Additionally, there is specialized functionality for modeling DC in shells with multiple layers. Electromagnetic shell modeling makes it possible to replace the thickness of a thin solid in a CAD model with physical property of a surface resulting in the much more efficient representation.

The multiphysics capabilities of the COMSOL Multiphysics software make it possible to investigate the impact of other physical effects – such as heat transfer, structural mechanics and acoustics – on an electromagnetics model. It is also possible to combine modules with each other whenever certain type of physics is required. To examine the real-world behaviour of a system or design virtually, easily couple multiple physical effects in one simulation with the multiphysics modeling capabilities included in the software.

The Heat Transfer Module includes a comprehensive set of features for investigating thermal designs and effects of heat loads. Researcher can model the temperature fields and heat fluxes throughout components, enclosures and buildings. All of the capabilities in the Heat Transfer Module are based on the three modes of heat transfer: conduction, convection and radiation. Conduction in any material can have an isotropic or anisotropic thermal conductivity, and it may be constant or a function of temperature. Convection, the motion of fluids in heat transfer simulations, can be forced or free (natural) convection. Thermal radiation can be accounted for using surface-to-surface radiation or radiation in semitransparent media. There are many variations within the modes of heat transfer and the different modes must be considered together – in some cases, all three at once. All of this requires different equations that must be handled simultaneously to ensure accurate models.

Researcher may be interested in simulation a multiphysics modeling approach for the many types of heat sources

- model Joule heating (also known as resistive heating) in solids, fluids, shells and layered shells;
- model inline induction heaters and metal processing applications;
- model microwave or radiofrequancy, heating in waveguides, tissue and other bio-applications;
- use the Beer–Lambert Law to model laser heating, ablation in various manufacturing and biomedical processes;
- understand the effects of thermal expansion and thermal stress for a variety of operating conditions;
- include the contact thermal conductance coefficient, which depends on the contact pressure from the solid mechanics model;
- thermoelectric effects: account for the Peltier–Seebeck–Thomson effects and include common materials, such as bismuth telluride and lead telluride;
- thin shells: analyze thermal performance when designing electronic devices and power system components;
- heat transfer in porous media: account for conduction and convection in a porous media, as well as thermal dispersion;

- simulate heat transfer in porous media where a local thermal equilibrium is not assumed, as with a rapid flow in the pores;
- electronic cooling: analyze cooling capacity with efficient and accurate simulations, to avoid malfunction and suboptimal designs;
- heat exchangers: analyze fluids carrying energy over large distances, while the solids separate the fluids to exchange energy without mixing;
- medical technology and bioheating: use the bioheat equation to analyze processes in medical applications;
- model heat and moisture transport in air to determine saturation pressure, account for evaporation and avoid condensation;
- thermal management in buildings: analyze thermal performance of wooden frames, window frames, porous building materials and other building structures;
- freeze drying: compute coupled heat and mass balances to simulate an advancing fluid-solid interface through a porous medium;
- spacecraft thermal analysis: compute the spacecraft temperature from the direct solar radiation, albedo and planet infrared flux, as well as the radiative heat transfer between various spacecraft parts.

The Heat Transfer Module offers specialized functionality for modeling heat transfer effects and works seamlessly in the COMSOL Multiphysics platform for a consistent model-building workflow. The Heat Transfer Module contains features for modeling conjugate heat transfer and nonisothermal flow effects. Laminar and turbulent flow can be modeled with natural and forced convection. Pressure work and viscous dissipation can also be activated to affect the temperature distribution.

The Heat Transfer Module provides features for modeling surface-to-surface radiation on diffuse surfaces, mixed diffuse-specular surfaces and semitransparent layers. These features are available for two-dimensional, two-dimensional axisymmetric and three-dimensional geometries. Predefined settings are available for solar and ambient radiation, where the surface absorptivity for short wavelengths (the solar spectral band) may differ from the surface emissivity for the longer wavelengths (the ambient spectral band). In addition, the sun radiation direction can be defined from the geographical position and time. The view factors are computed using the hemicube, the ray-shooting or direct integration area method. For computationally effective simulations, it is possible to define planes or sectors of symmetry. When combined with a moving frame, the surface-to-surface radiation interface automatically updates the view factors as the geometrical configuration deforms.

To simulate phase change phenomena in heat transfer analyses, the Heat Transfer Module provides two methods. The Phase Change Material feature implements the apparent heat capacity formulation and accounts for enthalpy of phase change and changes in material properties. This method includes the ability to model volume and/or topology changes. Alternatively, the Phase Change Interface feature models phase change following the Stefan energy balance condition to compute the velocity of the interface between two phases that may have different densities. Combined with deformed geometry, this approach is very efficient and effective, when there is no topology change.

With the Heat Transfer Module, researchers have the tools to simulate many types of radiation in semitransparent media: participating media, absorbing and scattering media, also beams in absorbing media.

For heat transfer in thin layers, the Heat Transfer Module provides individual layer models and layered material technology, to investigate heat transfer in layers that are geometrically much smaller than the rest of a model. This functionality is available for thin layers, shells, thin films and fractures. For individual layers, the thermally thin layer model is used for highly conductive materials with heat transfer tangential to the layer and negligible temperature difference on either side of the layer. Conversely, the thermally thick layer model can represent poorly conducting materials that act as a thermal resistance in the shell’s perpendicular direction; this model computes the temperature difference between the two layer sides. Finally, the general model provides a highly accurate and universal simulation, as it embeds the complete heat equations. The layered material technology includes preprocessing tools for detailed layered material definition, load/save of layered structure configurations from/to a file and layer preview features. Researcher can visualize the results in thin and layered structures, as if they were originally modeled as three-dimensional solids. The layered material functionality is included in the AC/DC Module, making it possible to include multiphysics couplings like electromagnetic heating or thermal expansion on layered materials.

Heat and moisture transport requires extensive multiphysics capabilities to couple heat transfer with moisture flow, moisture transport in building materials, moist air and hygroscopic porous media. To study these effects, the Heat Transfer Module includes settings for modeling moisture transport in air and moist porous media coupled with nonisothermal flow. There are tools to analyze water condensation and evaporation on surfaces, also additional features to analyze heat and moisture storage, latent heat effects, as well as diffusion and transport of moisture.

Features are available for computing the heat transfer rate and temperature distributions in a thermal network. The Lumped Thermal System interface supports lumped features such as thermal resistors, heat rate and thermal mass. The software solves an energy conservation equation using the temperatures and heat rates as dependent variables.

For radiative loads and temperature on a spacecraft, the Orbital Thermal Loads interface provides ready-made features for modeling the radiation from the Sun and Earth for satellites orbiting around Earth. This feature makes it possible to include the spacecraft radiative properties, orbit and orientation, orbital maneuvers and planet properties. In addition, the interface computes and generates results that show direct solar radiation, albedo, planet infrared flux, as well as the radiative heat transfer between the different spacecraft parts. The interface can be combined with a Heat Transfer Interface to account for heat conduction in a spacecraft’s solid parts.

There are a couple of general steps for building a model in COMSOL Multiphysics. First step is to create the geometry and apply a mesh to it, also apply physics to the geometry. The Physics Menu contains two different settings, which are the Subdomain and Boundary Settings. The Subdomain Settings are used for installing the material properties of the geometry different domains. The Boundary Settings are used for installing boundary conditions on the different materials, also to install boundaries between materials and their surroundings. The last step is solving the model that has been set up. The researcher can select different settings for the Solver.

There are different submenus in the Comsol simulation environment. The Global Definitions Submenu is used to define the relevant parameters and variables needed in order to create a simulation. Under the Definitions Submenu researcher can do different operations and assign them variables, also chose the relevant coordinate system needed. The Geometry Submenu is used to create the geometry that the finite element analysis is applied on. The Materials Submenu is used to apply different materials (or properties) for different parts of the geometry. The next important Submenu contains the different equations and boundary conditions used in order to simulate. The Study Submenu is used to choose what type of solver that is going to be used. The Results Submenu is used to derive information and results from the finite element analysis. The Mesh Submenu is used to choose what type of mesh that is going to be applied on the geometry.

The main tendency of development for the power engineering and turbogenerator construction always consisted in the constant increasing of capacity unit for electric power station turbo-aggregates, since it reduces the specific cost of both the turbo-aggregates manufacturing and the mounting works, decreases in number of operating personnel and the materials expense per unit of installed power, and also increases the efficiency [101, 102].

The manufacturing of high-power turbogenerators would be impossible without the application of modern cooling systems of the most loaded units. This is especially true for the stator winding. The introduction of direct liquid cooling for the stator winding bars allows to increase the linear load of turbogenerators (up to 3000 A/cm) and the capacity units consequently (up to 1000–1300 MW). At the same time, the introduction of direct liquid cooling for the stator winding is relation with design the additional systems for preparation and circulation distillate, control and support of dielectric indices etc. The reliability of a turbogenerator depends on the reliability of all elements for the stator winding cooling system.

A necessary condition for the reliability during a turbogenerator operation is ensuring of compactness for the liquid cooling system, especially inside the housing. Each the stator winding bar consists of transposed elementary conductors, some of them are hollow and has canals for distillate circulation. Failure of hollow conductor’s compactness leads to distillate leakage, moistening of the main insulation, reducing the electrical stability of insulation and, as a result, its electrical breakdown.

When detection of distillate leakage inside turbogenerator housing, for locate and possibly eliminate of damage, the staff immediately stops a generator and inspects of the cooling system state. If the cause of distillate leakage is damage of elementary hollow conductor (or several), an electrical machine is usually requires long-term repairs for replace the damaged bar.

Some turbogenerators manufacturers (for example, the Kharkiv plant «Electrovazhmash») the design of distillate supply to the winding frontal part performs collapsible [103].

When detection damage of hollow conductor’s compactness in bar, the distillate supply hose is disconnected, a head bar is opened and access to the distillate inlets into hollow conductors appears. If known which hollow conductors have cracks in the walls, these conductors are plugged (stoppled) from the side of the distillate inlet (a turbine side). This eliminates the need for immediate repair, so replacement of the damaged bar can be performed during the next medium or capital planned and preventive repair. A number of stopple hollow conductors must be limited, and the bar temperature under such conditions should not exceed permissible value for heat resistance class of the winding insulation. Thus, in the operation instruction for turbogenerators by the Kharkiv plant «Electrovazhmash» a number of adjacent stoppled hollow conductors should not exceed two. But it is not contains recommendations for a larger number of stoppled conductors and their location in bar separately from each other.

With the help of a mathematical model realized a simplified (estimated) heat calculation, which not requires a large amount of work and can ensures a correct estimate of heat state for separate elements and units of study object [104, 105, 106]. The use of approximate calculation methods for generators typical designs is permissible [107, 108]. Since heat influence of the stator and the rotor on each other is small, a separate consideration of their heat state is conventional [104-113].

The heat processes in the stator winding bar of a turbogenerator type TGV-250-2P3 are investigated.

The peculiarity of the bars design is making according to the principle «robel in robel», when their section contains two transposed bars, one of which is located inside the other (Figure 1). For the internal bar on one hollow conductor there are two solid conductors, for the external conductor – three solid conductors. Such design ensures effective transfer of heat losses from elementary conductors even under conditions of partial damages of refrigerant circulation in separate hollow conductors.

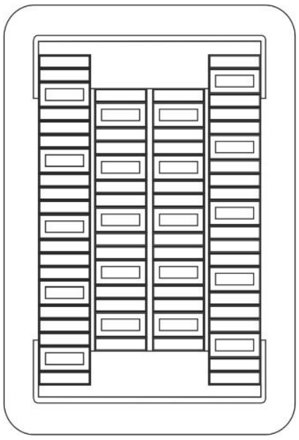


Figure 1. The section of the stator winding bar of a generator

During the development of a mathematical model, a number of assumptions that simplify the calculation and at the same time ensure the reliability of results are applied:

– taking into account the presence of elementary conductors transposition, it is assumed that heat losses in copper is uniformly distributed;

– heat losses in the stator core steel on the radial direction in accordance with the experimental studies results for an analogous power turbogenerator are given [114];

– the calculation area elements as homogeneous anisotropic solids with averaged thermophysical parameters of materials in accordance with the corresponding direction within the calculated elementary volumes are considered [112];

– the calculation area surfaces are smooth, the cooling flow velocity for the surfaces is constant [112];

– heat transfer coefficients of the cooled surfaces according to the known equation [112, 115, 116, 117] and experimental data [114] are determined;

– dependence of thermophysical parameters (coefficients of heat conductivity, specific heat and density) for the stator winding and the stator core materials on temperature is not taken into account;

– when choosing the calculation area, the symmetry and periodic repeatability for the structural elements of the stator winding and the stator core, as well as conditions of the cooling and heat transfer on the tangential direction of the stator core are taken into account [113];

– bar copper losses and the stator core steel losses, as well as thermophysical parameters (coefficients of heat conductivity, specific heat and density) for the expected calculation temperature are given.

Taking into account assumptions, design feature of a turbogenerator and the existing refrigerants circulation system, considered the joint calculation task of three-dimensional temperature field for sector of the stator core packet and the stator winding. Figure 2 shows the finite element mesh of the calculation area for the tooth (slot) division of the stator. The heat connection of the winding slot part with the stator core (steel), as well as the packet surface with the cooling hydrogen is mathematically correctly described.

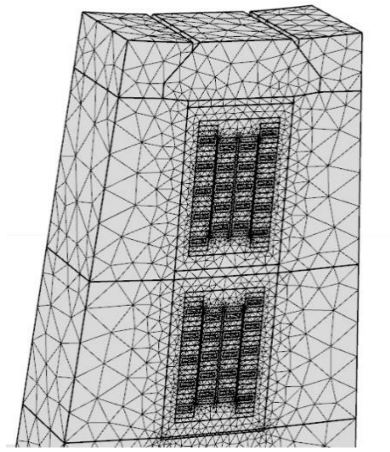


Figure 2. Finite element mesh of the calculation area

The temperature field by the differential equation of heat conductivity is described

$$c(T,l)\rho(T,l)\frac{\partial T}{\partial t}=div\Big(k(T,l)\cdot gradT\Big)+Q(T,l),\qquad(1)$$

where T is the temperature of the calculation area; c, ρ, k are the specific heat, density and heat conductivity coefficients of material for the calculation area, respectively; Q is the specific volumetric heat losses; l is the corresponding spatial coordinate.

The equation (1) by the following boundary conditions on the external bounds of each calculation subregion is supplemented:

– for the cooling canals of hollow conductors

$$\Delta T_{xi}=\pm\frac{k_C}{h_{xi}}\frac{\partial T}{\partial l_i},\qquad(2)$$

where k_C is the heat conductivity coefficient of hollow conductor cooper; h_{xi} is the heat transfer coefficient from the sides hollow conductor to water;

– for the external heat exchange surface of the stator core packet

$$\Delta T_{xi}=\pm\frac{k_S}{h_{xi}}\frac{\partial T}{\partial l_i},\qquad(3)$$

where k_S is the heat conductivity coefficient of steel packet; h_{xi} is the heat transfer coefficient of the corresponding heat exchange surface to hydrogen;

– the equality of heat flows on the border of elements contact surface is installed

$$\begin{cases} \pm k_i \dfrac{\partial T_i}{\partial n}(\xi - 0) = \Lambda_c \left[T_i(\xi + 0) - T_j(\xi - 0) \right] \\ \Lambda_c \left[T_i(\xi + 0) - T_j(\xi - 0) \right] = \pm k_j \dfrac{\partial T_j}{\partial n}(\xi + 0) \end{cases}, \quad (4)$$

where $\Lambda_c = h_c \cdot F_c$ is the equivalent heat conductivity, h_c is the heat transfer coefficient of contact surface, F_c is the contact area.

Table 1 shows thermophysical parameters for the main materials of structural elements of the stator core and the stator windings, which are used in the calculation.

Table 1.

Thermophysical parameters of the main structural materials of a generator

Material	Calculated value of heat conductivity coefficient, W/(m·K)
Copper of bar conductors	400
The main insulation of bar	0,185
Steel of packet - along the sheets - across the sheets	 20 1,9
Glasstextolite of gaskets between bars	0,34
Insulation of elementary conductors	0,22
Epoxy mastic	0,59

Table 2 presents heat transfer coefficients for the heat exchange surfaces of the main structural elements, which are used in the calculation.

Table 2.

Heat transfer coefficients for the heat exchange surfaces of structural elements

Surface	Calculated value of heat transfer coefficient, W/(m^2·K)
Surface of stator boring	200
The inner surface of hollow conductors of winding bar	175
Radial canal between stator packets - in the tooth zone - in the yoke zone	 160 100
The outer surface of the yoke	120

Thin-layer structures, such as the insulation of elementary conductor (0,17 mm per side) and the insulation of hollow conductor (0,2 mm per side), are taken into account by using the equivalent heat transfer coefficient – the ratio for heat conductivity of corresponding insulation to the thickness of corresponding insulation ($\alpha_{eq} = k_i/\delta_i$).

The reliability of a mathematical model for heat processes in the stator winding bar by comparing the test calculation results with the data of heat control staff system for analogous type and power turbogenerator under rated load conditions is verified [114]. The discrepancy between temperature distribution in the active elements (copper bars, iron packet) obtained with the help of a mathematical simulation and operational data not exceeds 10 % that for test heat calculations is permissible. As can be seen in Figure 3, the maximum temperature (70 °C) there is in the steel packet at the tooth root.

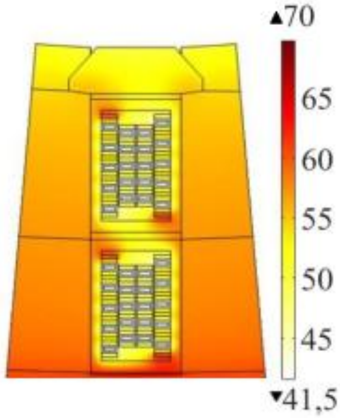
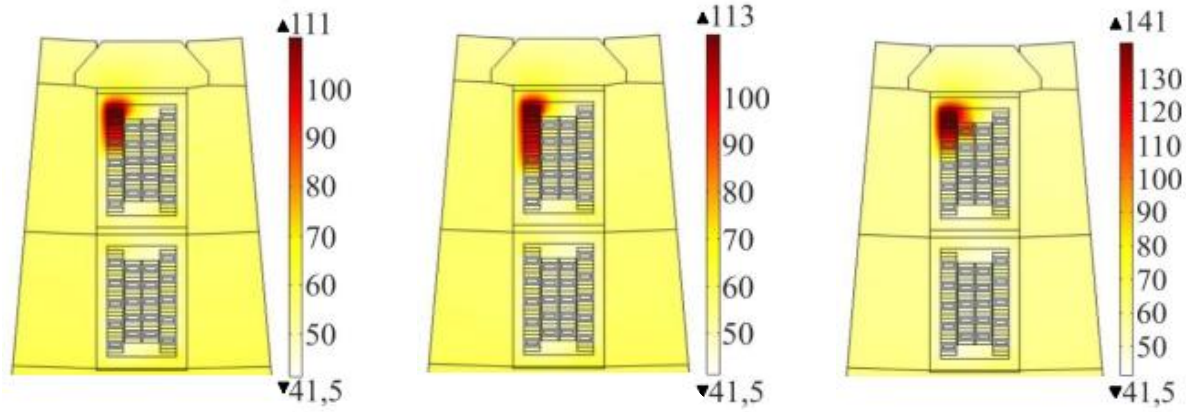


Figure 3. Temperature distribution in the calculation area of a turbogenerator under rated load conditions without refrigerant circulation damage

Following a mathematical simulation founded that under turbogenerator rated load conditions and damage of distillate circulation in two adjacent hollow elementary conductors, the maximum temperature of bar copper not exceeds the limit permissible value (140 °C) and at the rated temperature distillate (40 °C) is 111 °C (Figure 4, a). If three elementary hollow conductors without distillate circulation, the maximum temperature of bar copper depends on their mutual position. When three stoppled hollow conductors are located in the same column, the temperature is 113 °C (Figure

4, b). If these conductors are concentrated in the angular zone of bar section, the maximum temperature reaches the limit permissible value (Figure 4, c).



a **b** **c**

Figure 4. Temperature distribution in the calculation area of a turbogenerator under rated load conditions at the various variants of refrigerant circulation damage

When in the same column a number of adjacent hollow conductors without refrigerant circulation does not exceed three, a turbogenerator without any restrictions on the active load can be operated. If four stoppled conductors are located in the internal bar, a similar conclusion can be made. The maximum temperature of copper in these cases is 113 °C and 105 °C respectively, and the transfer of excess losses there is due to the heat connection between the internal and external bars.

If three stoppled conductors are concentrated in one place (for example, one stoppled conductor – in the external bar, and two stoppled conductors – in the internal bar, or vice versa), the maximum temperature reaches the limit permissible value (140 °C). This requires concentration attention on the control by staff means – the resistance thermometers, which are located between bars and at the distillate outlet from bar. If in the first case due to the winding transposition the probability of detection damage is not more than 5 %, then at the distillate outlet increase in the temperature as compared with normal state is almost 3 °C, which can be defined as a indication of the cooling damage.

In the case a larger number of hollow conductors without distillate circulation, the maximum temperature depends on their mutual position. If hollow conductors without distillate circulation are concentrated in one zone, the maximum temperature exceeds the limit permissible value: for four conductors in one zone, the maximum temperature is 160 °C, and for five conductors in one zone – 170 °C. In such cases it is possible to operate further a turbogenerator only under conditions of active load limitation. Thus, when near located four stoppled hollow conductors, the active load should be reduced to 85 % from rated value, and at the five near located stoppled conductors – down to 75 % from the rated value.

For cases other combinations of stoppled conductors location in the bar section, the additional researches of maximum temperature definition of the stator winding bar is required. If it is necessary to operate temporarily a turbogenerator with stoppled conductors in the stator winding bar, a permissible number of damaged conductors and their possible mutual position in the bar should be defined. At the same time, it is necessary to define the permissible load level of a turbogenerator with the damaged winding.

It is proved with the help of experimental and theoretical studies that during a powerful turbogenerator operation there is the heat tangential unevenness of the stator core end packets, especially under conditions of reactive power consumption [118–121]. In some cases, the temperature of separate teeth can vary by 1,8–2,0 times. For the interphase zone teeth, the adjacent slots of which contain the different phase’s bars of the stator winding, this is especially true. The heat level of interphase zone teeth depends on location of the different phase’s bars in the adjacent slots. The maximum heat there is in the teeth, the adjacent slots of which contain the different phase’s bars of the winding lower layer. The temperature level can exceed permissible value for the stator iron (120 °C) that negatively effects on the reliability of the stator winding and a turbogenerator as a whole. Therefore, the scientific substantiation of technical solutions efficiency for the decrease in heat of teeth at phase zones junction of the stator winding, as well as the heat tangential unevenness of the stator core end packet is an urgent task. For realize variations calculations of temperature in the packet separate zones under different cooling conditions, the development of a mathematical model of heat processes in the stator core end packet is required.

With the help of a mathematical model realized a simplified (estimated) heat calculation. The use of approximate calculation methods for generators typical designs is permissible [107, 108]. Since heat influence of the stator and the rotor on each other is small, a separate consideration of their heat state is conventional [104-113].

The heat processes in the stator core end packet of a turbogenerator type TGV-200 are investigated.

During the development of a mathematical model, a number of assumptions that simplify the calculation and at the same time ensure the reliability of results are applied:

– taking into account the presence of elementary conductors transposition, it is assumed that heat losses in copper is uniformly distributed;

– heat losses in the stator core steel on the radial direction in accordance with the experimental studies results for an analogous power turbogenerator are given [114];

– the calculation area elements as homogeneous anisotropic solids with averaged thermophysical parameters of materials in accordance with the corresponding direction within the calculated elementary volumes are considered [112];

– the calculation area surfaces are smooth, the cooling flow velocity for the surfaces is constant [112];

– heat transfer coefficients of the cooled surfaces according to the known equation [112, 115, 116, 117] and experimental data [114] are determined;

– dependence of thermophysical parameters (coefficients of heat conductivity, specific heat and density) for the stator winding and the stator core materials on temperature is not taken into account;

– when choosing the calculation area, the symmetry and periodic repeatability for the structural elements of the stator winding and the stator core, as well as conditions of the cooling and heat transfer on the tangential direction of the stator core are taken into account [113];

– bar copper losses and the stator core steel losses, as well as thermophysical parameters (coefficients of heat conductivity, specific heat and density) for the expected calculation temperature are given.

Taking into account assumptions, design feature of a turbogenerator and the existing refrigerants circulation system, considered the joint calculation task of three-dimensional temperature field for sector of the stator core end packet and the stator winding. The calculation area includes three tooth (slot) divisions of the stator for the possibility of comparing the heat level in the interphase zone teeth, the adjacent slots of which contain the different phases bars of the stator winding lower layer, with heat in the teeth that contain one phase bars in adjacent slots (Figure 5). Figure 6 show the finite elements mesh for part of the calculation area. The heat connection of the winding slot part with the stator core (steel), as well as the corresponding packet surface and the bar cooling tubes with the refrigerant (hydrogen) is mathematically correctly described.

Figure 5. The calculation area of the stator core end packet of a turbogenerator

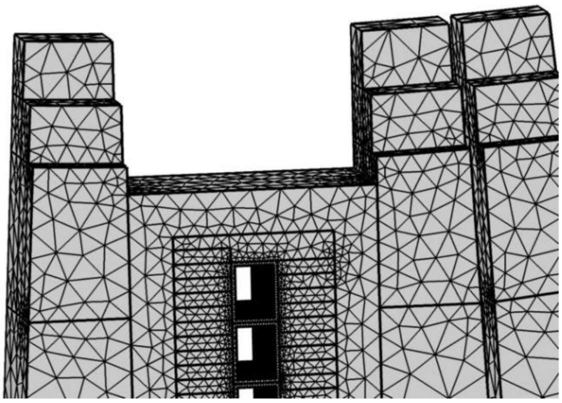


Figure 6. Finite elements mesh for the calculation area

The temperature field by the differential equation of heat conductivity (1) is described

$$c(T,l)\rho(T,l)\frac{\partial T}{\partial t}=div\Big(k(T,l)\cdot gradT\Big)+Q(T,l). \qquad (1)$$

The equation (1) by the following boundary conditions on the external bounds of each calculation subregion is supplemented:

– for canals of cooling tubes of the winding bars

$$\Delta T_{xi}=\pm\frac{k_{S.S}}{h_{xi}}\frac{\partial T}{\partial l_i}, \qquad (5)$$

where $k_{S.S}$ is the heat conductivity coefficient of tube stainless steel; h_{xi} is the heat transfer coefficient from the sides cooling tube to hydrogen;

– for the external heat exchange surface of the stator core packet is installed (3)

$$\Delta T_{xi} = \pm \frac{k_S}{h_{xi}} \frac{\partial T}{\partial l_i}; \tag{3}$$

– for the border of elements contact surface is installed (4)

$$\begin{cases} \pm k_i \dfrac{\partial T_i}{\partial n}(\xi - 0) = \Lambda_c\left[T_i(\xi+0) - T_j(\xi-0)\right] \\ \Lambda_c\left[T_i(\xi+0) - T_j(\xi-0)\right] = \pm k_j \dfrac{\partial T_j}{\partial n}(\xi+0) \end{cases}. \tag{4}$$

Table 3 shows thermophysical parameters for the main materials of structural elements of the stator core and the stator windings, which are used in the calculation.

Table 3.

Thermophysical parameters of the main structural materials of a generator

Material	Calculated value of heat conductivity coefficient, W/(m·K)
Copper of bar conductors	400
The main insulation of bar	0,185
Steel of packet - along the sheets - across the sheets	 20 1,9
Glasstextolite of gaskets between bars	0,34
Insulation of elementary conductors	0,22
Insulation of colling tube	0,2
Stainless steel of cooling tube	17
Epoxy mastic	0,59

Table 4 presents heat transfer coefficients for the heat exchange surfaces of the main structural elements, which are used in the calculation.

Table 4.

Heat transfer coefficients for the heat exchange surfaces of structural elements

Surface	Calculated value of heat transfer coefficient, W/(m^2·K)
Surface of stator boring	200
The inner surface of cooling tube of winding bar	175
Radial canal between the first and second stator packets - in the tooth zone - in the yoke zone	 160 100
Canal between the press plate and the stator end packet - in the tooth zone - in the yoke zone	 90 100
The outer surface of the yoke	120

Thin-layer structures, such as the insulation of elementary conductor (0,17 mm per side) and the insulation of colling tube (0,2 mm per side), are taken into account by using the equivalent heat transfer coefficient – the ratio for heat conductivity of corresponding insulation to the thickness of corresponding insulation ($\alpha_{eq} = k_i / \delta_i$).

Heat losses in the interphase zone tooth in accordance with the experimental studies data on a scale physical model of a similar turbogenerator end zone are defined [114]. In particular, found that heat losses in the teeth, the adjacent slots of which contain the different phase's bars of the stator winding lower layer, 1,795 times as higher than heat losses in the teeth with only one phase bars in adjacent slots.

The reliability of a mathematical model for heat processes in the stator end packet is verified by comparing the calculated temperature field with the experimental studies data for the tooth outside of interphase zone, the adjacent slots of which contain the one phase bars, obtained for analogous type and power turbogenerator under rated load conditions [114]. According to results of calculation and experimental studies, the temperature discrepancy of separate zones is not more than 7 % that for heat calculations is permissible (Figure 7).

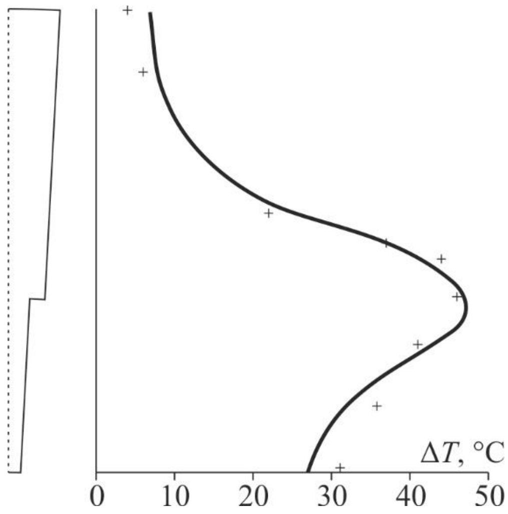


Figure 7. Comparison for the calculated steel overheat on the end packet surface (solid curve) with the experimental studies data (marked by «+»)

Figure 8 shows obtained with the help of a mathematical simulation the temperature distribution in the stator core end packet for the interphase zone tooth and the tooth outside of interphase zone under turbogenerator rated load conditions (temperature of the cooling hydrogen is 40 °C). For clearness, the temperature values on the end packet surface are also shown in Figure 8. The maximum temperature of packet steel in interphase zone exceeds the permissible level (120 °C) and there is in the middle of thickness at the tooth root. During a turbogenerator operation under conditions of reactive power consumption, the temperature level will be still more that negatively effects on the main insulation of the stator winding and the reliability of electrical machine [114, 122-126].

A well-known method to the decrease in tangential unevenness and heat level of the stator core end packet of a turbogenerator is primarily the intensification for transfer of heat losses to the cooling hydrogen. As the experimental studies data show [114], the most part of heat losses transfers from the end packet surface into the radial ventilation canal between the end packet and the second packet of the end stator core, as well as into the ventilation canal between the press plate and the end packet (total volume is almost 95 %). Therefore, one of the effective means to the decrease in heat tangential unevenness of the stator end packet is the redistribution of the cooling hydrogen flow between the press plate and the end packet with a simultaneous increase in volume, which towards on the cooling of interphase zone, by appropriate apertures in the gas-distributive cylinder. As a result, the hydrogen flow in interphase zone (and the heat transfer coefficient, correspondingly) can be increased by 1,5–2 times without the cooling deterioration other elements and units of the stator end zone.

According to the mathematical simulation results (Figure 9), with the increase in heat transfer for the end surface of interphase zone tooth in the ventilation canal between the press plate and the end packet by 1,5 times, the maximum temperature of end packet can be reduced to 109 °C (by 11,4 %).

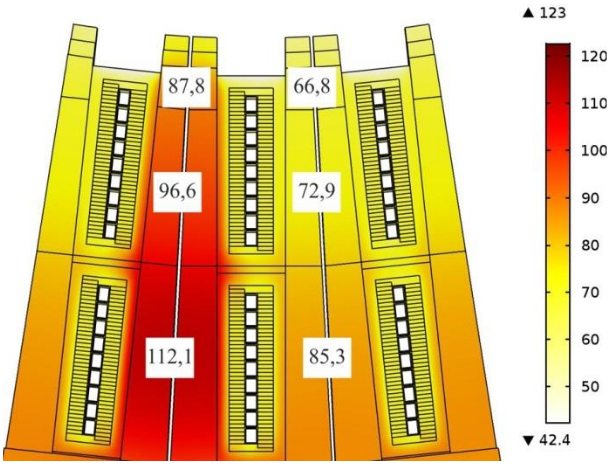


Figure 8. Temperature distribution in the stator core end packet of a turbogenerator under rated load conditions

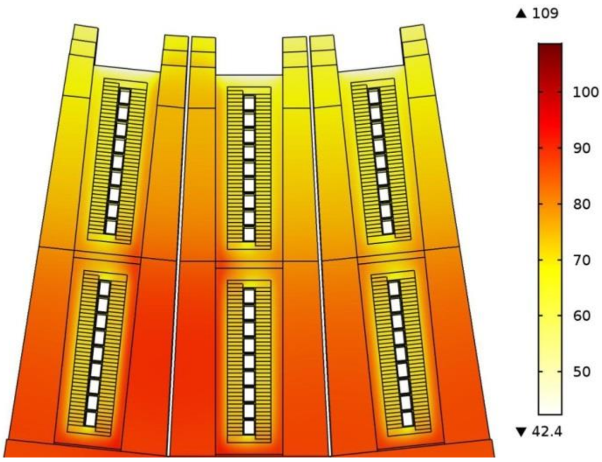


Figure 9. Temperature distribution in the stator core end packet of a turbogenerator at the cooling intensification of interphase zone

Another promising way to the decrease in total heat level of the stator core end packet is the increase in heat conductivity of laminated iron across the sheets. One of technologies that allows to increase in transverse heat conductivity is gluing of the packet sheets, for example, with the help of epoxy glue EK-3. This increases the mechanical stiffness of a turbogenerator stator packet under conditions of variable load and reactive power consumption. The heat conductivity of the glued packet averages 3,4 W/(m·K) that almost twice as high analogous value in the absence of gluing (1,9 W/(m·K)) [117]. The addition of dispersed insulating fillers with a high heat conductivity ((≥ 5–10 W/(m·K)) in glue allows to increase in equivalent heat conductivity of packet to 5–6 W/(m·K).

As can be seen in Figure 10, according to the mathematical simulation results, the maximum temperature level of the teeth steel is 118 °C (decreases by 4 %) at the transverse heat conductivity 3,4 W/(m·K).

Figure 11 shows the mathematical simulation results for a simultaneous application of the cooling intensification of interphase zone tooth and the increase in transverse heat conductivity of steel. According to these results, this technical solution allows to reduce in maximum temperature level of the tooth steel to 103 °C (by 16,3 %). The maximum temperature reserve of the packet teeth is 20 °C that allows to increase in load diapason of a turbogenerator under conditions of reactive power consumption.

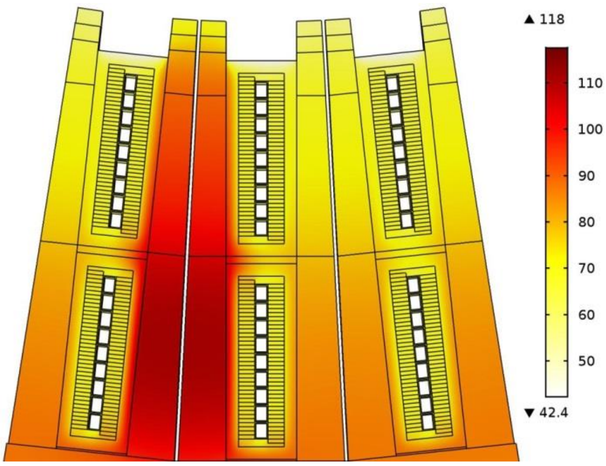


Figure 10. Temperature distribution in the stator core end packet of a turbogenerator at the transverse heat conductivity of steel 3,4 W/(m·K)

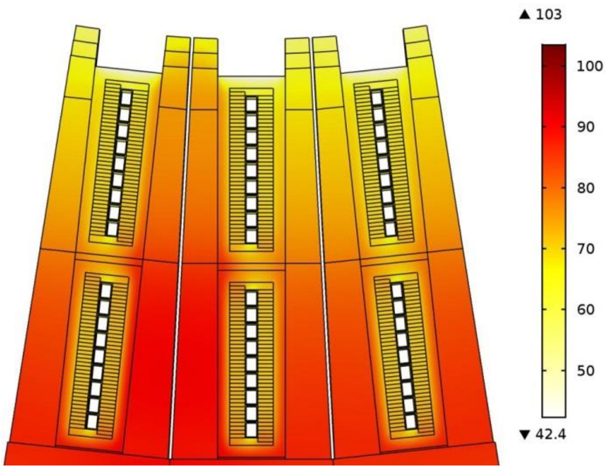


Figure 11. Temperature distribution in the stator core end packet of a turbogenerator at the transverse heat conductivity of steel 3,4 W/(m·K) and the cooling intensification of interphase zone

For reduction of addition losses from the axial magnetic field, in more new modifications of a turbogenerator type TGV-200 in the stator core end packets there are longitudinal cuts (slits) on the height of the tooth (from crown to root). To ensure the mechanical stiffness of packets, the slits are filled with epoxy resin with certain admixtures (performed monolithic). The refrigerant circulation in slits of interphase zone teeth allows significantly to increase the efficiency for transfer of heat losses. The temperature distribution on the end packet surface obtained with the help of a mathematical simulation at the heat transfer coefficient in slits 100 W/(m^2·K) is shown in Figure 12. Under such conditions the maximum temperature of packet can be reduced to 106 °C (by 13,8 %).

As can be seen in Figure 13, a simultaneous (complex) application of the above measures allows to reduce in maximum temperature of stator core end packet to 94,6 °C (by 23,1 %). In this case, the maximum heat there is in depth of the tooth outside of interphase zone and the highest temperature of interphase zone tooth is 89,6 °C.

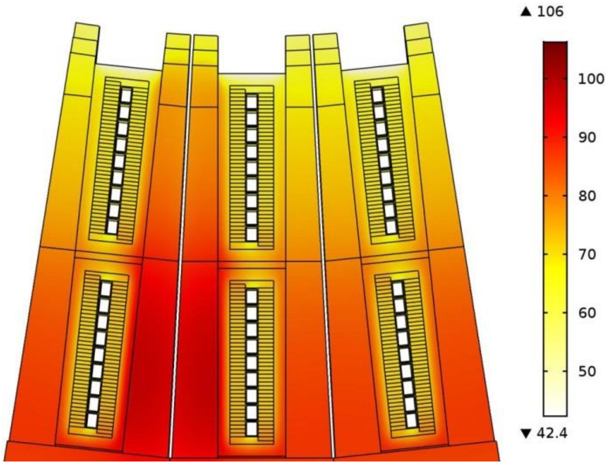


Figure 12. Temperature distribution in the stator core end packet of a turbogenerator at the ventilation of longitudinal slit of interphase zone tooth

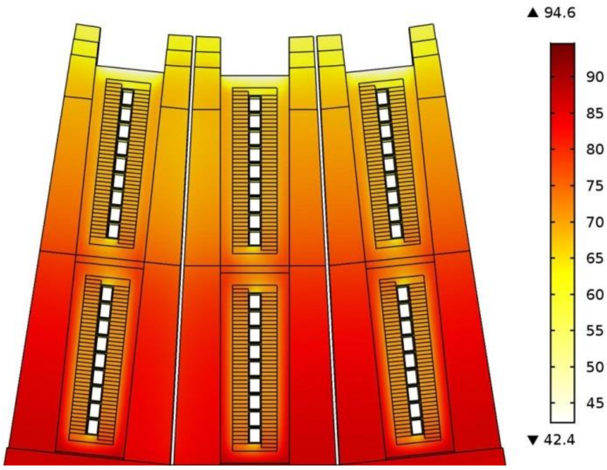


Figure 13. Temperature distribution in the stator core end packet of a turbogenerator at the complex application of technical solutions

Thus, the complex application of the above technical solutions allows to obtain almost the same level for the heat teeth of the stator core end packet on the tangential direction regardless of their location relatively the stator winding under turbogenerator rated load conditions. In general, the maximum temperature reserve of the stator packet steel is 25,4 °C that allows to increase the reliability and load capacity of a turbogenerator.

The technological progress of cooling systems and the cooling intensification of turbogenerators active parts caused a significant increasing of material use coefficient that is development for the economical method of manufacturing turbogenerators, despite construction complication due to the need of auxiliary systems for the cooling systems: gas system, oil supply system of shaft compression, water cooling system of the windings [102].

Because the probability of a turbogenerator unfailing operation P_{ot} is defined as the product of unfailing operation probability for component parts and auxiliary systems P_{oi}

$$P_{ot} = \prod_{i=1}^{n} P_{oi}\,, \qquad (6)$$

the use of each new system will be at the bottom of reduce the probability of a turbogenerator unfailing operation as a whole, unless simultaneously the unfailing operation probability for all or a certain number of component parts and auxiliary systems is increased accordingly [127]. But if the P_{oi} is close to 1 and meets the limits of technological capabilities, due to the growth of power unit and the rise of use degree coefficient, a turbogenerator complication leads to the inevitable reduction of reliability operation and the increase in losses from unplanned repairs [128, 129, 130].

The reliability statistics of generators 200–1000 MW [102, 103, 127] illustrates the above facts (Figure 14).

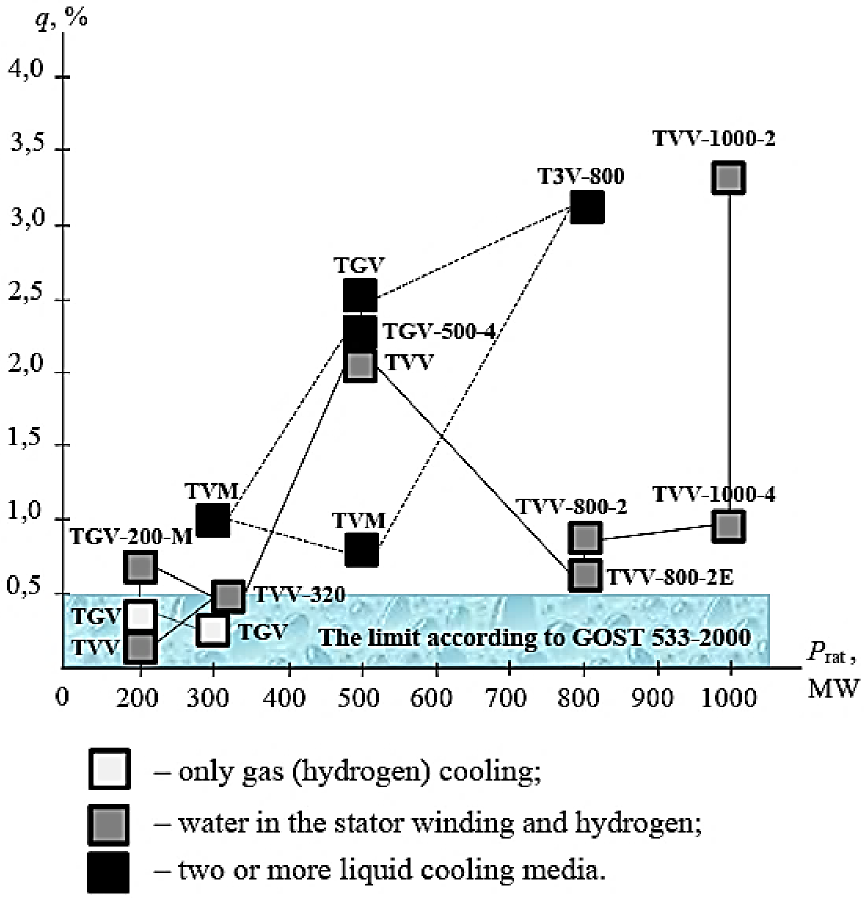


Figure 14. The forced downtime coefficient q of turbogenerators according to the average data for 1993–2022 years

The lowest forced downtime coefficient q = 0,2–0,3 % (at a limit normative value 0,5 %) has only generators with hydrogen cooling, a power 200 and 300 MW. The next group is machines with hydrogen-water cooling contain only 2 of 8 machines types that satisfy the standards of reliability. In the group of machines with windings water cooling and full water cooling, no generator satisfies the requirements of reliability. Foreign statistics gives quantitatively similar results [103, 127, 131].

Therefore, for achievement of the highest possible reliability of a turbogenerator with any unit power, it is necessary to limit the use of water and other liquid agents as a cooling media, and for achievement of sufficient fire and explosion safety – do not use hydrogen at all.

It is very important for nuclear power stations, to ensure fire and explosion safety of turbogenerators in the engine room. This is requires a number of protective arrangements for turbogenerators with hydrogen cooling, but the most radically method can be realized in practice by refusal for hydrogen cooling. The hydrogen cooling of a turbogenerator active parts requires not only the presence of a gas system with special equipment that allow safe filling a generator housing with hydrogen and it displacement with inert gas and then air, but also the presence of oil supply system with pumps, filters, heat exchangers for the operation of shaft compression. If in bearings oil systems today fire safety can be ensured by the use of non-combustible lubricating oil, due to the inevitability entering oil from the shaft compression in a turbogenerator housing and the aggressiveness of non-combustible oil to high-voltage insulation and lacquer protective coats, for compression oil systems this way is unacceptable. Therefore, refusal for hydrogen cooling of a turbogenerator active parts and the absence of oil shaft compression allow completely excluding combustible materials from the zone, where these materials can ignite.

Approximately 15–20 % failures of turbogenerators with hydrogen cooling occurs due to a damage in the operation of gas system elements and oil compression with oil supply system, in particular, – a damage of gas-compactness. Most cases for a damage of gas-compactness are not accompanied by hydrogen ignition.

The probability of fire in gas-oil systems is estimated 0,5–1 % for a generator operation period at the year. The typical causes of fire are the hydrogen ignition when leakage through a damage of compactness or crack of gaskets in the flanges, through the valves hydro-seals on the discharge oil with compression when defect of valves or level regulators, through damage of compactness in the connectors of outer shields, the compression frame, through the shaft compression at the various defects of compactness, when the wrong work of regulators change pressure «oil-hydrogen» and reserve systems etc.

The oil may also fire, when leakage through damage of compactness or crack of gaskets in the flanges or fitting.

With the sharp increase in shaft-conductor vibration that accompanied by damage of shaft and bearings, there are also damage of hydrogen compressions, outer shields and, consequently, catastrophic damages of the compressions for hydrogen cooling system with subsequent ignition of oil-hydrogen blend and fire in the engine room that leads to damage or collapse of the roof structure. Such severe accidents are negligible quantity (approximately 0,1–0,3 % for a generator operation period at the year), but leads to significant economic losses. In this case, there is the high probability of human death. These accidents usually occur as a result of the turbogenerator failure for reasons unrelated to the generator itself (for example, breaking of blades turbines, motor condition, shaft damage). Therefore, the prevention of catastrophic fires and explosions or reduction of significant losses in such cases is possible only with the help of complex systems for vibration diagnostics, which provides immediate stop of a machine and automatic accelerated displacement of hydrogen when vibrations speed over 45 mm/sec.

Improvement of gas-oil system for a turbogenerator with hydrogen cooling allows to prevent the most of known causes of fire, but it is impossible to prevent everything, especially considering that more malfunctions in the gas-oil system and shaft compressions related with insufficient qualification of maintenance crew [132].

Therefore, the possibility of refusal for powerful turbogenerators with hydrogen cooling of electric power stations is advisable, especially for nuclear power stations taking into account the high level of power unit. In this case, the main attention should be focused on turbogenerators with air cooling that are simplicity and reliability in operation.

Today in the world already accumulated some experience in the manufacturing of turbogenerators with direct air cooling and a power up to 500 MW. «Toshiba» has created a unique turbogenerator with air cooling and a power 520 MW. Further increasing power unit of machines with air cooling is limited by the windings heat.

At the Kharkiv plant «Elektrovazhmash» was developed a series of turbogenerators with air cooling and a power unit from 120 to 320 MW. Thus, at the beginning of 2000 years was tested and sent to customer the main model of a new unified series TA with full air cooling for steam and gas turbines – a turbogenerator type TA-120 with a power 120 MW (Figure 15).

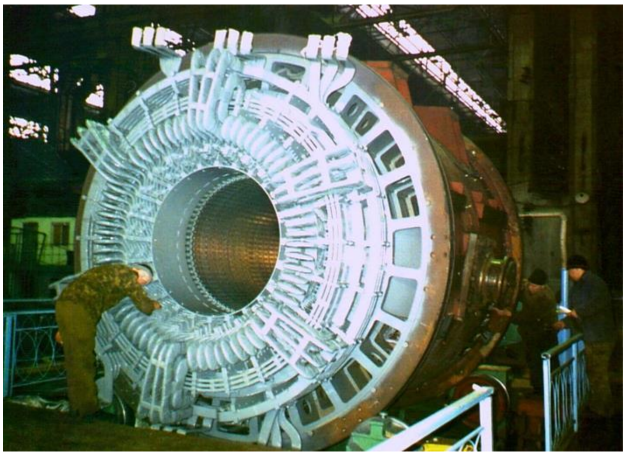


Figure 15. The main model of a turbogenerator type TA-120

Turbogenerators with full air cooling have a number of advantages against turbogenerators with hydrogen cooling and hydrogen-water cooling. These advantages determines the technical and economic expediency of the use in electric power stations with high requirements for reliability and environmental compatibility, increasing of permissible load diapason, reduction of operating costs etc. The main of them are:

– increased readiness coefficient 0,997–0,998 in comparison with 00,95–0,995 for machines with direct liquid cooling and hydrogen cooling;

– simplified operation and repair conditions, that reduction of realization time and cuts in expenditure of repair works;
– increased fire and explosion safety;
– design simplicity that is a prerequisite for reduction of development time and a start in manufacturing of the main models;
– facilitation of automation procedure and diagnosis;
– increased maneuverability;
– the possibility for creating a frame with less gas compression, as well as the absence of oil shaft compression and oil supply system;
– no other cooling systems (hydrogen and water);
– no need to use of scarce materials at the manufacturing, for example, rubber compressions, fluorine-plastic hoses, hollow copper conductors etc.

In addition, on the economical standpoint, it is necessary to take into account the estimation of prevention loss from possible fire and cuts in expenditure of fire protection.

The use of full air cooling was made possible due to the application of a new design and technical solutions. The winding direct cooling with gas distribution from the slot canal on the radial slit-like apertures in the winding conductors and displacement of gas into the air gap between the stator and the rotor were applied for the rotor. The stator core and the stator winding are cooled by presence of gas on the system of radial and axial canals without inflow gas (which cools the stator) to the air gap – that significantly reduces mechanical losses and heat of cooling gas. The use of indirect cooling for the stator winding was made possible due to the application of a new thinner insulation of Class F, electrotechnical steel with thickness 0,35 mm and reduced specific losses, also reduced current density by the use of asymmetrical multi-parallel windings with the number of parallel branches exceeds the number of poles, together with the phases connection according to the scheme «triangle» (for some performances).

All this made it possible to create a unified series of turbogenerators with the same transverse geometry and almost identical electromagnetic loads that allow unifying equipment and tools, cuts in expenditure of preparation production of the whole series and, as a result, accelerates simultaneous manufacturing of turbogenerators with a various power.

For increasing maneuverability of generators, the special elastic junction system of stator core component parts is used. For ensure the operation under conditions of reactive power consumption, the stator core end zone with the copper shield under press plate, stepped form of end packets, reduction of their thickness and gluing is applied [124]. In addition, for identify the optimal design of the stator core end zone, a different variants on the main model of a turbogenerator are tested.

A new series of turbogenerators with full air cooling is designed taking into account the possibility for mounting on the foundations of machines with identical power, hydrogen cooling and hydrogen-water cooling, which have ended rated life. In the first place, such turbogenerators can be mounted instead of generators with powers 100, 150 and 200 MW. At the same time, the possibility for replacement of turbogenerators type TVV with a power 220 MW (Rivne nuclear power stations) is being considered.

Subsequently, at the Kharkiv plant «Elektrovazhmash» was developed a series of generators with air cooling and a power up to 320 MW, including asynchronized generators, and realized the non-hydrogen (nitrogen) cooling system for a quadripolar turbogenerator type TGV of power 500 MW (Novovoronezh nuclear power stations).

Conclusions

One of the main problems in the thermal study of electrical machines concerns their winding, where the temperature rises to maximum value. The thermal characteristics of an electrical machine are important, since the temperature rise in the windings usually defines the power that can be obtained from the machine. With the use of COMSOL Multiphysics based on the FEM, hot spots in the stator winding of a powerful turbogenerator are found. When in the same column a number of adjacent hollow conductors without refrigerant circulation does not exceed three, a turbogenerator type TGV-250 without any restrictions on the active load can be operated. When near located four stoppled hollow conductors, the active load should be reduced to 85 % from rated value, and at the five near located stoppled conductors – down to 75 % from the rated value.

The heat level of interphase zone teeth of the stator core end packet, the adjacent slots of which contain the different phase’s bars of the winding lower layer, exceeds permissible value (120 °C) under rated load conditions of a powerful turbogenerator type TGV-200. Effective methods to the increase in transfer of heat losses from the end packet of a powerful turbogenerator are the cooling intensification of interphase zone by the redistribution of the hydrogen flow between the press plate and the end packet, the increase in transverse heat conductivity for packet steel by gluing of the packet iron sheets, as well as the ventilation of longitudinal slit of interphase zone teeth. The complex application of these technical solutions allows to reduce the maximum temperature of the stator core end packet by 23 %, to eliminate the heat tangential unevenness of the stator end packet, to increase the reliability and load capacity of a turbogenerator, as well as to increase in regulation diapason under conditions of reactive power consumption.

A design complication and the use of new auxiliary systems for the cooling intensification with increasing power unit lead to reduction of generator reliability. Therefore, the possibility of refusal for powerful turbogenerators with hydrogen cooling of electric power stations is urgent task, especially for nuclear power stations. In this case, it is important to take into account the tendency to the increasing of reliability for turbogenerators operation with the help of a design simplification and simultaneous non-use in a number of auxiliary systems. The modern level of engineering and technologies allows to develop high-power turbogenerators with full air cooling for ensuring a fire and explosion safety of thermoelectric and nuclear power stations.