SECTION 4. ELECTRICAL ENGINEERING

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4.1 The physical processes in turbogenerator end zone

The main tendency of development the power engineering and turbogenerator construction always consisted in constant increase the capacity unit of electric power station turbo-aggregate, since it reduced the specific cost of both the turbo-aggregate production and the construction and installation works, decreases the number of operating personnel and the materials expense per unit of installed power, and also increased efficiency [225, 226] (Figures 1 and 2).

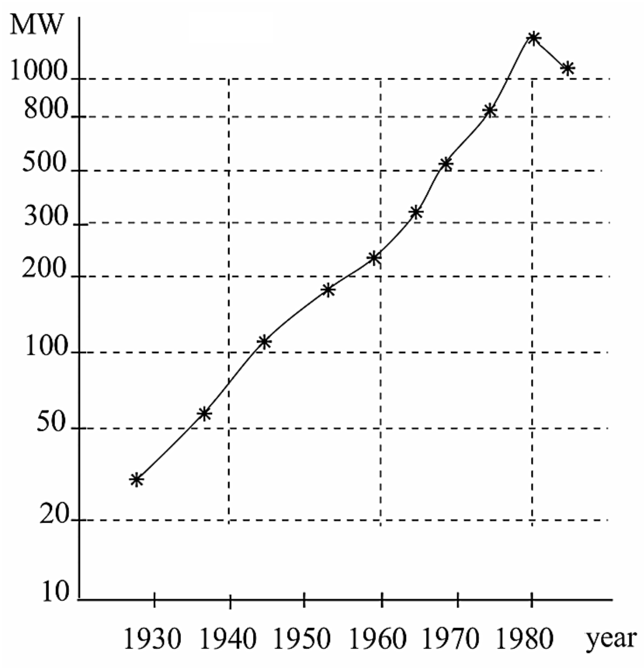

Figure 1. Rise dynamics of power unit by years

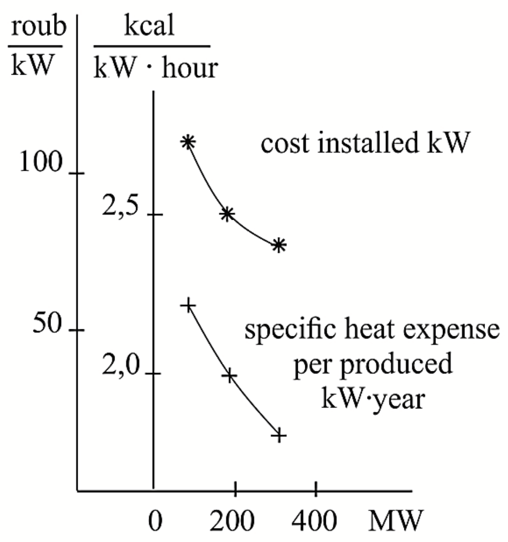

Figure 2. Improvement of electric power station economic indices with the increase of turbine power

However, an increase of generators unit capacity is a complex engineering and design task that can be seen from the known formula (in kilovolt-amperes) [226]

$$P = 1{,}11 D_1^2 l_1 n AS_1 B_\delta k_{y1} 10^{-2}, \quad (1)$$

where D_1 is the diameter of stator boring, m; l_1 is the active length of stator, m; n is the nominal frequency of rotation, rpm; AS_1 is the linear load of stator, A/cm; B_δ is the magnetic flux density (of first harmonic) in the air gap, T; k_{y1} is the coefficient of stator winding step reduction.

Thus, at the same frequency of rotation n and almost invariable (depending on the properties of electrotechnical steel) magnetic flux density in the air gap an rise of a turbogenerator power can occur by increasing the linear load AS_1 and the stator sizes (D_1, l_1). The increase of magnetic flux density B_δ is limited the stator and rotor magnetic condition. The use of electrotechnical cold-rolled steel allows some to increase the magnetic flux density in stator teeth, but the rapid saturation of rotor tooth zone of a generator with not changed magnetic properties of materials does not to give increase considerably the magnetic flux density for extension of a machine power. The increase of sizes D_1 and l_1 are limited by the diameter of rotor D_2 according to the metallurgy requirements (D_2 = 1,2–1,3 m), that limits, respectively, the length of rotor L_2, which in accordance with the vibration resistance conditions must be within L_2 = (3–6,5)D_2, as well as railway dimensions (transport conditions).

Therefore, the power increase is achieved mainly by rise the linear load AS_1, that is, in limited stator sizes – by increasing the current density that is only possible with the simultaneous cooling intensification.

Air, hydrogen, water (distilled), transformer oil were practically used as the cooling medium for turbogenerators. Comparison of their properties with respect to air is given in Table 1 [225, 227].

Table 1.

Cooling medium properties with respect to air, c.u.

The main characteristics	Hydrogen at the excess pressure, MPa		Water (distillate)	Transformer oil
	0,003	0,2		
Density	0,0696	0,21	1000	848
Volumetric heat capacity	0,996	3,0	3500	1400
Thermal conductivity	6,69	7,1	23	5,3
Expenditure	–	1,0	0,01	0,01
Heat diversion	1,5	3,0	50	21

The transition from the air use to the hydrogen use in turbogenerators construction with a power above 25–50 MW began at the end 1930 year, and in the USSR countries – at the end 1940 year. This allowed increasing a turbogenerators power unit up to 200 MW, reducing the overall dimensions of turbogenerators 25–50 MW and increasing the efficiency (Table 2) [225].

Table 2.

Efficiency dependence on the cooling medium, %

Cooling medium of turbogenerator	Power of turbogenerator, MW		
	25	50	100
Air	97,3	97,7	98,0
Hydrogen	98,2	98,6	99,0

Consider the stages of cooling systems development in turbogenerators construction on the example of their designs developed and produced by plants «Elektrosyla» (Leningrad), «Elektrovazhmash» (Kharkiv), «Sybelektrotyazhmash» (Novosibirsk).

A turbogenerators cooling intensification was initially due to the increase of hydrogen excess pressure in the housing from 0,03 to 1,0–2,0 kGs/cm^2 with maintaining the indirect (external) gas cooling of the stator and rotor windings (50’s years, series TV and TV2, power 25–150 MW – «Elektrosyla», series TGV and TVS, 25 and 30 MW – «Elektrovazhmash»); then due to the application of direct (internal) gas cooling of the winding copper, first of all, the rotor (50–60’s years, series TVF, power 60, 100 and 200 MW – «Elektrosyla» and «Sybelektrotyazhmash»), and then the stator (series TGV, power 200 and 300 MW – plant «Elektrovazhmash»).

The efficiency of direct cooling application was greatly enhanced by a further increase of hydrogen pressure. It can be seen from Figure 3, the possibility of rotor losses decrease when hydrogen cooling has sharply increased with increasing hydrogen pressure, especially with the direct cooling of the copper winding [228].

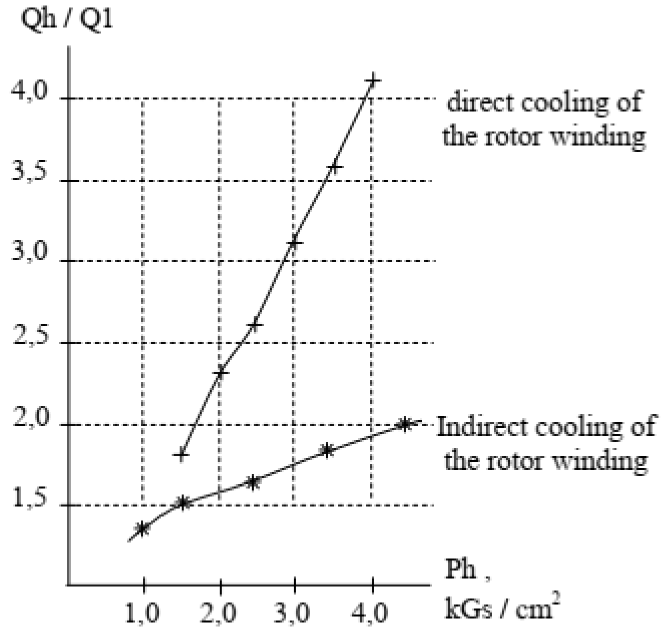

Figure 3. Hydrogen pressure influence Ph and cooling type on the ratio of rotor maximum losses, that can be decreased with hydrogen cooling Qh, to the corresponding losses with air cooling Q1 (at atmospheric pressure)

If the transition to hydrogen cooling of turbogenerators provided power up to 150–200 MW, then a new way of cooling – direct windings cooling – together with the hydrogen pressure up to 5 kGs/cm^2 made it possible to build a generator of power 1000–1200 MW with direct hydrogen cooling of the rotor [229]. The calculations showed the possibility application of direct hydrogen cooling of the rotor for a turbogenerator with power 1600 MW.

A number of firms were taken direct liquid cooling with distilled water or oil flows in hollow copper conductors of the stator winding (50–60's years) [230]. The high efficiency of direct liquid cooling of the stator bar is illustrated in Table 3 [231].

Direct water cooling of the stator winding was taken by plant «Elektrosyla» for a series bipolar generators TVV (power 165, 200 and 220, 320, 500, 800, 1000, 1200 MW) and for a quadripolar turbogenerator 1000 MW; plant «Elektrovazhmash» – for bipolar generators of power 200 MW, for bipolar and quadripolar turbogenerators of power 500 MW (TGV-200 and TGV-500, respectively).

Table 3.

The maximum relative permissible current load on the stator winding bar with different cooling

Hydrogen pressure in a turbogenerator, kGs/cm^2	Indirect cooling	Bar direct cooling				
		Gas	Liquid			
			Water		Oil	
			a	b	a	b
0	1,0	1,2	3,5	4,9	1,4	1,9
0,6	1,03	1,4	–	–	–	–
1,2	1,07	1,6	–	–	–	–
1,8	1,13	1,8	–	–	–	–

Note:
1) all values represent the ratio of the maximum current load with bar indirect hydrogen cooling at pressure close to atmospheric;
2) the fluid pressure for liquid cooling is 1,2 kGs/cm^2 (a) and 3,7 kGs/cm^2 (b);
3) the maximum permissible temperature for bars gas cooled is 130 °C, for bars liquid cooled – 60 °C.

Direct cooling of the winding and stator core with insulating oil was applied by plant «Sybelektrotyazhmash» for generators type TVM-300 (power 300 MW, without hydrogen).

Due to technical difficulties the direct water cooling of rotor was later applied than stators (60–70's years) and used by plant «Sybelektrotyazhmash» for turbogenerators type TVM-300, as well as by plant «Elektrovazhmash» for TGV-500-4. Plant «Elektrosyla» has also developed and applied in industry an essentially new turbogenerators with direct water cooling of the rotor windings, the stator windings and stator core – a series T3V (so-called «three waters») of power 60 and 800 MW.

Technological progress of turbogenerators cooling systems development and cooling intensification of active parts caused a significant increase the material use coefficient [231, 232] (Figure 4 and Table 4), that is rise a generator production efficiency, despite construction complication due to the need of auxiliary systems provides functioning of cooling systems: gas system, oil supply system of shaft compression, water cooling system of the windings.

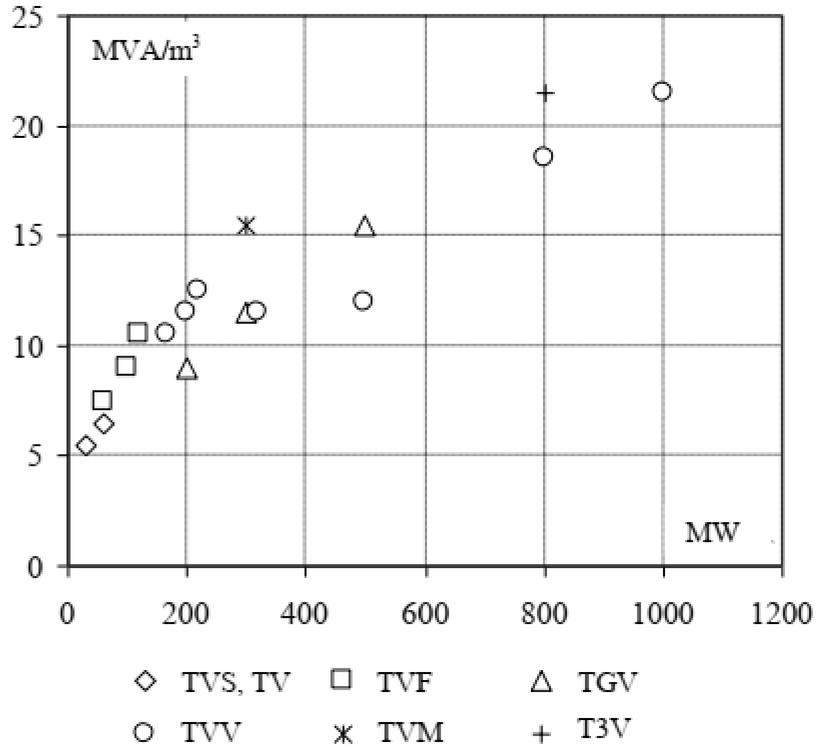

Figure 4. Increase of a turbogenerator use coefficient with rise of power unit

Table 4.

Turbogenerators cooling systems of various types

Sings (Figure 4)	Turbogenerator type	Stator winding cooling	Rotor cooling	In a housing of turbogenerator
◊	TVS-30 TV-60-2	Indirect, hydrogen	Indirect, hydrogen	Hydrogen
□	TVF-60-2 TVF-100-2 TVF -120-2	Indirect, hydrogen	Direct, hydrogen	Hydrogen
Δ	TGV-200 TGV-300	Direct, hydrogen	Direct, hydrogen	Hydrogen
	TGV-500	Direct, water	Direct, water	Hydrogen
○	TVV-165-2 TVV-200-2 TVV-220-2 TVV-320-2 TVV-500-2 TVV-800-2 TVV-1000-2	Direct, water	Direct, hydrogen	Hydrogen
ж	TVM-300	Direct, oil	Direct, water	Oil
+	T3V-800-2	Direct, water	Direct, water	Water

The further growth of a turbogenerators power unit was inhibiting by the energy systems development.

So, today in the post-Soviet countries at the electric power station are existing high-use turbogenerators with various constructions, maximum power and cooling type (Table 5).

Table 5.

Maximum power of working turbogenerators in the post-Soviet countries

Series, type	Power, MW	Frequency of rotation, rpm	Cooling medium		
			Stator		Rotor
			winding	core	
Thermoelectric power stations					
TVV-1200-2U3	1200	3000	Water	Hydrogen	Hydrogen
T3V-800-2	800	3000	Water	Water	Water
TGV-500-2	500	3000	Water	Hydrogen	Water
TVM-300	500	3000	Oil	Oil	Water
Nuclear power stations					
TVV-1000-2U3	1000	3000	Water	Hydrogen	Hydrogen
TVV-1000-4U3	1000	1500	Water	Hydrogen	Hydrogen
TGV-500-4	500	1500	Water	Hydrogen	Water

At one time the desire to reduce operating and capital costs of power units led to the building a capacity limit generators of 300, 500, 800–1200 MW. Primarily, this is was due to economic efficiency, since for more powerful turbogenerators decreases the construction and installation works, reduces the operating costs and increases thermal efficiency [225].

When building a powerful generator the geometric scales remain almost unchanged, and the stator linear load is constantly rising. The increase of linear loads at constant geometric scales leads to intensive rise the leakage flux of winding frontal parts. These flows excite eddy currents in constructive parts of the end zone that cause additional losses in these elements. Additional losses distribution in the elements of end zone design is quite uneven leads to increase and sometimes unacceptable local heat of separate units.

Therefore, the increase of stator linear load raises the probability of breakdown a generator due to overheating and failure of some units in the end zone. It is necessary to build a working reliably machines in the required operating conditions, since the cost of downtime a powerful generator exceeds the cost of construction.

In direct cooling generators due to a sharp increase the linear load AS_1 rise additional losses of short circuit. Additional losses on the surface of rotor and stator teeth caused by higher harmonics not increase, since the magnitude of leakage flux density in the gap are limited at increase AS_1 by raising the gap length. At the same time, leakage flux losses in the stator winding frontal parts increases because almost unchanged the magnetic conductivity in a generator end parts and the magnetize strength of leakage flux increases proportional to AS_1. These losses causes increased heat of the stator core end packets, the press plates and other structural elements located near the winding frontal parts.

In a generator designs with high using materials provides the special means to reduce additional losses.

The end packets stator teeth are made with the slits for reduce eddy currents losses caused the end magnetic field.

A very good mean for reducing the leakage flux in end parts is installation the damping shields of thick copper sheets placed on the outer side of press plate or between it and the end packet. In the presence of a copper shield between press plate and end packet the leakage flux additional losses entering into packets end zone are reduced. It is advisable to provide artificial cooled copper shield (for example, water).

In some designs instead of the copper shield in stator winding frontal parts placed the circular core of electrical steel sheets in order to prevent the penetration of the leakage flux in massive parts of press plate and stator housing.

In more modern generators in order to reduce losses and heat of the stator end packets used the magnetic shunts that are packets of electrotechnical steel similar to packets of the main core, but less thickness (20 mm) and with considerably short teeth (or completely without them). Thus, these packets not have the main flux, but close the axial leakage flux of stator winding frontal parts penetrating through the press plate and shield. For better ventilation the magnetic shunts are separated from the main core by press fingers (Figure 5). Magnetic shunts reduce the heat of core end packets compared to the usual design and allow operating generators in underexcitation modes without a high heat of core end packets.

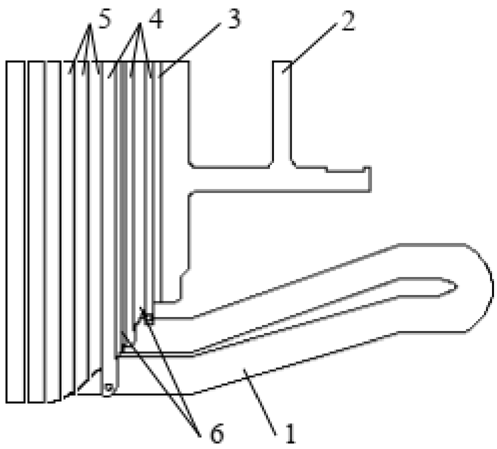

Figure 5. Stator core end zone of a generator type TVV-1000-2U3:
1 – winding frontal part; 2 – press plate;
3 – electromagnetic shield; 4 – press fingers;
5 – core packets; 6 – magnetic shunt

At the revolution of rotor the end leakage flux of stator and rotor winding frontal parts crosses the massive units placed in this zone of a generator and thereby causes losses in them. Usually all fastening units of core and stator winding in order to reduce losses are made from non-magnetic materials. The rotor bandage rings of non-magnetic material also help to reduce end flux. The press plate of stator core is made of non-magnetic steel ($\mu_e = 1{,}05$) with the high electric resistance $\rho = 0{,}8$ Ohm·mm^2/m.

The non-magnetic press plate is also an electrical shield.

The thicker shield will better shielding the constructive units. So usually try to work in strong shielding zone, that is, in zone with a large thickness of a shield taking into account the economic and constructive factors.

It is necessary to note the unwanted side of the action of electrical shield related with placing in the circuit excites a flux. The shield currents cause not only the weakening of general flux penetrates into shield, but also the distortion of magnetic field. So, part of flux is displaced in the space near shield together with the shielding of constructive units located directly behind shield. Therefore, the losses in some units may increase. For example, the electrical shield protecting the core back displaces the partial end flux in a machine tooth zone.

The transposition of wires in slot for one full turn along the length eliminates the potential difference between conductors due to their different position in height of slot. At the same time, however, there is potentials difference due to uneven position the conductors in section of frontal parts. As a result, currents causes the additional losses in bars with a normal transposition on 360° in slot will circulate.

The transposition conductors on one and a half turns (540°) in large generators with a high current density in the winding are appropriate. This is partially compensates for the absence of transposition in the frontal parts and minimizes the magnitude of circulate current within a half-bar.

The increase of unit capacity and current loads generators made task the research and development of a new insulating materials and technological processes that meet the high requirements in this field. As a result, the researches a series of insulation types have different kinds the initial materials and manufacturing method, but very similar physical properties. Such insulation is called thermo-reactive.

However, the mounting of winding bars with thermo-reactive isolation requires great precision and care because of inelasticity it prevents deformation.

Usually for direct cooling machines the more parallel branches in the cooling system the more even heat of winding. For direct cooling machines the coolant temperature flows inside of winding ducts is also of great importance.

It is necessary to take into account the constructive factors influences on magnetic field distribution in the end zone in order to achieve the most efficient cooling of an electrical machine end zone (including a turbogenerator). The analysis of theoretical studies showed for magnetic field determination in the end zone it is important to consider the following:

1. Location of teeth the most loaded end magnetic flux and the values of flux on their surfaces depend on the shift direction of stator winding layers at a given the

revolution direction of rotor. It is advisable to perform the stator winding so that the lower layer is shifted relative to the upper against the rotation of field for the goal of more even the end magnetic flux distribution between a generator teeth and decrease its concentration.

The value of axial magnetic flux through the surface of teeth located at the phase zone junction of stator winding is greatest [233–236]. In this case there are two possible variants, namely: at the junctions of the lower layer if it is displaced relative to the upper in the revolution direction of field; at the junctions of both the lower and upper layers if the lower layer is displaced relative to the upper against the revolution direction of field. In the second variant a load unevenness of separate teeth is less as compared with the first variant.

One of the effective methods of reducing the heat tangential unevenness is the redistribution of cooling hydrogen flow between the press plate and the end packet with an increase its volume towards on cooling the interphase zones by increasing the appropriate apertures in the gas-distributive cylinder. Thus, the hydrogen flow in interphase zone (correspondingly, and the heat transfer coefficient) can be increased in 1,5–2 times without the cooling deterioration other elements and units stator of a generator.

In particular, in [237] the increase in 1,5 times the heat transfer of tooth end surface of interphase zone in the ventilation duct between the press plate and the packet was considered. According to the obtained results, such cooling intensification of interphase zone allows reduced the maximum temperature of packet at 7 %.

Another promising direction of reducing the total heat level of stator core end packet is increase the thermal conductivity of laminated iron across the sheets. One of the technologies allows to increase the transverse thermal conductivity is glue together the end zone packets, for example, with help an epoxy paste EP-3. On the one hand, this increases the packets mechanical stiffness in the changeable load modes and the underexcitation modes of a generator. On the other hand, studies [238] show the thermal conductivity of glued together packet an average is 3,4 W/(m·K), that is almost twice above a similar indices in the absence of glue together 1,9 W/(m·K). Addition in paste the dispersive insulating fillers with high thermal conductivity (≥ 5–10 W/(m·K)) allows bring the equivalent thermal conductivity of the packet up to 5–6 W/(m·K).

The temperature maximum level of packet steel teeth decreases by 7 % according to the calculating results of end packet heat at the transverse thermal conductivity 3,4 W/(m·K) [237]. Simultaneous introduction of intensification the interphase zone cooling and increase of transverse thermal conductivity of steel allows reducing the tooth maximal heat to 14 %. In this case the margin of packet teeth maximum temperature can be achieved allows extending the generator load diapason in underexcitation modes with respect to permissible temperature of stator core.

2. Influence of structural modifications (the shape of chamfer the end packets, the ratio of length the stator core and the rotor, the geometric shape of stator and rotor winding frontal parts, for example, the scale of frontal parts, the angle of bend the stator winding frontal junctions etc., relative values of width the teeth and slot stator, the presence of slits and stepped form the end packets teeth etc.) on the end magnetic field. Using the chamfer of stator core end packets provides a reduction of magnetic flux concentration in chamfer zone, but causes an increase of magnetic flux density on the vertical surface area adjoined with chamfer. Thus, the shape of chamfer affects the magnetic flux density on the surface end packets bevelled and located above the chamfer. It is necessary to consider the permissible heat of end packet under-slot zone and the stator core mechanical stiffness when increasing the chamfer almost on the entire height of tooth. The magnitude and distribution of magnetic flux along the bevelled surface depend on the shape of chamfer, as a rule, inappropriately make the chamfer beginning with an angle of slope to the horizontal more than 20°. Using a chamfer convex to air gap side instead of a uniform one allows reducing the maximum values of magnetic flux density on the surface located over chamfer. Changing the rotor length in respect of the stator core length affects the equivalent values of magnetic flux density on the separate areas of end surface at different configurations. It is necessary to note, with an increasing of chamfer rises the beneficial effect area of rotor diminution. But too much rotor diminution may be inappropriate, for example, in

turbogenerators of asynchronized type for operate in deep underexcitation modes recommends the rotor core length to take a little longer than the stator core length. It is necessary to take into account, when designing a generator the implementation of stator core with wider and smaller slots allows weakening the influence of leakage slot magnetic field on the end magnetic field.

Constructive feature of the stator core end packets unlike the active zone packets may be the slits (for the monolithic of teeth the slits are oblique, angled to the radial direction and the lamination is performed with the overlapping of segments for the cross-overlap of slits), longitudinal slots and ducts in the teeth. This is done in order to reduce the eddy current losses created in the sheets when entering the axial flux in it. In addition, an increase of slots and apertures total surface in teeth end part leads to more intensive cooling of end packets. The splitting on the entire height of tooth reduces the teeth end packets losses of a 300 MW generator by 35 % under rated load conditions and by 44 % when a power factor cos φ ~ 1,0 is shown in [239, 240].

The diameter of end packets boring increases with approach to the machine end zone, in other words, the stepped form of end packets teeth is used. This is achieved the round of active iron lugs in end zone of a generator and reducing the stator core end packets losses. Although the axial component leakage flux of frontal parts is greatly reduced with that much share of one enters the stator core along the height of laminated sheets tooth zone. With this always a compromise between the need of reduction the axial component leakage flux and preservation the core compression force in the tooth zone by the use of the press fingers is found. The end packets are made monolithic, that is specially pressed and baked and to some extent takes the function of additional press plates.

The presence of sharp angles and ferromagnetic parts lugs also affects the field distribution causing its local concentrations in certain areas of the end zone. Thus, the research carried out with help simulation method by Holly [241] showed the magnetic field in zone of the ferromagnetic press plate lower edge with a profile under the angle 90° increases by 40–50 % as compared with the field in edge zone with a round profile.

3. As a rule, all stator packets have the same width. However, the end packets with additional losses due to the end leakage flux for the goal of more intensive cooling are performed less width than in central part. The narrower ventilation ducts allow reduces the packet width and increases the air speed.

4. In quadripolar generators the values of magnetic flux density are lower than in bipolar ones.

5. As a rule, the appropriate constructive decisions should be different for generators with the main load conditions are nominal and underexcitation when a power factor cos φ ~ - 0,95 and generators for operate in deep underexcitation modes.

6. According to results of analysis the magnetic field components of separate sources on the end packets surface and it interaction in different load conditions [242–246] for the goal of facilitate the choice of suitable variants the end zone design, the most significant are magnetic flux density components because of displacement the magnetic field from the air gap and the stator core slots, and eddy currents of press plate with shield in the under-slot zone, also because of motive-magnetic forces the stator and rotor winding frontal parts. The relative value of magnetic flux density of separate sources in the result magnetic field depends on the end zone configuration.

Provided a number of practical measures obvious in physical substantiation and aimed at improving the conditions of machine end parts when constructing new series generators. The basic ones are: reduction of total level temperature the main parts; introduction of the automatic control cooling system ensures a decrease of windings and gas temperature variations when changes a load conditions of a generator; reduction of relative length the active zone and increase the mechanical stiffness of rotor, the stator core and stator winding fastening elements.

As a rule, the operation reliability of high-use turbogenerators decreased when the use of a new auxiliary systems with own specific defects causes generator failures as a whole, that is disconnections. A turbogenerator complication with the use degree rise occurs not only due to an increase in number of auxiliary systems, but also due to the design complication of a turbogenerator main component parts – stator, rotor, housing, etc., and is accompanied by the specific defects of these parts, typical for this system. These defects are as following [225, 226, 229, 231, 232, 247, 248]:

1) Only a turbogenerator without cooling systems.

- Defects in high-voltage stator insulation and aging insulation.
- Fastening slackening of the stator winding and core.
- Pressing slackening and local heat of core.
- Presence of ferromagnetic objects into the stator.
- Coil and housing faults in the stator winding.
- Cracks of the rotor shaft, bandage rings and other rotor parts.
- Damage of rotor balancing.
- Damage of heat exchangers compactness (air- and gas-coolers, distillate coolers) and their binding elements.

2) A turbogenerator with hydrogen cooling system (indirect or direct).

- Damage of stator housing gas-compactness, rotor, gas system elements.
- Damage of oil seals and shaft.
- Failures of gas-oil system elements.
- Presence of oil inside a generator.

3) A turbogenerator with water cooling of the stator winding.

- Damage of hydraulic tract joints compactness, including water-connecting pipes and insulation hoses.
- Cracks in the hollow copper conductors of the stator winding.
- Corrosion and obstruction of conductors.
- Damage of high-voltage insulation due to moisture.
- Failures of water cooling system elements for the stator.

4) A turbogenerator with water cooling of the rotor winding.

- Damage of hydraulic tract joints compactness, including water-distribution bushings and water-inlets.
- Cracks in the hollow copper conductors of the rotor coils.
- Corrosion and wear of copper conductors.
- Thermal imbalance.

The main reliability indices for turbogenerators are time between failures and readiness factor.

Average time between failures is defined as the ratio of the total operation time of an object with restoring efficiency to the mathematical expectation in a number of failures during that operation. A statistical estimate of the average time between failures for an each turbogenerator can be obtained as the ratio of the total operating time for a given period to the number of failures during this period

$$T = \frac{t_\Sigma}{r}, \qquad (2)$$

where r is the number of failures during the total operation time t_Σ.

The readiness factor characterizes the ability of an object for required use at any time except for planned periods when its use is not provided. In the general case, it is defined as the ratio of operation time for a given period to the amount of operation and restoration time after failures during the same period

$$K = \frac{t_\Sigma}{t_\Sigma + t_{R\Sigma}}, \qquad (3)$$

where $t_{R\Sigma}$ is the time required for restoration after failures for a given period.

According to GOST 533-2000 reliability and durability indices for turbogenerators should not be lower shown in Table 6.

Table 6.

Turbogenerators reliability indices according to GOST 533-2000

Index name	Average value of index for a turbogenerator with power	
	to 350 MW	over 350 MW
Readiness factor	0,996 (99,6 %)	0,995 (99,5 %)
Time between failures, hours	22000	18000
Resource between major repairs, years	8	5
Full period operation, years	40	40

It is also used for analyze the forced downtime factor

$$q = 1 - K. \tag{4}$$

These indices fully determines the probability of unfailing operation during a given period operation t

$$P_o = K \exp(-t/T). \tag{5}$$

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

$$P_{ot} = \prod_{i=1}^{n} P_{oi}, \tag{6}$$

it is clear that the use of each new system will be accompanied by a decrease in the probability of a turbogenerator unfailing operation as a whole, unless simultaneously the probability of unfailing operation for all or a certain number of component parts and auxiliary systems is increased accordingly. But if the P_{oi} are close to one and meet the limits of technological capabilities, that is at this stage it is impossible or entails great rise in price of P_{oi} by improvement of the design and manufacture technology, then a turbogenerator complication due to the growth of a power unit and the rise of use degree leads to the inevitable decrease of reliability operation and the rise of losses from unplanned repairs.

Reduced turbogenerators reliability with transition to a more complex design solutions related to cooling intensification is illustrated in Tables 7–9 shows the probabilities of unfailing operation P_{oi} for the main generator component parts obtained by processing the damage operational data of many machines for a series of years [231, 249]. It can be seen that the transition from air to indirect hydrogen cooling for a power 25–30 MW leads to a decrease in the probability of a generator unfailing operation P_{ot} from 0,92 to 0,78–0,82. The transition from indirect hydrogen cooling to direct hydrogen cooling of the rotor for a power 50–100 MW leads to a decrease in P_{ot} from 0,74–0,87 to 0,62–0,66.

Table 7.

Cooling type influence on the probability of turbogenerators unfailing operation with a power 25–30 MW

Turbogenerator component parts	Cooling type and generator type		
	Air T2-25-2	Hydrogen TGV-25	Indirect TV2-30-2
Stator	0,97	1,0	0,98
Rotor	0,97	0,98	0,99
Brush-contact apparatus	0,99	0,99	0,97
Exciter and excitation system	0,99	0,99	0,98
Gas-compactness (generator housing, pipelines, fittings, etc.)	–	0,95	0,96
Shaft oil seals and oil supply system	–	0,9	0,89
Turbogenerator as a whole	0,92	0,82	0,78

Table 8.

Cooling type influence on the probability of turbogenerators unfailing operation with a power 50–100 MW

Turbogenerator component parts	Cooling type and generator type				
	Indirect hydrogen			Direct hydrogen	
	TV-50-2	TV-60-2	TV2-100-2	TVF-60-2	TVF-100-2
Stator	0,99	0,98	0,98	0,95	0,96
Rotor	0,98	0,98	0,97	0,99	0,97
Brush-contact apparatus	0,98	0,96	0,97	0,95	0,94
Exciter and excitation system	0,99	0,96	0,93	0,95	0,91
Gas-compactness (generator housing, pipelines, fittings, etc.)	0,97	0,97	0,91	0,9	0,9
Shaft oil seals and oil supply system	0,96	0,86	0,95	0,79	0,86
Turbogenerator as a whole	0,87	0,74	0,74	0,66	0,62
as a whole without exciter and excitation system	0,88	0,77	0,80	0,7	0,68
as a whole without seals and gas system	0,94	0,88	0,86	0,85	0,8

Table 9.

Cooling type influence on the probability of turbogenerators unfailing operation with a power 150–300 MW

Turbogenerator component parts	Cooling type and generator type			
	Direct hydrogen		Direct hydrogen plus water cooling of the stator winding	
	TGV-200	TGV-300	TVV-165-2	TVV-200-2
Stator	0,96	0,97	0,87	0,78
Rotor	0,92	1,0	0,99	1,0
Brush-contact apparatus	0,9	0,54	0,86	0,93
Exciter and excitation system	0,79	0,8	0,86	0,95
Gas-compactness (generator housing, pipelines, fittings, etc.)	0,75	0,68	0,74	0,93
Shaft oil seals and oil supply system	0,8	0,84	0,75	0,86
Turbogenerator as a whole	0,38	0,24	0,34	0,55
Stator and rotor	0,88	0,97	0,86	0,78

The transition influence to stator water cooling with direct hydrogen cooling of the rotor for turbogenerators with a power150–300 MW can only be estimated by eliminating the influence of the sharp difference P_{oi} for excitation systems, brush-contact apparatus and other component parts for turbogenerators of different types. For that end in view can compare P_o for the «rotor-stator» complex: this value is 0,88–0,97 without water cooling of the stator winding (for TGV-200, TGV-300) and decreases to 0,78–0,86 with water cooling of the stator winding (TVV-165-2, TVV-200-2).

Very volumetric data in 1993–2005 and 2006–2010 years (after operating time) for a large group of turbogenerators with a power 165, 200, 300 MW are given in [249]. According to these data the average specific ungenerate electricity due to stator defects is calculated (Table 10). For turbogenerators with hydrogen cooling of the stator winding the specific ungenerate in 2006–2010 years was 2 kW·h/gen.yr, and for turbogenerators with water cooling of the stator winding – 4,7 kW·h/gen.yr, that is more than twice. The average values for the whole period from 1993 to 2010 years were 5,6 and 6,9 kW·h/gen.yr, respectively, that is 23 % higher with direct water cooling against gas.

Table 10.

The average specific ungenerate electricity due to stator defects for turbogenerators different types

Generator type and stator winding cooling	1993–2005 years		2006–2010 years		Total	
					Ungenerate	
	Ungenerate, kW·h/yr	Number of turbo-generators	Ungenerate, kW·h/yr	Number of turbo-generators	kW·h/yr 1993–2005	per 1 generator 2006–2010
Direct hydrogen						
TGV-200	293,7	74	104,9	84		
TGV-300	691,5	66	203,9	69		
As a result	985,2	140	308,8	153	7,04	2,02
Average magnitude					5,6	
Direct water						
TGV-200M	344	15	38,2	26		
TVV-165-2	261,1	64	418,5	68		
TVV-200-2	445	13	119,2	13		
TVV-200-2A	35,3	15	51,2	23		
TVV-320-2	230,5	62	322,3	69		
As a result	1315,9	169	949,4	199	7,78	4,77
Average magnitude					6,9	

It is stated in [249] that for turbogenerators with a power 200–1000 MW the lowest forced downtime factor q = 0,2–0,3 % has generators 200–300 MW with hydrogen cooling, q increases to 0,5 % and more for a power 200–500 MW and higher with stator hydrogen-water cooling and rotor hydrogen cooling, q increases significantly above 0,5 % (normal) and reaches 1–2 % and more for turbogenerators with rotor water cooling. Foreign statistics gives quantitatively similar results (Figure 6).

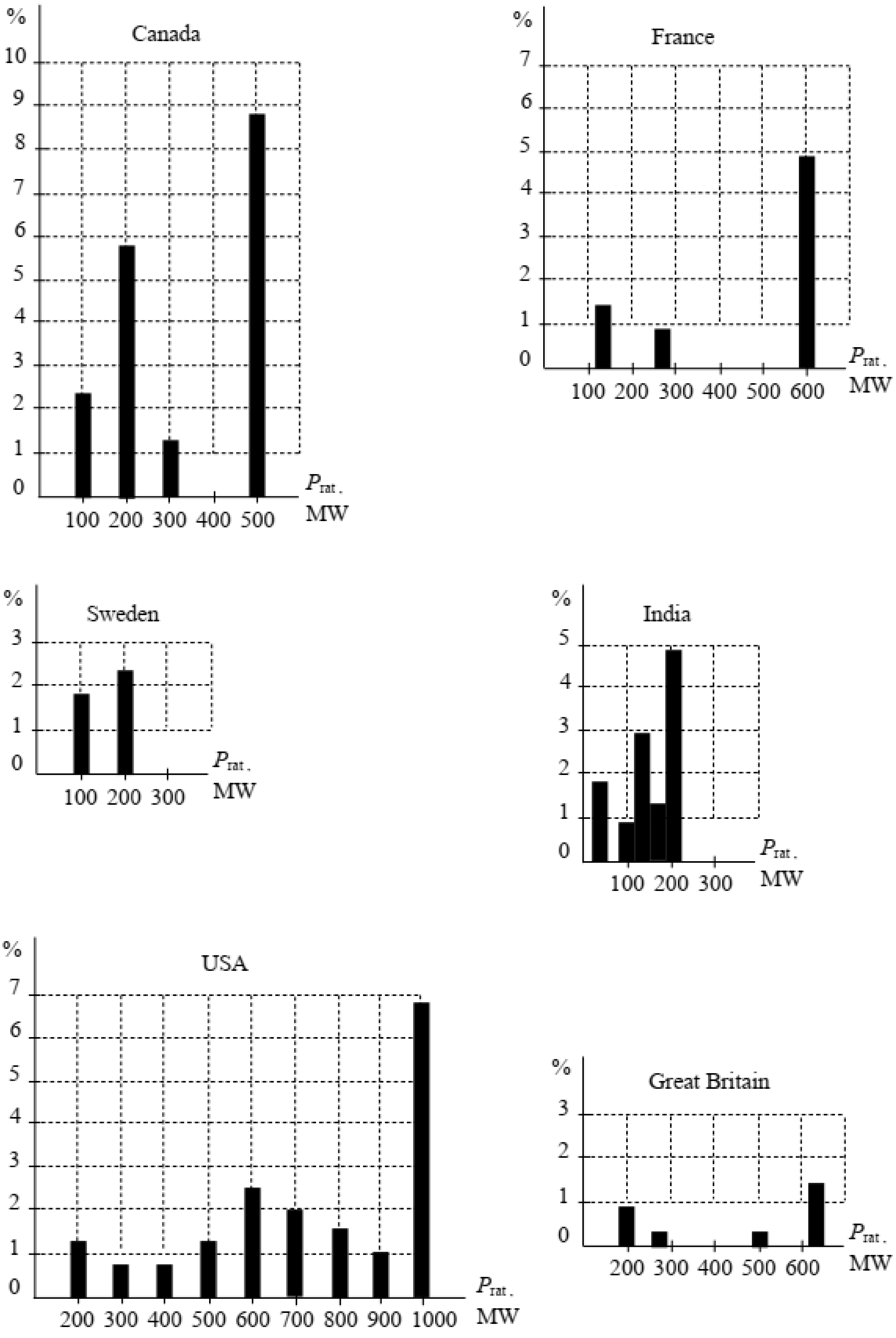

Figure 6. The relative duration of turbogenerators forced downtime

Thus, a turbogenerator design complication and the use of new auxiliary systems for the cooling intensification with increasing power unit leads to the decrease of generator reliability [228, 237, 250]. Therefore, the system and methods control and diagnostics of generators main component parts (SCDG) for compensate this decrease in the reliability of turbogenerators were developed. The purpose of SCDG is early detection of progressive errors in the operation of generators component parts and auxiliary systems that can causes forced disconnections and large losses, as well as timely elimination of these errors, for example during planned-preventive repairs. The effective functioning of SCDG increases the operation reliability (P_{oi}) of generators component parts and auxiliary systems and therefore economically advisable, despite the need of the cost for creation and maintenance of SCDG on conditions that SCDG have the high reliability and the low probability of false diagnoses. Another way for ensure reliability with complication of a turbogenerator and auxiliary systems is reserve. So, it is necessary to reserve unreliable excitation systems due to the low quality of component parts and the large quantity of systems elements. Finally, the third way for ensure reliability is simplification of the main component parts design and non-use in a number of auxiliary systems with help return to less efficient cooling on conditions that it ensures given power unit with a modern technical solutions [243–246]. In this case, the inevitable reconsideration of the approaches and criterions previously adopted from the standpoint of economic efficiency (for example, specific losses reduction per 1 kW of installed power) towards the increase in reliability and the reduction in price of maintenance, even if are material use deterioration and efficiency reduction.

At present developed a lot of different 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 [251] deserves special attention, because used today in many universities of the world, as well as the professional researchers of various fields.

The most significant advantage of COMSOL Multiphysics software is the ability to solve multiphysical problems allows creating the complex (interrelated) mathematical models. Also an important advantage is the simplicity of interface in a coefficient form, that enables the researcher to simulate of physical processes without focusing directly on the solving of differential equations, while paying serious consideration to variation calculations (experiments) for solving of set tasks [252].

As known, the construction of mathematical models for analysis the physical processes in end zone of a powerful turbogenerator is very problematic [239, 253–258], because the difficult of this problem makes researcher to use a series of simplifications in the task formulation, suitable in some cases and unsuitable for others, as a result obtained solutions often too approximately describe the conformity to natural laws of electromagnetic field distribution.

A three-dimensional model have not found wide application because of complexity the end zones design of powerful generators requires very much computing trouble and even with modern computer technology needs a series of simplifications, also because the formation of meaningful and sufficiently detailed conclusions concerning parameters and characteristics of the object requires a large number of variation calculations [253]. Therefore, used an approach for the analysis of heat processes in the stator core end zone of a turbogenerator with help a consecutive logic transition from the solution of a simple calculation model the electromagnetic field in active part machine to more difficult calculations models in end zone using the previous results in the following, that allows to obtain a solution for determination of temperature distribution in difficult areas. The use of specialized software for development of mathematical model allowed creating a one that is sufficiently flexible in terms of modification the individual components and allows the researcher to concentrate on achieving of set goal, rather than solve of utilitarian tasks.

As a research object, a serial turbogenerator type TGV-500 of 500 MW capacity (by Kharkov State Enterprise plant "Electrowazhmash") is considered. The presence of experimental data [239, 256, 259] allows correction the accuracy of electromagnetic and thermal calculations and simplification the heat calculation due to known heat transfer coefficients.

A staged construction algorithm of a mathematical model is as following.

On the first stage, a two-dimensional electromagnetic field model in transversal section of central (active) zone of a turbogenerator is considered (Figure 7).

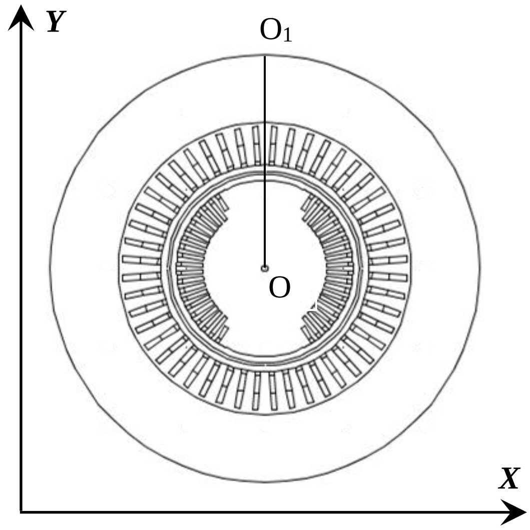

Figure 7. The calculation area of a turbogenerator central zone

In general case the equation of a two-dimensional electromagnetic field for the axial component of the magnetic vector potentials A_z will be:

$$j\omega\sigma A+\nabla\times\left(\mu_0^{-1}\mu_r^{-1}\nabla\times A\right)=J_z^e e_z,\ A=A_z e_z\,, \tag{7}$$

where ω is the angular frequency; σ is the electric conductivity; ∇ is the Hamilton operator; μ_0 is the permeability of vacuum; μ_r is the relative permeability; A is the magnetic vector potential; J_z is the external current density; e_z is the unit vector.

Since the stator core is laminated of sheets the high-alloy cold-rolled electrical steel with a thickness 0,5 mm, eddy current from the radial field can be neglected. The calculation of additional losses in the stator end packets of a turbogenerator with acceptable accuracy can be made only for the axial component of the magnetic flux density. So, the electromagnetic field of a turbogenerator central part in the Cartesian coordinate system satisfies the Poisson equation and, in this case, the well-known model [260] is considered:

$$\frac{\partial^2 A_z}{\partial x^2}+\frac{\partial^2 A_z}{\partial y^2}=-\mu J_z\,. \tag{8}$$

Equation (8) is supplemented by next boundary condition on the outside of solving region:

$$A_z\big|_G = 0 \tag{9}$$

and continuity condition for the magnetic flux on the inside of solving region.

In the stator winding taken a symmetric system of phase currents [253, 254]:

$$\begin{cases} i_A = I_m \cos\left(\omega t + \beta\right) \\ i_B = I_m \cos\left(\omega t + \beta - 120^o\right), \\ i_C = I_m \cos\left(\omega t + \beta + 120^o\right) \end{cases} \tag{10}$$

where I_m is the magnitude of stator current; β is the angular displacement of axis along which operates the motive-magnetic force of three-phase stator winding in relation to the longitudinal axis of rotor d.

The angle β is determined by the formula:

$$\beta = 90^o + \theta + \varphi, \tag{11}$$

where θ is the load angle of a machine; φ is the phase displacement between voltage and stator current.

The load angle θ can be found from the equation [239]:

$$tg\theta = \frac{I_s \cos\varphi}{(U_s / x_d) \pm I_s \sin\varphi}, \tag{12}$$

where I_s , U_s are the phases stator current and voltage, respectively; x_d is the main inductive resistance; the «plus» sign corresponds to overexcitation mode of a turbogenerator, and the «minus» is underexcitation mode.

The magnitude of currents in the stator and rotor windings and the angle β are given in accordance with the load conditions of a turbogenerator.

The model takes into account the rotor movement relative to the stator. The rotation is simulated using a Moving Mesh (ALE). The displacement of the finite-element mesh is given by the transformation equation:

$$\begin{cases} dx = \cos(2\pi nt)\cdot X - \sin(2\pi nt)\cdot Y - X \\ dy = \sin(2\pi nt)\cdot X + \cos(2\pi nt)\cdot Y - Y \end{cases}, \tag{13}$$

where dx, dy are the displacement along x and y coordinates, respectively; X, Y are the coordinates of initial points; n is the speed of rotation.

The expression in brackets is the certain angle (in radians), and time t is the parameter by which the rotor does movement on angle ($2\pi nt$) relative to the initial position. A static calculation is performed, and one fixed position of rotor and fixed magnitude of currents in the windings (at t =0) are considered, the results of which then used as initial conditions for the dynamic effect (more precisely, the parametric calculation). In this case, the Poisson equation does not depend on time, its solution is determined by the instantaneous values of currents in the windings and the geometry of solving region, which varies because of displacement of rotor coordinates.

After calculated the electromagnetic problem individually solves the problem of the eddy currents distribution from the main radial field for each massive element of a turbogenerator (press plate, press fingers, copper shield), and it's the average magnitude is used for calculation the thermal problem.

On the second stage, in consideration of the electromagnetic field distribution in central part, the electromagnetic field in longitudinal section is simulated (Figure 8). Taking into account the symmetry of a machine along axial and radial directions, the calculation area of end zone is considered as the rotor section along its axis and the section of the stator core tooth in the tangential direction [257, 258]. This section coincides with the rectangular coordinate plane *XY* and is the symmetry plane of rotor (in Figure 7 it passes along the radius OO_1).

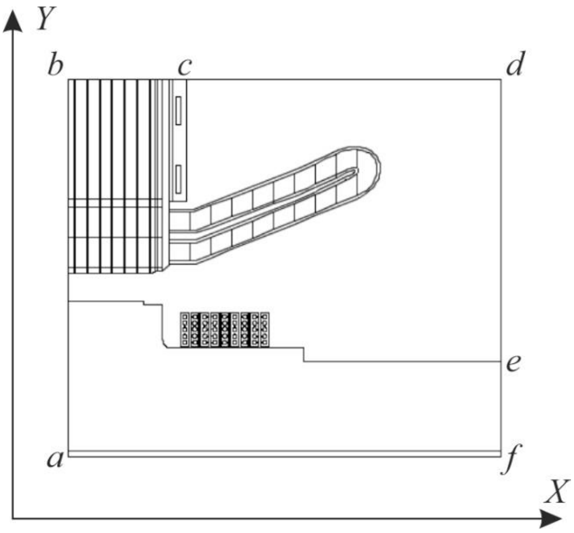

Figure 8. The calculation area of a turbogenerator end zone

The equation of a two-dimensional magnetic field for the component A_z (is tangential component in the solving region) has the form (7). The required structure lines of force for electromagnetic field are formed by means of boundary conditions complex on lines *abcdef* for the magnetic vector potentials and magnetic field (Figure 8).

On the line *bc* installed the magnitude of magnetic field in the point O_1 (Figure 7):

$$H\big|_{bc} = H\big|_{O1}, \qquad (14)$$

and on the line *af* – condition of symmetry the magnetic field concerning rotor axis:

$$n \times H\big|_{af} = 0. \qquad (15)$$

Along the line *ab* installed the distribution of magnetic field, a similar to the distribution along the same line in transversal section (lines OO_1, Figure 7):

$$H\big|_{ab} = H(r)\big|_{OO1}. \qquad (16)$$

It is assumed that for remote the lines *cd*, *de* and *ef* the magnetic field fails, so on the lines installed:

$$A_z\big|_{cdef} = 0. \qquad (17)$$

At the same time installed the distribution of magnetic permeability along the radius OO_1 – $\mu|_{OO1}$, which varies due to different saturation of stator magnetic core because of the radial field.

Thus, the interconnection of electromagnetic fields in the central and end zones of a turbogenerator is installed. The effect of load condition is taken into account by the magnitude of currents in the stator and rotor windings, angle β and boundary conditions.

An important stage for calculation of electromagnetic field in the end part is the description of currents in the winding frontal part. The proposed model of a turbogenerator end zone allows description of currents in the stator winding frontal part considering the geometric shape of frontal connections and, most importantly, the load condition [242, 261]. The direction of instantaneous phase currents i_A, i_B, i_C of the stator winding frontal part and a portion of its scheme (together with section OO_1) is shown in Figure 9. The currents in the winding frontal part (Figure 9) less than taken in the system (10) at $\sqrt{2}$ time, since the front parts are bent an average on 45°. Since the longitudinal section of a turbogenerator passes along the longitudinal axis of rotor *d*

(Figure 7), the magnitude of current density for the rotor winding frontal part corresponds to the given excitation current.

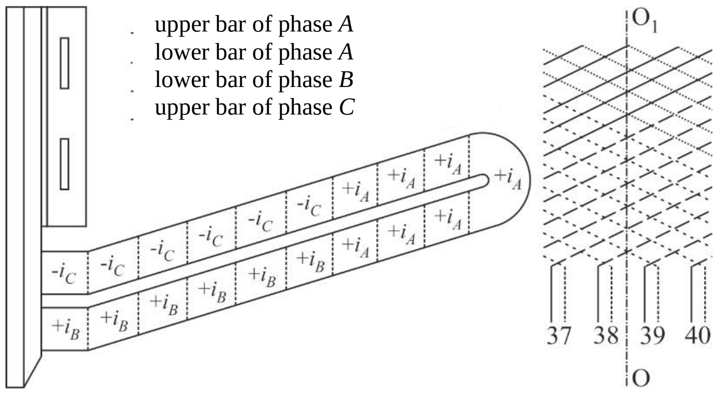

Figure 9. The instantaneous phase currents of
the stator winding frontal part and a portion of winding along the section

The electromagnetic calculation is performed for the whole of solving region.

Individually solves the problem of eddy currents distribution from the axial magnetic fluxes of windings frontal parts. Since the rotor moves synchronously with the field, non-zero conductivity is given in the stator core packets, press finger, copper shield and press plate.

Taking the obtained results of electromagnetic calculation as a source of heat losses, the problem of distribution temperature is solved.

The equation of a two-dimensional stationary temperature field is given by equations:

$$\nabla\left(-k\nabla T\right)=Q \ , \qquad (18)$$

where k is the thermal conductivity; T is the temperature; Q is the heat source.

The heat calculation is performed for only in the stator core end zone.

A turbogenerator under consideration has a radial ventilation system. Cold hydrogen is fed into the radial channels between the stator packets and between the press fingers and the press plate from side of the gap with the further movement towards the stator yoke.

The boundary conditions are installed. Heat transfer to the environment is carried into effect by means of convective heat exchange between a heated surface and a stream of cooling hydrogen. The general equation has the form:

$$-\vec{n}\cdot\vec{q} = q_0 + h\left(T_{\text{inf}} - T\right), \tag{19}$$

where h is the heat transfer coefficient, T_{inf} is the external temperature.

Installed the next boundary condition for the water circulating in the cooling channels of the press plate and the stator winding frontal part:

$$T = T_0 \,. \tag{20}$$

Installed the boundary condition of symmetry on line passes in the middle of the last ninth packet of solving region:

$$\vec{n}\cdot\left(k\nabla T\right) = 0 \,. \tag{21}$$

The finite element mesh is the same for both the electromagnetic and thermal problems.

In order to verify the reliability of developed algorithm was performed a control calculation and comparison for obtained temperature values in the end zone of a turbogenerator type TGV-500 under rated load conditions in accordance with the experimental data for temperature field of the stator core end packet and the heat transfer coefficients [239, 256, 259].

The heat transfer coefficients [in W/(m^2·K)] for a turbogenerator type TGV-500 have the following values [239, 256, 259], Figure 10:

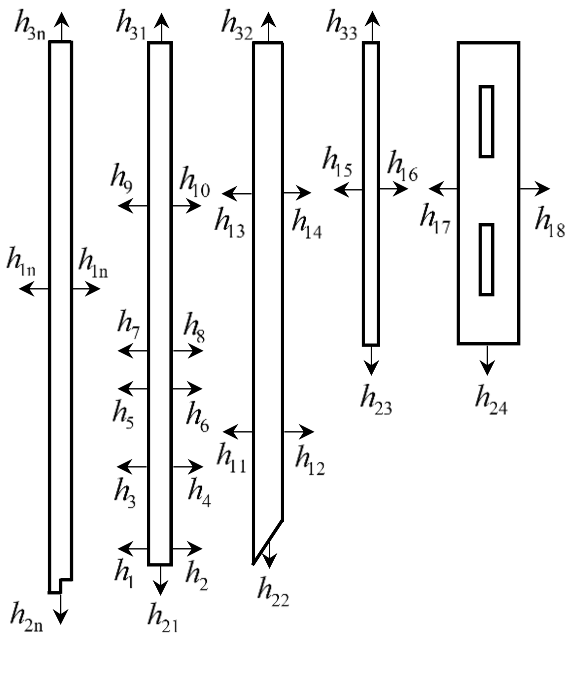

Figure 10. The heat transfer coefficients
for a turbogenerator type TGV-500

– for the end packet:

$h_1 = 474$; $h_2 = 332$; $h_3 = h_5 = h_7 = 354$; $h_4 = h_6 = 248$; $h_8 = 225$; $h_9 = 221$; $h_{10} = 209$; $h_{21} = 1330$; $h_{31} = 205$;

– for the press finger:

$h_{11} = h_{12} = 280$; $h_{13} = h_{14} = 243$; $h_{22} = 1280$; $h_{32} = 243$;

– for the copper shield:

$h_{15} = h_{16} = h_{23} = 280$; $h_{33} = 243$;

– for the press plate:

$h_{17} = 280$; $h_{18} = 200$; $h_{24} = 384$;

– averaged value for the other packets:

$h_{1n} = 241$; $h_{2n} = 1000$; $h_{3n} = 200$.

With help a mathematical simulation according to the given algorithm (7)–(21) for a turbogenerator type TGV-500 under rated load conditions the following results were obtained.

The instantaneous distribution of magnetic flux density and vector magnetic potential in a turbogenerator central zone (for t = 0,02 sec corresponding to one full revolution of the rotor, the step size of time is 1^{-4} sec, that is, at one step the rotor turns to 1,8°) is shown in Figure 11. The distribution of magnetic permeability is shown in Figure 12. As can be seen in this figure, the maximum value is 8542 and appears in the stator yoke.

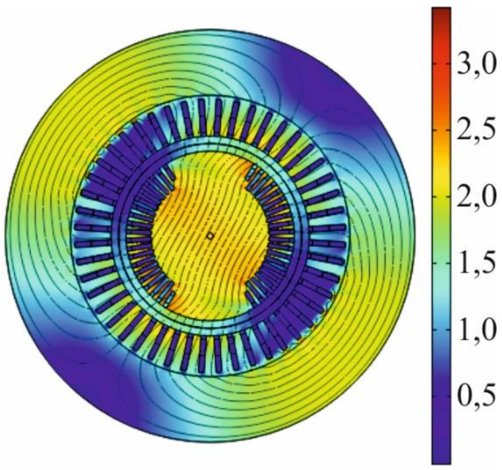

Figure 11. Electromagnetic field distribution in the central zone of a stator and a rotor under turbogenerator rated load conditions

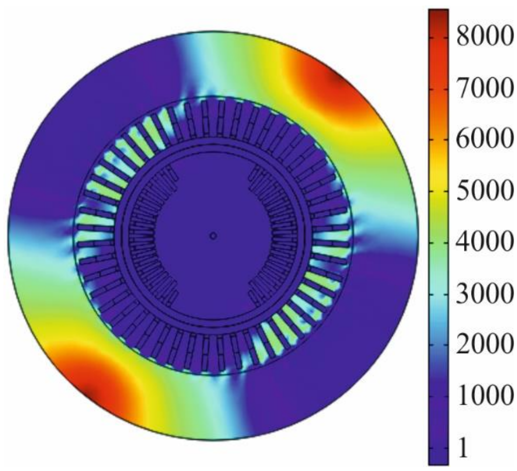

Figure 12. Magnetic permeability distribution in the central zone of a stator and a rotor under turbogenerator rated load conditions

As can be seen in Figure 13, the maximum magnetic flux density of the stator core is 3,4 T and appears in the tooth crown, the magnetic field distribution is symmetrical along the pole central line and the maximum values appears in the pole central line [258]. The distribution of magnetic flux density in the press fingers is shown in Figure 14. The magnetic flux density values of the non-magnetic steel fingers are lower and the maximum value is 0,53 T.

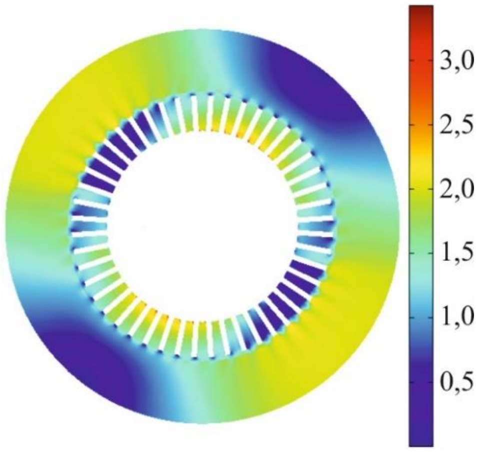

Figure 13. Magnetic flux density distribution in the stator core under turbogenerator rated load conditions

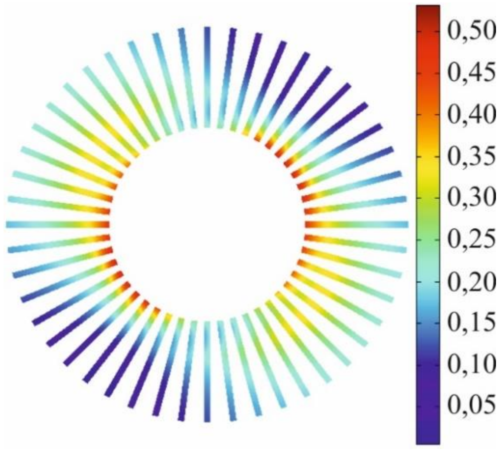

Figure 14. Magnetic flux density distribution in the press fingers under turbogenerator rated load conditions

The press plate and the copper shield materials are nonmagnetic too, and the press plate is before to the copper shield. So, their magnetic field distributions are coincident [258]. The maximum magnetic flux densities are 0,36 T and 0,33 T, respectively (Figures 15 and 16).

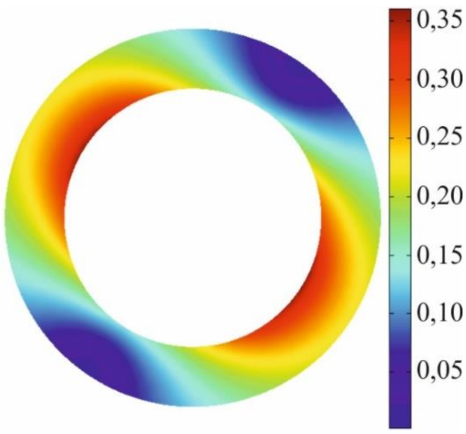

Figure 15. Magnetic flux density distribution in the press plate under turbogenerator rated load conditions

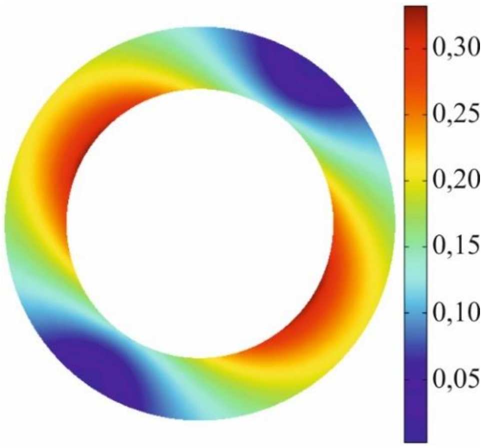

Figure 16. Magnetic flux density distribution in the copper shield under turbogenerator rated load conditions

Figures 17, 18 and 19 show the eddy current density distribution from the main radial field in the press fingers, the press plate and the copper shield. For the good conductivity of the copper, the eddy current value of the copper shield is much larger than that of the non-magnetic press fingers and press plate [258].

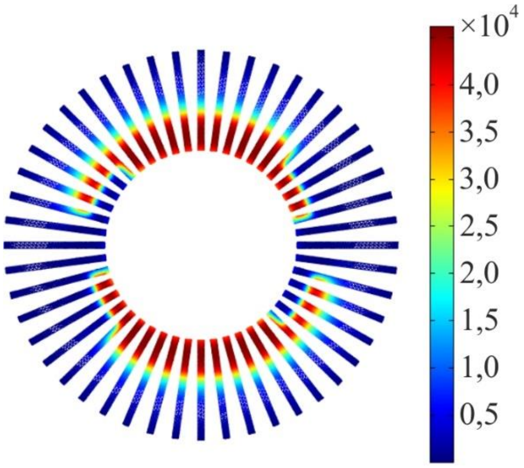

Figure 17. Eddy current density distribution in the press fingers under turbogenerator rated load conditions

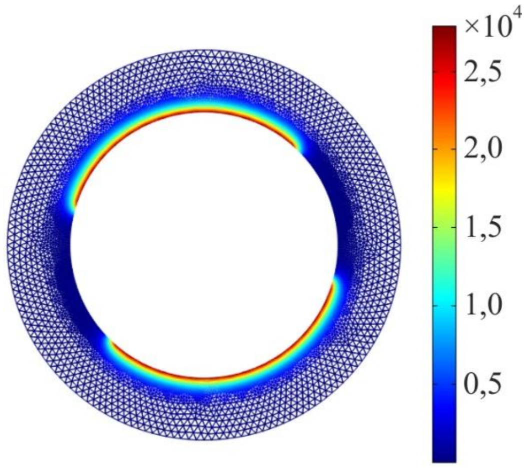

Figure 18. Eddy current density distribution in the press plate under turbogenerator rated load conditions

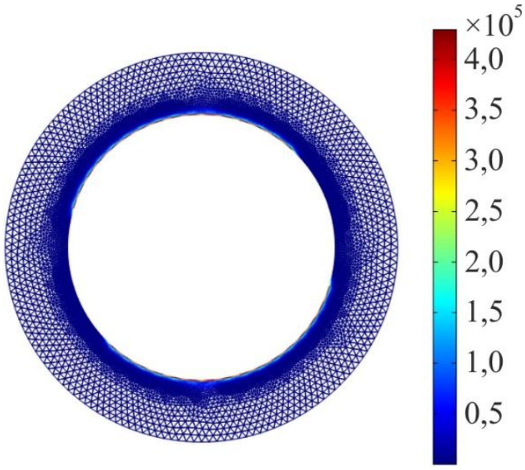

Figure 19. Eddy current density distribution in the copper shield under turbogenerator rated load conditions

The instantaneous distribution of magnetic flux density and vector magnetic potential in a turbogenerator end zone is shown in Figure 20. Temperature distribution in the stator core end zone is shown in Figure 21. As can be seen in this figure, the maximum temperature in the tooth root of stator end packet is 97 °C, the press plate is 91 °C, the copper shield is 86 °C and the press finger is 85 °C.

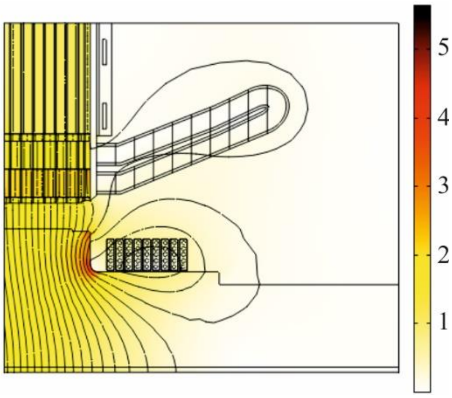

Figure 20. Electromagnetic field distribution in the end zone of a stator and a rotor under turbogenerator rated load conditions

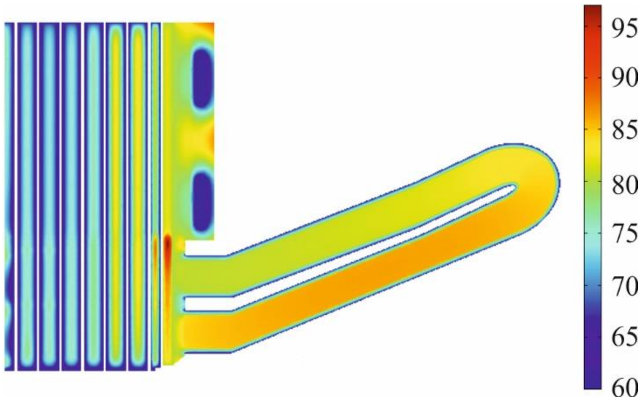

Figure 21. Temperature distribution in the stator core end zone under turbogenerator rated load conditions

The maximum temperature in the end packet tooth zone is explained by the combined effect of the main radial field, the axial leakage flux of the windings frontal parts of a stator and a rotor, as well as by the «displaced» portion of the main field from the air gap and the stator core slots. In addition, the shield effect of the press plate is cause of local concentration for electromagnetic field in the end packet tooth zone. Temperature distribution in the press plate depends on the channels with cooling water. However, they are effective only in beside the plate. With the distance from the end packet tooth zone towards the stator yoke, the temperature sharply decreases due to the shield effect of the press plate and the copper hoop. The temperature also decreases with approach to the gap. The axial component of magnetic flux density in the tooth crown is 0,70–0,75 T (the end packet), however, this zone is intensively cooled with gas circulating in the gap.

In order to verify the reliability of obtained results was performed a comparison for temperature values in the end zone of a turbogenerator type TGV-500 under rated load conditions in accordance with the experimental data [239, 256, 259]. The experimental data corresponds to the stationary heat of stator core end packet from the turbine side at section 1/8 width of packet along the axis of a turbogenerator. The differences of calculated and experimental values did not exceed 7 % (Table 11), indicating a high reliability of the applied approaches and assumptions.

Table 11.

Calculation results and experimental data corresponds to the stationary heat of stator core end packet for a turbogenerator type TGV-500

Source of information	Temperature, °C			
	Tooth			Yoke
	Crown	Middle	Root	Middle
Nominal load condition (P = 495 MW, cos φ = 0,848)				
Calculation, °C	50,9	51,25	72,37	56,63
Experiment, °C	–	54,90	76,20	53,70
Error, %	–	6,65	5,03	5,46

Thus, the algorithm, detailed mathematical description and solution of a quasi-three-dimensional task for determination of electromagnetic field and temperature distributions in the stator core end zone of a powerful turbogenerator using a numerical method were presented. A mathematical model differs from are known more complete account of the physical factors and the high accuracy of the calculation results with a relatively simple the software implementation.

Conclusions

Modern level of technology, stored experience of operation and researches for power turbogenerators, the use more improved materials (stator and rotor winding insulation, electrotechnical steel, etc.) and cooling systems allows building high-power generators with air or air-water cooling, and also with full water cooling, that provide fire and explosion protection of electric power station. For all this it is necessary take into account the maximum simplicity principle for construction and maintenance, the minimum number of auxiliary systems and the maximum reliability.

The end zone shielding, using the stepped end packets of stator core, the chamfer for end packets teeth of stator core, the longitudinal slits for end packets teeth, using the magnetic shunts and others are the main constructive methods for reduction the eddy currents losses and improvement the cooling of powerful generators end zone. Taking into account the considerable unevenness of electromagnetic and heat loads of generator constructive units especially end parts of the stator and the rotor, tends to rise with increase of generators unit capacity, these methods solves a limited field of tasks from general problem.

A turbogenerator design complication and the use of new auxiliary systems for the cooling intensification with increasing power unit leads to the decrease of generator reliability. Therefore, the system and methods control and diagnostics of generators main component parts for compensate this decrease in the reliability of turbogenerators were developed. Another way for ensure reliability with complication of a turbogenerator and auxiliary systems is reserve. Finally, the third way for ensure reliability is simplification of the main component parts design and non-use in a number of auxiliary systems with help return to less efficient cooling on conditions that it ensures given power unit with a modern technical solutions.

The advantages of constructing models in COMSOL Multiphysics software are shown. The most significant advantages are the ability to solve multiphysical problems, the interface simplicity, the easiness simulation and powerful visualization.

A quasi-three-dimensional mathematical model of coupling calculation for electromagnetic field and temperature distributions of a powerful turbogenerator end zone is developed. A mathematical model differs from are known more complete account of the physical factors and the high accuracy of the calculation results with a relatively simple the software implementation. In particular, a method for calculating electromagnetic field of a turbogenerator end zone is developed, which allows description the currents of stator winding frontal part considering geometric shape of frontal connections and, most importantly, the load condition of a turbogenerator. It is important to emphasize, that all known today a quasi-three-dimensional models the end zone of a powerful electrical machine have a homogeneous character of stator winding frontal part.

The presented mathematical model allows evaluation the efficiency of design solutions for the stator end zone of a turbogenerator under different load conditions, including the conditions of reactive power consumption.