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Series of Powerful Water-cooled Turbine Generators

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SUMMARY

A series of T3B type turbine generators with full direct water cooling with a capacity up to 1,333 MVA is presented. The main design features as well as the technical and energy characteristics of these turbine generators are considered.

Since water is a highly efficient refrigerant, along with direct water cooling of the stator windings, the T3B series turbine generators use direct water cooling of the rotor windings, as well as water-cooling of the stator core.

Water cooling of the stator core is provided by silumin cooling elements located between the core stacks. The cooling elements have built-in stainless steel tubes through which the distillate is flowing. Silumin cooling elements also provide shielding from axial stray magnetic fields in the end zone and increased stiffness of the core when exposed to electromagnetic forces.

Stator core is held in compressed state with the aid of fins, pressing plates and tooth supports. The fins and pressing plates are fitted with cooling elements made from copper tubes through which the distillate is flowing. At the disc part of pressing plates and at the supports there are copper circular water-cooled shields interconnected by current connectors.

The rotor winding is made in the form of hollow copper tube coils, through which distilled water is flowing. Water cooling of the rotor winding made it possible to increase electromagnetic loads without increasing the overall dimensions.

Current connections of the rotor winding coils are made in series while the cooling water connections are made in parallel. The rotor winding diagram ensures the operation of the self-pumped water cooling system. Incoming for distillate ends of coils are located in the circular row of smaller diameter, while the outgoing ends are located in the circular row of larger diameter. From the top turn of the coil the distillate enters the internal surface of the drain ring; from here the distillate is discharged into the drain chamber of the shield.

A feature of high-power turbine generators with full water cooling is also the presence on the rotor of a special damper winding in the form of single-turn hollow copper coils with water cooling, located directly under the wedges in the longitudinal slots of the rotor. Coils of damper winding in their end turns areas are connected to each other by copper segments. The damper winding is used to cool the rotor surface, retaining rings and air in the generator gap - both in steady-state operating modes and in dynamic non-stationary modes, in accordance with the modern requirements of grid operators.

The stator ends are made from non-magnetic steel. The walls of ends parts are jacketed, with distillate flowing in the gap between the jacket walls.

The losses in the characteristic sections of the turbo generators stator core end during variations of reactive power from the rated load to under-excitation modes are estimated.

KEYWORDS

Turbine Generator – Design – Water-cooling - Rotor - Self-pump - Under-excitation - Losses.

INTRODUCTION

A series of T3B type turbine generators with full water cooling with a capacity within the range from 78.5 to 1333 MVA is presented. The main design features, as well as the technical and power characteristics of these turbine generators, are considered.

Since water is a highly efficient heat transfer fluid, the T3B series turbine generators, along with direct water cooling of the stator windings, use direct water cooling of the rotor windings and the rotor damper system, including water cooling of the stator core, pressure plates, tooth supports, core keybars and end shields.

Fully water-cooled turbine generators have been successfully operated at power plants in Russia for more than 50 years with high efficiency (Fig. 1).

Fig. 1. Fully Water-Cooled Turbine Generator at a Power Plant

1. BASIC PARAMETERS

Table I shows the main performance data of the series of water-cooled turbine generators with a capacity of up to 1333 MVA. Turbine generators can be installed on the foundations of conventional hydrogen-and-water-cooled turbine generators and, as can be seen from the table, are not inferior to these turbine generators in terms of efficiency and weight and size characteristics.

Table II shows the increase in electromagnetic loads for a series of fully water-cooled turbine generators with increasing rated power. With an increase in the rated power, the electromagnetic loads of the stator and rotor increase. The electric current density in the rotor winding of high-power turbine generators exceeds 13 A/mm2.

Table I. Basic Performance Parameters of Fully Water-Cooled Two-Pole Turbine Generators

Generator Type	Full Power, MVA	Efficiency, %	Voltage, kV	Rotation Speed, rpm	Total Weight, t	Weight per Power, t/MVA	Year of Production Start
T3B-63-2	78.75	98.4	6.3/10.5	3000	100	1.27	1968
T3B-110-2	137.5	98.6	10.5	3000	171	1.24	1995
T3B-220-2	258.8	98.8	15.75	3000	233	0.9	1998
T3B-320-2	376.5	98.8	20	3000	268	0.71	1998
T3B-800-2	888.9	98.9	24	3000	495	0.56	1980
T3B-890-2A	988.9	98.85	24	3000	544	0.55	2010
T3B-1200-2A	1333	98.97	24	3000	682	0.51	2012

Table II. Main Dimensions and Electromagnetic Loads of Fully Water-cooled Turbine Generators

Generator type	Full power, MVA	D1, mm	L1, mm	δ, mm	Bδ, T	A1, A/m	j1, A/mm2	J2, A/mm2
T3B-110-2	137.5	1075	2600	70	0.88	1200	4.7	7.35
T3B-220-2	258.8	1075	3800	70	0.92	1490	5.9	9.3
T3B-320-2	376.5	1075	4700	70	0.99	1710	6.7	10.1
T3B-800-2	888.9	1200	7000	100	0.97	2040	8.4	11.4
T3B-890-2	988.9	1200	7000	100	1.0	2270	10.1	12.2
T3B-1200-2	1333	1250	8000	145	0.92	2390	8.6	13.4

2. STATOR DESIGN

The stator core is conventionally assembled from 0.5 mm thick electrical steel segments coated with electrical-insulating varnish. Sheets of the core end stacks from each end of the core are glued and baked together. The teeth of the core end stacks have slots and are chamfered to reduce losses and to ensure smooth changes in the magnetic field in the stator core end.

Stator core is held in compressed state with the aid of keybars, pressure plates and tooth supports.

Water cooling of the stator core is provided by silumin (aluminum-silicon alloy) cooling elements located between the core stacks (Fig. 2, 3). The cooling elements have built-in stainless steel tubes through which the distillate is flowing. The core cooling system has a large margin and does not require an unscheduled generator shutdown if one of the coolers is obstructed. Silumin coolers also provide shielding of the axial stray magnetic fields in the stator core end. In addition to that, the increased stiffness of the core is provided, with prevention of possible local squeezing of the insulating coating of the active steel sheets by spacers between the stacks.

In the stator core end (Fig. 4), water-cooled copper screens are installed, while copper water-cooled buses are fitted into the annular grooves made in the core pressure plates. The copper shield is mounted between the disc part of the end plate and the tooth supports.

Keybars, tooth supports, stator end shields, housing end parts, end leads and outlet buses in T3B series turbine generators are also water-cooled.

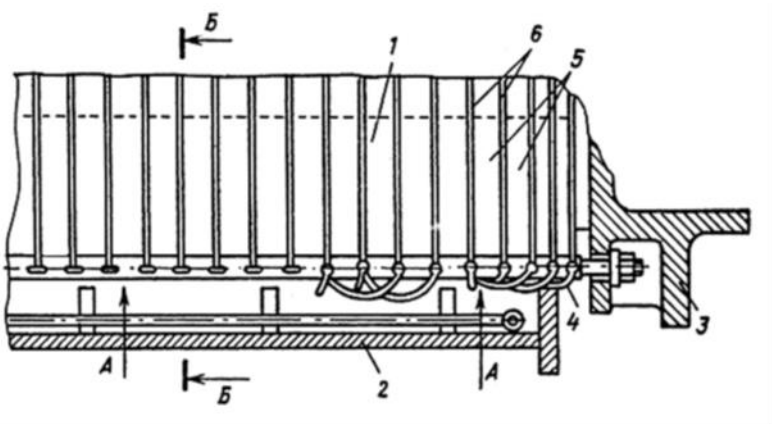


Fig. 2. Longitudinal Section of the Stator Core of a T3B Turbine Generator with Coolers.

1 — stator core; *2* — stator housing; *3* — pressure plate; *4* —keybar;
5 — active steel laminations stacks; *6* — stator steel coolers

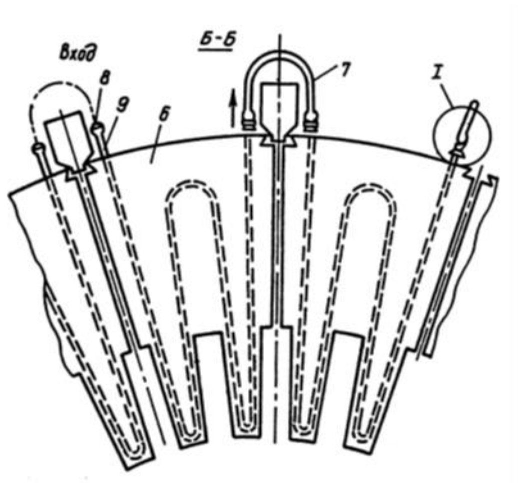


Fig. 3. Stator Steel Coolers with Connecting Tubes.

7 - fluoroplastic tubes; 8 — nozzle flare; 9 — nozzles

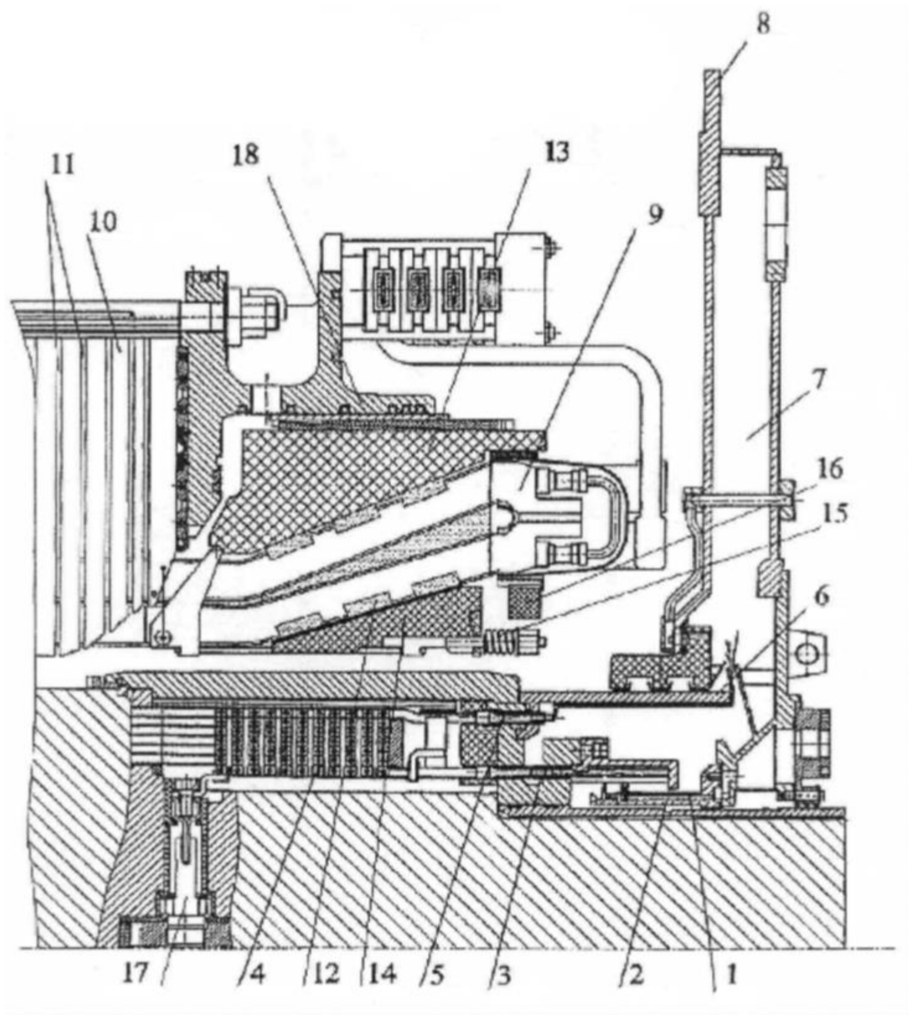


Fig. 4. Stator end zone of the T3B Turbine Generator.

1 — fixed pressure manifold; *2* — water cooling pressure ring; *3* — rotor winding bottom terminals; *4* — rotor winding; *5* — rotor winding upper terminals; *6* — drain ring; *7* — drain chamber; *8* — stator housing end shield; *9* — stator winding end part; *10* — stator core; *11* — stator core cooler; *12* — putty; *13* — outer fiber glass ring; *14* — inner fiber glass ring; *15* — spring; *16* — spacer ring; *17* — rotor winding current supply; *18* —pressure plate.

3. ROTOR DESIGN

The rotor winding is made in the form of coils of a rectangular hollow copper tube with a round channel through which distilled water flows (Fig. 5, 6). In high-power turbine generators, the winding consists of two coils located in the top and bottom parts of the slots. Current connections of the rotor winding coils are made in series while the cooling water connections are made in parallel. Efficient water cooling has allowed increasing the electromagnetic loads without increasing the overall dimensions of the unit.

Fig. 5. General View of the Rotor Winding of the T3B Turbine Generator

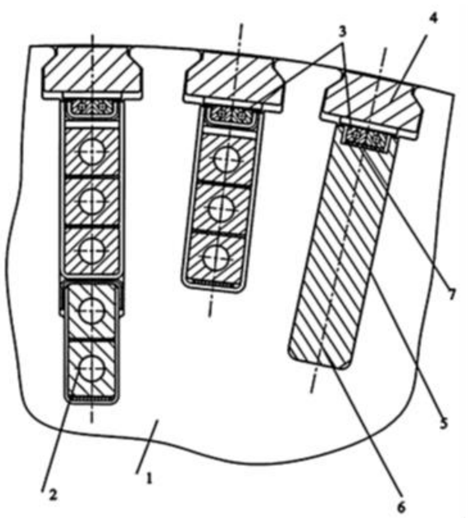


Fig. 6. Sectional View of the Rotor of the T3B Turbine Generator in the Slot-embedded Part.

1 — rotor shaft; *2* — excitation winding hollow copper conductors; *3* — damper winding hollow copper conductors; *4* — wedges; *5* — slots on the poles for the rotor uneven stiffness aligning; *6* — steel inserts; *7* — fiberglass gaskets

There are designs of water-cooled turbine generators [1], where the water cooling the rotor winding is pumped through an axial channel into the rotor shaft. Then water enters the winding through radial channels in the shaft end and numerous steel and insulating tubes located in the area of stator end windings under the retaining ring, and at last through similar drain pipes water brought back into the shaft and discharged.

In turbine generators of T3B series, there are no hydraulic connections between the rotor winding and the shaft. The so-called self-pumped water cooling system of the rotor winding [2] is used instead. Input for distillate ends of coils are located in the circular row of smaller diameter, while the outlet ends are located in the circular row of larger diameter. From the top turn of the coil the distillate is entering the internal surface of the drain ring; from here the distillate is discharged into the drain chamber of the shield.

Let's consider the operation of the self-pumped cooling system of the rotor winding in more detail. Cooling distillate (Fig. 4) is pumped into a pressure manifold attached to the end shield of the generator housing *1*. Through the outlet openings of the pressure manifold, the distillate is fed into the inner cavity of the rotating pressure ring *2*, in which a rotating annular layer of distillate is formed under the action of centrifugal forces.

Due to the pressure in this layer, the distillate enters the inlet tubes of the bottom terminals of the excitation winding *3* and enters the channels of its first turns. Subsequently, the distillate passes from turn to turn of the excitation winding, using the additional head arising from the difference in the peripheral velocities of the water flow in the input *3* and output *5* ends of the coils located on a larger diameter in the drain ring *6*, from where it is discharged into the drain chamber *7* of the end shield *8*.

In this case, each cooling circuit is made of conductors with holes of the same cross-section, and the turns are made with a certain radius, which does not allow abrupt changes in the water flow rate. Stepped sections and abrupt changes in the cross-section of the channels in the cooling circuit are excluded.

The pressure ring and drain ring are attached to a thrust ring, through the holes in which the ends of the coils with attached nozzles and fitted insulating tubes are axially brought out, and the places where the tubes pass through the holes are sealed. The pressure ring has a U-shaped cross-section, which eliminates the possibility of distillate getting into the rotor under-shroud space.

The specified flow rate of the distillate through the windings is ensured at its certain radial level in the pressure ring. The level is monitored using an indicator tube, one end of which is fixed in the pressure header and is located towards the rotating movement of the distillate. At the specified level of distillate, the tube edge will touches the distillate surface, and distillate will flow into the tube and from the tube to the indicator tank. Presence of a moving stream in the indicator tank indicates that the distillate level inside the rotor pressure ring is normal.

The design and principle of operation of the self-pumped cooling system are protected by Russian patents.

A feature of high-power turbine generators with full water cooling is also the presence on the rotor of a special damper winding in the form of single-turn hollow copper coils with water cooling, located directly under the wedges in the longitudinal slots of the rotor. Coils of damper winding in their end turn areas are connected to each other by copper segments.

High efficiency of the water cooling allowed the damper winding to be introduced while maintaining the rotor dimensions of the hydrogen-cooled machine.

The damper winding is used to cool the outer rotor surface, retaining rings and air in the generator gap - both in steady-state operating modes and in dynamic transient modes, in accordance with the requirements of grid operators.

4. STATOR END WINDINGS FASTENING

Fig. 4 shows the structure of the fastening of the stator end windings of T3B turbine generator. Stator end windings of turbine generators are constantly exposed to vibration under the action of significant electromagnetic forces with a frequency of 100 Hz, as well as thermal deformations due to heating (moreover, uneven heating) of the bars in the stator core slots. Therefore, there may be deformations in soldered joints of the heads of the bars at the points of their connection, dangerous abrasion of the insulation of the bars at the exit from the stator core slots, as well as fatigue damage to conductor strands in them.

The latter circumstance creates an increased danger namely in fully water-cooled turbine generators. The fact is that when leaks occur in the hollow conductors of water-cooled windings of water-and-hydrogen cooled generators filled with hydrogen under a pressure of 3-4 atmospheres, the moisture is "driven" into the hollow conductors, and hydrogen gets into them, which is manifested by its appearance in a special trap provided for this very purpose in the water cooling systems of these generators. This allows the maintenance personnel to promptly deliver the generator for repair to identify and eliminate such leaks.

But in fully water-cooled turbine generators, the inner space is filled with air, the pressure of which differs little from atmospheric pressure. In the absence of any signs indicating moisture penetration outside the conductor, this may lead to humidification, and then to insulation breakdown, i.e. severe internal damage to the generator. Therefore, it is especially important to use hollow conductors made of non-magnetic steel in stator bars for fully water-cooled turbine generators, and to reduce mechanical stresses in conductor strands.

For this purpose, the end windings are placed between the outer and inner solid fiberglass rings (Fig. 4), the inner part of which has a conical shape corresponding to the bend angle of the end windings. The space between the bars is filled with epoxy compound. This eliminates the need to use both the cord tying and spacers between the bars.

The outer fiberglass ring is wedged along the outer surface in the spigot of the pressure ring of the stator core. This creates a rigid connection of the ring, and with it a rigid connection of the entire end winding with the stator core end plate in the radial and tangential directions and ensures the vibration stability of the winding. To compensate for the temperature stresses of the bars in the axial direction between the upper fiberglass ring and the spigot of the end plate, heat-resistant rubber gaskets are installed around the circumference. The gaskets, which are fixed in the intervals between them around the circumference of the ring with titanium plates, have a compressive stiffness, but retain high shear compliance of the rubber. This creates the possibility of axial movement of the ring along with the entire package of the end windings relative to the end plate of the stator core and determines a low level of temperature stresses in the winding bars that arise during load increase and load shedding.

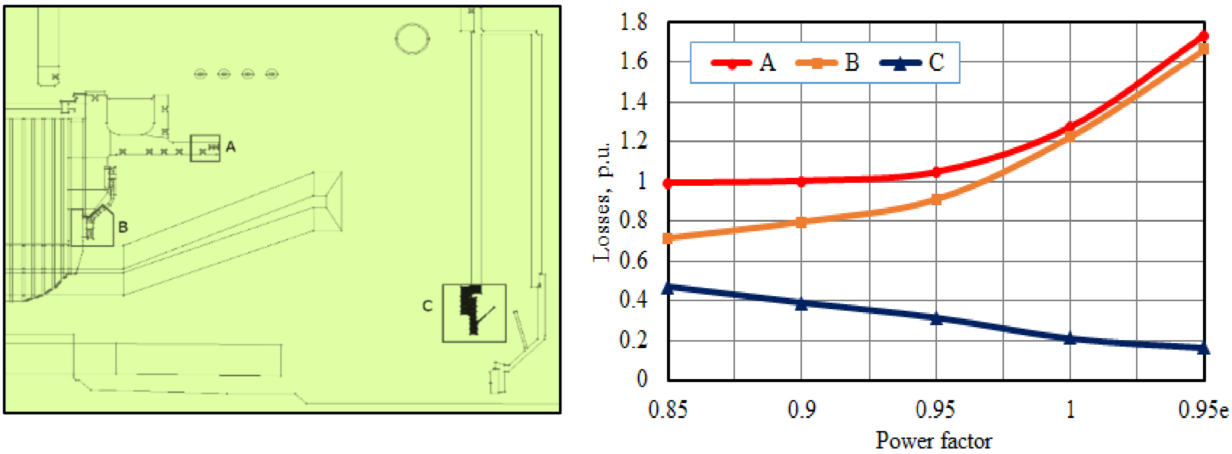
5. HOUSING

The inner space of the turbine generator is filled with air under a slight overpressure and is sealed by two hydraulic locks installed on both sides of the rotor on a stationary pressure header. Dry air from the turbine room is blown through the air filter by the fan into the middle part of the stator housing, then enters the distillate drain chambers from the rotor windings located in the stator end shields, and the humidified air is discharged through separators back into the turbine room.

The stator ends are made of non-magnetic steel, which reduces losses and heating, however, making the structure "transparent" to external stray magnetic fields. The walls of ends parts are double, with distillate flowing in the gap between the walls.

6. STATOR END LOSSES

The stator core end of a high-power turbine generator is exposed to significant electromagnetic, thermal and vibration loads. The operating mode significantly affects the losses in the stator core end. In this regard, the cooling system and the design of the pressure plate and screens that protect the end plate and the end stacks of the stator core from penetration of the axial component of the magnetic field are of great importance. Fig. 7 shows the estimated losses [3] in the characteristic sections of the stator core end during variations of reactive power from the rated load to under-excitation at a constant active power. In the under-excitation mode, losses in the extreme section *A* of the end plate increase by 70%, in section *B* of the screen of the end plate and tooth supports - by 140% compared to the rated mode, and in the fan shield in section *C* they decrease by 60%, respectively.



a b

Fig. 7. Computational model (a) and the results of calculations of losses (b) in the characteristic sections *A, B, C* of the stator core end when changing the reactive load in the over-excitation and under-excitation modes

A special check of the thermal state of the stator core end of turbine generator type T3B-800–2 installed at the Permskaya SDPP showed that due to effective water cooling at an active power equal to the rated value of 800 MW and a power factor of 0.95 in the under-excitation mode, the maximum temperature rise of the active steel of the core end steel stacks does not exceed 70 °C, in the disk part of the pressure plate - 58 °C, in its cylindrical part - 64 °C, tooth supports - 70 °C.

7. OPERATING EXPERIENCE

For the creation and development of a series of turbine generators with full water cooling of the T3B type with a capacity of up to 900 MVA, the specialists of the manufacturing plant and the personnel of power plants were awarded the State Prize of the Russian Federation in the field of science and technology.

For a turbine generator with a capacity of 1333 MVA, the customer determined the availability factor for a period of more than three years from the start of commercial operation as a reliability indicator. The obtained value exceeds the requirement of the technical task 0.995 and is: $K_g = t_w /(t_w+t_p) = 0.998$, where t_w is the total uptime, t_p is the total downtime.

CONCLUSION

Features of the developed design and high efficiency of full water-cooling ensure reliable operation of the developed series of high-power turbine generators, taking into account the modern requirements of the grid operator.

BIBLIOGRAPHY

[1] Wiedemann E. Fully Water-Cooled Turbogenerators // The Brown Boveri Review. 1966. - IX. - p. 501 -511.
[2] Kadi-Ogly I.A. Issues of Creating Fully Water-Cooled Turbogenerators with a Self-Pumping Rotor [Text]: thesis by ... Doctor of Engineering / I.A. Kadi-Ogly. — Saint-Petersburg, 2003 (In Russian).
[3] Roytgarts M., Smirnov A. Electromagnetic Analysis in the End Zone of Powerful Turbogenerator. (CIGRE. Meeting and Colloquium “Rotating Electrical Machines. Requirements, Operation & Maintenance” September 6th-11th 2015 Madrid, Spain).