SMALL-SCALE PROTOTYPE OF A FULLY HTS-2G SIX-PHASE INDUCTION ELECTRICAL MACHINE

D Dezhin, I Dezhina, R Ilyasov
Department of electrical machines and power electronics, Moscow aviation institute, (national research university), Moscow, Russia

Abstract. HTS direct drive generators with high specific output mass power and specific output volume power (at the boiling point of liquid nitrogen 77 K) are needed for aviation. Elimination of the reduction unit will reduce the weight of the entire generation system. However, this puts high demands on the strength of the high-speed rotor. Other important requirements are: brushless; the possibility of adjusting the output voltage (by changing the excitation current) depending on the magnitude and type of the connected load; autonomy (no external power supply of excitation current). To satisfy all the above requirements, a fundamentally new technical solution for an electric machine was developed. The generator is a two-package hybrid of the Induction machine with combined excitation. HTS-2G windings (2x3-phases of HTS-2G armature windings and axial excitation coil) are in stationary cryostats on the stator. The rotor has alternating poles of high coercive permanent magnets and ferromagnetic poles. To ensure the alternating magnetic field of the poles of the rotor and to avoid demagnetization of permanent magnets by a counter-directed field of the axial excitation HTS coils, the rotor packages are rotated by one pole. In this case, the demagnetizing part of the axial flux is intercepted by the ferromagnetic pole of the neighboring packet.

1. Introduction
All types of electric machines existing up to the present time have had various disadvantages, which do not meet all the stringent requirements for aviation generators at the same time [1, 2, 3, 4, 5]. For example, a traditional generator with electromagnetic excitation has rotating windings. A rotor with rotating HTS-2G windings requires a rotating cryostat with thick walls that increase the working magnetic gap [6]. The insufficient mechanical strength of the HTS-2G tapes does not allow the use of such rotors in high-speed direct turbine drives [7]. Current supply to the rotating excitation windings, contact rings or a cascade of sub-exciters and rotating rectifier are needed. Disadvantages of Induction machines — homopolar inductor alternators (HIA) — is a homopolar field, coupled with armature windings which vary from the maximum value to zero. In accordance with the Faraday law, the alternating magnetic field induces twice as much EMF as the homopolar field. The placement of permanent magnets between the ferromagnetic poles makes it possible to create an alternating magnetic field, but the counter magnetic flux of axial excitation produced by HTS coil demagnetizes even high-coercive magnets [8]. Rotors of the Lundell-type claw pole machine are able to create an alternating magnetic field, but the console fastening of the claws does not allow reaching high speeds due to mechanical forces, and solid claws are heated by induced Foucault currents due to tooth harmonics [9]. The combination of claws with magnets increases the value of the destructive centrifugal force. The three phases of the generator direct turbine drive (without stabilizing the gearbox), operating on the rectifier, has large pulsations, in comparison with the two three-phase generators.
All the disadvantages of conventional electric machines have been considered, and a new technical solution was found.

2. Design and development

The design and the principle of operation of an electric machine are discussed in detail earlier [4, 10, 11]. When creating a prototype, several different designs were considered. The single-pack generator has significant unused axial length: magnetic shunts in this design are not involved in the induction of EMF directly. In a three-pack machine, the problem is the connection of HTS windings of neighboring packets in three phases. The presence of two independent sets of three-phase windings in different packages allows creating a 6-phase magnetic system with a shift of 30 electrical degrees. When working on a rectifier, such a 6-phase system reduces the pulsation of the rectified voltage. One of the methods used to reduce the mass of the generator is to mount it directly on the drive. Thus, one bearing shield can be dispensed with. To ensure the universality of the generator, and to maintain the ability to conduct autonomous tests in no-loads motor mode, it was decided to use designs with two bearing shields. To ensure the equality of axial magnetic fluxes, the thickness of each of the two bearing shields and the excitation windings is half as much.

An analytical calculation method is created that allows the calculation of an aircraft generator using traditional frequencies of 400 Hz with a power of 500 kW.

Three-dimensional sketch of the geometry is shown in figure 1 [10, 11]. Cross-section sketch of the Stack 1 and Stack 2 is shown in figure 2. Superconducting coils of axial excitation 1 is turned on against the radial permanent magnets 5 on the rotor of both packages and is located on the stator to ensure non-contact. In this case, the operation of superconducting windings requires a cryogenic temperature, which can be achieved by pumping a cryogen (for example, liquid nitrogen). The location of the windings on the stator allows for the removal of the rotating cryostat and sliding seals. To ensure equality of the axial magnetic flux in both packages of relatively long machines, it is possible to symmetrically arrange two oppositely connected axial field windings outside the packages. The inductors on the rotor consist of alternating ferromagnetic poles 3 and poles of permanent magnets 5. The axial excitation coil 1 creates two types of axial currents: a flux passing through the ferromagnetic poles of the inductor of the closest packet 2 and the flow passing through the ferromagnetic poles 3 of the inductor far from the axial excitation of the packet. The permanent magnets 5 of the inductors on the rotor create traditional excitation fluxes, closing at the ferromagnetic poles of the inductors through the stator yoke 7 in the radial plane, and the currents closing along the ferromagnetic poles of the neighbouring packets in the axial plane are relatively small due to the transverse direction of the stacking of the stator packs. Both of these fluxes are coupled to the armature winding and participate in the EMF guidance. Over the ferromagnetic pole, the fluxes from the excitation winding and from the permanent magnets are added together. In the event of exclusion of the excitation current, the axial flux from the excitation coil becomes zero, and the EMF is induced only by fluxes from the magnets.

Unlike previously considered designs [10], the prototype of 500 kW generators has additional reserve copper windings of the armature 6 and excitation 16. In the event of a malfunction of the cryogenic supply system, the electric generator can remain operational at 10 percent of power. Copper windings are also necessary in the first stage for testing of the prototype.

Figure 2 shows that the windings of the armature right packages are rotated by 15 geometric degrees. Three-dimensional sketch of the rotor is shown in figure 3. Rotor packages are made of sheets of electrical steel; permanent magnets are in their closed grooves. The insignificant amount of pole scattering fluxes is compensated by a decrease in the air gap. The hollow shaft has a lower mass and sufficient rigidity to increase the critical speed. A variant of the elaborated principal design is shown in figure 4.
1 – axial excitation coil; 2, 3 – ferromagnetic poles; 4 – shaft; 5 – permanent magnets; 6 – armature windings; 7 – stators yoke; 8 – stators teeth; 9 – bandage (ferromagnetic, part of sheetelectrical steel); 10 – inter-package axial yoke; 11 – axial yoke; 12 – one bearing shield; 13 – bearing shield-shaft radial air gap; 14 – bearing shield-shaft axial air gap; 15 – framework; 16 – reserve excitation coils; 17 – reserve armature windings; 18 – stator tube.

**Figure 1.** Three-dimensional sketch of the geometry of the problem for FEM simulation

**Figure 2.** Cross-section sketch of the Packet 1 and Packet 2 (stators are shifted by 30 electrical degrees, rotors - by 90 degrees)
3. Results of FEM simulation

To confirm the correctness of the results of the analytical calculation, a series of FEM simulation (in COMSOL Multiphysics) magnetic fields in a three-dimensional formulation was carried out. A four-pole machine with a rated power of 500 kW was designed for the standard of the aviation frequency of 400 Hz and the rotor speed of 12000 RPM. The results of the magnetic field distribution modeling are shown in figures 5-13.

To visualize the flow paths of the main magnetic flux: consisting of the sum of the fluxes of permanent magnets and the axial magnetic flux of the superconducting field coil, the simulation results are shown in figures 5 through 13. The figures 5-13 shows that the value of magnetic induction in ferromagnetic parts (tooth, yoke) does not exceed the permissible values. The figures 5 through 8 show cross sections of an electric machine in the plane of the first packet (Fig. 5), in the plane of the axial interpacket yoke (Fig. 6), the second packet (Fig. 7), and also between the second packet and the axial excitation coil (Fig. 8).
An analysis of the magnitude of the magnetic induction shows that the iron is not in saturation mode - the magnitude of the induction does not exceed 2.1 T. The direction of magnetization of the poles of
permanent magnets and ferromagnetic poles is alternating. The values of the fluxes of pole scattering and scattering by the antennae of the stator teeth are insignificant. An analysis of the magnitude and direction of the axial magnetic flux in the sectional plane of the interpacket yoke (Fig. 6) shows that the fluxes from the poles in it are alternating. This confirms the need to use twisted silicon electrical steel as an interpacket yoke material to reduce the magnetic losses in it. Figure 7 shows that the three-phase coils of the superconducting windings of the armature of the second package are displaced by 15 geometric degrees relative to the coils of the first package. The constancy of the magnitude and direction of the axial component of the induction in the yoke of the bearing shield and in the ferromagnetic shaft show that there is no need to use a special electrotechnical steel as magnetic circuit materials.

Figure 9. Longitudinal the ZX half-section (normal B)

Figure 10. Longitudinal the ZX half-section (axial B)

Figure 11. Longitudinal the YX half-section (normal B)
Figures 9 through 12 show the distribution of magnetic field induction in longitudinal sections of an electric machine. Figures 9 and 10 in the ZX plane. Figure 9 shows the normal component of induction, and figure 10 shows the axial component of induction Bx. In figures 11 and 12 in the section plane YZ, respectively. It can be seen from the figures that the induction is distributed evenly and the axial magnetic circuits are unsaturated, which confirms the correctness of the analytical calculations. The general distribution of magnetic induction and the closure path of magnetic fluxes are shown in an isometric view (Figure 13). The detailed distribution of magnetic induction from Figures 9 to 12 and the general distribution of magnetic field in figure 13 are necessary to understand the principle of operation of an electric machine.

4. Weights and Losses diagrams
Traditional induction machines with an external closed magnetic circuit have significant mass characteristics. The mass of the presented Induction superconducting machine with combined excitation is significantly reduced due to an increase in linear load and magnetic induction in the air gap. And also due to the provision of an alternating magnetic field in the air gap. The mass diagram is shown in figure 14.
The diagram on figure 14 shows that the heaviest element of the generator is a ferromagnetic bearing shield. However, the presence of the remaining bearing shields is a necessary part of any rotating type electric machine. Steel bearing shields ensure alignment of the rotor and stator and rigidity of the entire structure.

From the loss diagram (analytical results) in Figure 15 it can be seen that most of the losses relate to the class of magnetic losses in the yokes and teeth. This means that for generators of the megawatt class of power it is necessary to use individual cryostats for HTS windings in order to reduce the consumption of cryogenic liquid. Calculation results are presented for operating temperature 77 K. It is planned to use a closed cooling system with high-cooled liquid nitrogen (65 K) using a cryogenic reverse Brayton cycle system. In the future on airplanes using liquid hydrogen fuel, an evaporative liquid hydrogen cooling system will be used. In during preliminary tests of the design without HTS windings and the event of cryogenic cooling failure, the resistive windings will be cooled by pumping dried air.
5. Analytically calculated characteristics
Figure 16 shows the distribution of the magnetic field in the air gap. The graph shows the contribution of the HTS axial field coils (green) and high-coercive permanent magnets (blue) to the total (red) magnetic induction in the working gap of the generator. The calculated load and angular characteristics are shown in Figures 17 and 18. A summary generator parameters is shown in Table 1.

![Figure 15. Losses and heat inflows diagram (watts)](image)

![Figure 16. The induction of the magnetic field (Tesla) in the air gap](image)
The load characteristic shown in figure 17 shows the dependence of the active power of the machine and the decrease in phase voltage with increasing load current. The decrease in phase voltage under the influence of the armature reaction, as shown in the characteristic, reduces the value of the active power. The demagnetizing effect of the armature reaction is compensated by an increase in the current of the axial superconducting field windings.

The figure 18 shows the angular characteristics of the generator, in particular the magnitude of the active load, phase current, efficiency and power factor, depending on the theta load angle. It can be seen from the graph that at a nominal load angle of 30 electrical degrees, all specified nominal values are achieved. When overloaded, reaching the operating point of 45 degrees, the output power increases to 700 kW and at the same time, the values of power factor and efficiency do not decrease, which indicates good overload capabilities of the generator.
Table 1. Parameters of 500 kW prototype

| Parameter                                                  | Value  | Unit   |
|------------------------------------------------------------|--------|--------|
| Rated active power                                         | 500    | kW     |
| Rotor speed                                                | 12000  | PRM    |
| EMF idling                                                 | 282    | volt   |
| Nominal load angle                                         | 30     | deg    |
| Angle between current and voltage                          | 9.8    | deg    |
| Angle between current and EMF                              | 39.8   | deg    |
| Longitudinal inductive resistance                          | 0.37   | ohm    |
| The number of turns of the armature winding phase           | 40     | turns  |
| Rated voltage phase                                        | 220.1  | volt   |
| Phase current                                              | 383    | amp    |
| Real active power                                          | 501.1  | kW     |
| Angular frequency of rotation                              | 1256   | sec\(^1\) |
| Nominal mechanical moment                                  | 0.4    | kNm    |
| The circumferential velocity of the rotor                  | 82.9   | m/s    |
| Diameter of stator bore                                    | 133    | mm     |
| Active stator pack length                                  | 93     | mm     |
| Outer diameter (back of the yoke)                          | 255    | mm     |
| External cryostat (overall)                                | 305    | mm     |
| Total axial length (without shaft overhang)                | 338    | mm     |
| Shaft diameter                                             | 44     | mm     |
| Electric frequency                                         | 400    | Hz     |
| Number of poles                                            | 4      | -      |
| Induction in the gap (average)                             | 1.037  | tesla  |
| Linear armature load                                       | 220000 | A/m    |
| Excitation Winding Current                                 | 75     | amp    |
| Magnetomotive force                                        | 4511   | ampturns |
| Field Winding Wire Length                                  | 241    | m      |
| Anchor Winding Wire Length                                 | 521    | m      |
| Cost of HTS Wires                                          | 30472  | $      |
| Electric losses                                            | 84     | watt   |
| Magnetic Yoke Loss                                         | 343    | watt   |
| Magnetic losses in the teeth                               | 319    | watt   |
| Magnetic loss in the inter-package axial yoke              | 53     | watt   |
| Heat influx in cryostat                                    | 77     | watt   |
| Total losses and heat gains                                | 886    | watt   |
| Required power of cryostation                              | 12     | kW     |
| Nitrogen evaporation consumption                           | 20     | L/hr   |
| Electric machine efficiency                                | 99.84  | %      |
| Efficiency with regard to cryogen system                   | 97.61  | %      |
| Specific full mass power                                   | 7.86   | kW/kg  |
| Specific gravity                                           | 0.127  | kg/kW  |
| Specific price of materials                                | 61.4   | $/kW   |
| Specific mass moment                                       | 6.25   | kNm/tonne |
| Specific volumetric moment                                 | 61.34  | kNm/m\(^3\) |
| Specific volumetric power                                  | 18.1   | kW/L   |
| Overall volume of the machine                              | 27.62  | L      |
| Full mass                                                  | 64     | kg     |
6. Conclusion

An electrical machine with combined excitation with high specific output power was invented. Compared to traditional aviation brushless controlled autonomous oil-cooled generators, the specific power of HTS generator is 3 times higher. A method of analytical calculation was developed. A series of 3-D FEM simulations have been carried out confirming the correctness of analytical methods. The design is confirmed by Russian patents. Small-scale prototype of the HTS generator will be completely manufactured and tested next year.

Acknowledgments

The reported study was funded by RFBR and JSC Russian Railways (project No. 17-20-05143)

References

[1] Haran K S, Kalsi S, Arndt T, Karmaker H, Badcock R, Buckley B, Haugan T, Izumi M, Loder D, Bray J W, Masson P and Stautner E W 2017 High power density superconducting rotating machines - Development status and technology roadmap Supercond. Sci. Technol. 30
[2] Zhang Y, Qu R, Li D, Cheng Y, Gao Y and Wang Q 2020 Design and Optimization of an HTS Claw-Pole Machine IEEE Transactions on Applied Superconductivity.
[3] Cheng Y et al. 2020 Comparison of Electromagnetic Performance of 10-MW HTS Double-Stator Flux Modulation Wind Generators With Different Topologies" IEEE Transactions on Applied Superconductivity 30(4) pp 1-7
[4] Dezhin D S, Ilyasov R I and Kovalev K L 2018 HTS inductor electric machine with combined excitation IOP Conference Series: Earth and Environmental Science 194
[5] Masson P J, Breschi M, Tixador P and Luongo C A Design of HTS axial flux motor for aircraft propulsion 2007 IEEE Transactions on Applied Superconductivity 17(2) pp 1533-1536
[6] Dezhin D S, Kovalev K L, Verzhbitskiy L G, Kozub S S, Firsov V P. Design and Testing of 200 kW Synchronous Motor with 2G HTS Field Coils. 2017. IOP Conference Series: Earth and Environmental Science 87(3)
[7] Kozub S et al. HTS racetrack coils for electrical machines 2014 13th International Institute of Refrigeration Conference on Cryogenics CRYOGENICS 2014. Refrigeration Science and Technology pp 283-287
[8] Kovalev K, Penkin V, Larionov A, Modestov K, Ivanov N, Tulinova E, Dubensky A, Verzhbitsky L and Kozub S 2016 Brushless superconducting synchronous generator with claw-shaped poles and permanent magnets IEEE Transactions on Applied Superconductivity 26(3)
[9] Ivanov N, Kobzeva I, Kovalev K and Semenihin V 2016 Analytical methodic of calculation of fully HTS electric machine for aircraft. Innovations in energetic. Russian academy of science (Moscow: Nauka vol 3 Applied high temperature superconductivity) pp 49-76.
[10] Ilyasov R et al. Superconducting Inductor Electric Combined Excitation Machine 2018 R.F. Patent RU2018102382A issued January 22, 2018
[11] Ilyasov R et al. Two-pack inductor electric machine with combined excitation (versions) 2018 R.F. Patent RU2696273C1 issued December 18, 2018