Development and testing of 10 kW fully HTS generator

K Kovalev, N Ivanov, S Zhuravlev, Ju Nekrasova, D Rusanov, G Kuznetsov
Department of electrical machines and power electronics, Moscow aviation institute, Moscow, Russia

Abstract. Electrical machines on the base of high temperature superconductors (HTS) could provide high specific (kW/kg) and volumetric (kW/m³) power. The most promising of them are fully HTS machines. Significant number of parameters and factors which have an impact on HTS windings make analytical analysis of the machine very complex. In this paper description of the prototype of fully HTS electrical machine is provided. Manufactured prototype was tested, experimental and calculation results were compared. In particular, open circuit performance is in good correlation with theoretical conclusions. Besides, results of experimental research of 15 HTS coils are provided. Some design features of the prototype are described.

1. Introduction
Electrical machines on the base of high temperature superconductors (HTS) could provide high specific (kW/kg) and volumetric (kW/m³) power. According to recent research the most promising ways of application of HTS machines are wind turbines, future electric aircraft and marine vessels [1].

In contrast to the usual magnetic systems, in superconducting ones the permissible deformations and stresses are determined not only by the corresponding strength and by stiffness limits, but also depend on a number of factors related to the stability of the superconducting state. When working as the windings of electric machines, HTS coils absorb centrifugal forces during rotation of the rotor, as well as electromagnetic forces arising due to the presence of strong magnetic fields. In addition, low operating temperatures invoke thermal stresses in the structural elements of the machine, especially when it is thermally cycled. It is experimentally established, that the effect of degradation arise, which means that the critical current in the superconducting winding turns out to be lower than the current of the short sample. It may be due to mechanical stresses in the SC and friction on the contact surfaces adjacent to the bandage and the frame, and between the layers. [2].

Significant number of parameters and factors which affect HTS windings make analytical analysis of the machine very complex. It could be used only for one or two aspects, for example electromagnetic or thermal analysis. That is why it is very important to manufacture and test HTS machine especially when it has AC HTS windings. In this paper calculation results of fully HTS machine are provided. Considered machine was produced and tested in MAI. Some experimental results are also provided in this paper.

2. Generator specification
Considered machine has HTS DC field winding on the rotor and HTS AC armature winding on the stator. Rotor and stator has racetrack coils due to limitation of bending radius of tape and decreasing of critical current when twisting [2,3]. Besides, application of racetrack form makes manufacturing of coils simpler. Principal scheme of the machine and main dimensions are shown on figure 1. The main...
The aim of production and testing of 10 kW prototype is to verify calculation methodic and to estimate AC losses in HTS winding operating in machine environment. Following limitations are used during the project: only racetrack coils with one double pancake are used, machine is filled with LN2, maximum field current is 40A, and maximum armature current is 25A. Parameters of the prototype are shown in Table 1.

![Principal scheme of 10 kW HTS generator](image)

**Table 1. Initial parameters of 10 kW prototype.**

| Parameter                          | Value                  |
|------------------------------------|------------------------|
| Nominal output power, kW           | 10                     |
| Rotational speed                   | 2500                   |
| Field winding current, A           | 40                     |
| Armature winding current, A        | 20                     |
| HTS tape                           | AMSC 5x0.5 mm          |
| Operating temperature, K           | 77                     |
| Rotational speed, rpm              | 2500                   |
| Axial length, m                    | 0.220                  |
| Number of phases                   | 3                      |
| Electrical frequency, Hz           | 125                    |
| Inductive reactance Xd, ohm        | 5.08                   |
| Inductive reactance Xq, ohm        | 4.46                   |
| EMF for I=40A, V                   | 206.3                  |
| Power factor                       | 1                      |
| Maximum output power, kW           | 12.5                   |
| Phase voltage corresponds to       | 145.9                  |
| maximum output power, V            |                        |

The machine consists of following parts: rotor with HTS DC winding, stator with HTS AC winding, housing with thermal insulation, current leads, and construction elements. Stator is made of electrical steel sheets 0.5 mm thick. Each sheet was produced with laser technology and then all of them were stuck together. Rotor core and poles were made of ferromagnetic materials. Contact rings were used to supply DC current to the field winding.
3. HTS windings

The main parts of this machine are HTS field and armature windings. Field winding has 6 identical coils connected in series. Figure 2 shows the design of field coil. Each coil has support which used for manufacturing of coil and also to provide electrical insulation. Support is made with 3D-printing technology. Each coil is compounded by «Loctite Stycast 2850». Stator winding consists of 3 phases, 3 coils connected in series per phase. Stator coil has more complex design (figure 3). First, support has cylindrical bottom surface. Second, it has axial cooling channels. That is why we use 3D printing with polyamide for production of stator coil support. Parameters of HTS coils are shown in Table 2.

![Figure 2. design of field coil](image1)

![Figure 3. Design of armature coil](image2)

To estimate operating current, each HTS coil was tested using special test bench described in details in [4], figure 4 represents its scheme and outer view. Operating temperature is 77K. We use Keysight Technologies (Agilent) 6680A as a current source, Yokogawa DL850E as oscilloscope. Current sensor consists of 10 non-inductive resistors Vishay LVR03. Each rotor and stator coil was tested individually without ferromagnetic core. According to testing results critical current of field coils is close to each other and exceed 63A for 1 μV/cm criteria, inductance is close to 1 mH. Critical current of stator coils is different. The parameters of stator coils are presented in Table 3. It is important to note that each coil was tested several times and critical current did not changed. Besides, coils were heat up to 300 K between experiments. It shows that there is no degradation after thermal cycling.

| Parameter          | Field winding | Armature winding |
|--------------------|---------------|------------------|
| Tape               | AMSC, 5 mm    | AMSC, 5 mm       |
| Insulation         | Kapton        | Kapton           |
| Type of coil       | Double pancake| Double pancake   |
| Number of turns    | 68            | 48               |
| Axial length, mm   | 220           | 220              |
| Coil height, mm    | 10            | 10               |
| Coil width, mm     | 17            | 12               |
| Length of HTS tape, m | 37.8  | 27.5          |
| Support material   | PLA           | Polyamide        |

| Coil | Critical current (for 1 μV/cm criteria), A | Inductance, μH | Resistance (300 K), ohm |
|------|--------------------------------------------|----------------|-------------------------|
| 1    | 80.3                                       | 667            | 1,023                   |
| 2    | 64.9                                       | 650            | 1,06                    |
| 3    | 65                                         | 631            | 0,946                   |
| 4    | 79.9                                       | 647            | 1,034                   |
| 5    | 70.9                                       | 637            | 1,053                   |
| 6    | 60                                         | 566            | 1,019                   |
| 7    | 76.6                                       | 624            | 0,966                   |
| 8    | 81.2                                       | 524            | 0,963                   |
| 9    | 75.1                                       | 688            | 0,948                   |
1 – PC, 2 – extension socket, 3 – Current source, 4 – current, 5- oscilloscope YAKOGAWA, 6 – coil, 7 – cryostat.

Figure 4. Test bench for experimental research of HTS coils

After testing of each coil rotor and stator were assembled and tested. Rotor and stator coils were connected with copper conductors. Critical current of the rotor winding is 44.5 A for 1 μV/cm and 46.5 A for 10 μV/cm criteria. Input speed was 0.5 A/s. After assembly the rotor was balanced. It is important that after it there was no degradation of critical current in the rotor. Stator winding also was tested. Each phase was tested separately. Critical current for phase A is 65 A, for phase B – 60 A, for phase C – 62 A. Input speed was 8 A/s.

4. The open circuit performance of the generator

Calculation of main parameters of fully HTS machine is described in [5]. The calculations of open-circuit characteristics of the machine were carried out with the use of 2D finite element (FE) modeling. 2D analysis was made because of symmetry of the machine.

Magnetic flux density $B$ distribution in the active zone of the machine for 40 A field current is shown on figure 5. It can be seen that stator magnetic core is unsaturated but magnetic flux density in ferromagnetic poles of rotor is rather high. Besides, value of $B$ in the area of HTS windings is close to 0.4 T. These means that the increase of field current is not rational because it will decrease field current and will saturate magnetic cores.

Figure 5. Magnetic flux density $B$ distribution in the active zone for 40A field current

Open circuit test of the prototype was provided in order to compare with calculation results. First, operating current of field winding and cooling time were estimated. Machine was filled with LN2 and rotational speed was 100 rpm. Cooling time was 20 minutes and sealing worked well. After that
rotation speed was increased up to nominal value 2500 rpm. Nominal value of field current 40 A was achieved.

Open circuit test was provided for 2500 rpm. Figure 6a represents EMF of one phase versus field current dependency. This dependency is in agreement with Figure 5, a change of the slope caused by saturation of ferromagnetic parts can be seen. Theoretical and experimental results are in good correlation. Figure 6b also shows it. Waveform of EMF is close to sinusoidal.

On-load characteristics of generator were calculated using FE modeling. Figure 7 shows on-load characteristic and output power versus phase current dependency for different field currents. It could be seen that 10 kW output power corresponds phase current 19 A and phase voltage 175 V if field current is 40 A.
On-load experimental results as well as results of measurement of AC losses in HTS stator winding will be provided in future papers after experimental study of the machine will be finished.

5. Conclusion
Significant number of parameters and factors which affect HTS windings make analytical analysis of the machine very complex. In this paper calculation results of fully HTS machine are provided. Considered machine was produced and tested in MAI. It is shown that nominal value of current in field HTS winding was achieved. Nominal speed of 2500 rpm also was achieved and sealing worked well. No-load characteristics are in good correlation with theoretical ones. On the next step experimental on-load characteristics will be obtained. In general, obtained results show that calculation technology and manufacturing process allow to develop new fully HTS electrical machine with higher output power to demonstrate high specific and volume power.

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