Design and Testing of 200 kW Synchronous Motor with 2G HTS Field Coils

D S Dezhin 1, K L Kovalev 1, L G Verzhbitskiy 2, S S Kozub 3, V P Firsov 1

1 Moscow Aviation Institute, Dept. 310, Volokolamskoe Shosse, 4, Moscow, 125993 Russian Federation
2 JSC “Scientific Research Institute of Electromechanics”, Panfilova Street, 11, Istra, Moscow region, 143502, Russian Federation
3 State Research Center of Russian Federation - Institute for High Energy Physics of National Research Centre "Kurchatov Institute" (IHEP), Nauki Square, 1, Protvino, Moscow region, 142281, Russian Federation

E-mail: dezhind@gmail.com

Abstract. Paper describes design and testing of the 200 kW synchronous motor with 2G HTS field coils. The superconductivity motor with two different temperature conditions of the stator and the rotor was designed and initially tested. This decision was dictated by the need to ensure high rotation speed. Design with the fully submersible cryo-rotor, in this case, was not justified because of the large friction losses in liquid nitrogen. So, more complex construction of the rotor with rotating cryostat based on super-insulation was used. A special rotating inlet pipeline for the transportation of nitrogen liquid in the location of the HTS coils was developed.

1. Introduction

One of the obvious trends in the field of transportation systems (automotive, for example) is gradual transition to the electric drivetrains. Such trends are due to several advantages: electric motors high efficiency, traction drive size reduction, operating with zero emission etc.

At the same time, for the number of transportation systems applications, applied superconductivity technologies can provide even greater benefits: the size reduction and the increase of efficiency up to 99%, development of electrical machines with high specific power etc. [2-5]

The project team used previous experience in cryogenic electrical machines creation as a basis for the development of the electric motor with 2G HTS rotor coils for transport applications, such as a large mining truck.

Currently, the following application areas of powerful high-performance superconducting electric motors as drives are the most promising:
– a drive for large oil pumps;
– a drive for large LPG pumps;
– leading wheel pairs of electric locomotives;
– cargo electric cars and electric buses etc.
Electric transport is a suitable area of application for the 200 kW HTS motor. The project team considers installation of a new HTS motor on the mining truck and the oil pump.

The paper presents the project, the results of design and testing of the 200 kW synchronous motor with 2G HTS field coils. The motor has a novel design of a rotor with rotating cryostat, a closed loop cryogen cooling system and an environment temperature stator. All of these features provide new advantages and simplify the use of the 200 kW HTS motor in transport and mining systems. The authors discuss the novel design and report on the results of experimental studies.

2. Development of 200 kW 2G HTS motor

2.1. The 50 kW test model

Before starting the design of the 200 kW HTS motor, 50 kW synchronous motor with field winding on the basis of 2G HTS tape was developed and successfully tested. The main objective in its development was to investigate the behavior and characteristics of 2G HTS materials as excitation coils of a synchronous electric machine [1]. The design of the poles and field coils was optimized to meet minimal magnetic field values in the body of HTS coils.

The 50 kW machine testing has shown that the current in the HTS field winding does not exceed above 30 A at the connection series of coils [1, 2].

For HTS coils manufacture, SuperPower tape (100 A, 77 K, self-field) was used [1]. Testing of the 50 kW HTS motor revealed the advantages and disadvantages of modern 2G HTS materials and its results underpinned development of the 200 kW synchronous motor.

2.2. Design features of 200 kW HTS motor

After successful 50 kW HTS motor testing, project team started the development of 200 kW synchronous motor. This motor is designed for installation at the electrical buses and other electric transport applications.

The project team investigated new approaches to design of electrical machines because traction drives have their own characteristics, such as high torque, high voltage (compared to the usual network 380/220 V) and powered by frequency converters.

The first challenge was a refuse of submersible motor design due to high friction losses in liquid nitrogen. Losses were high due to the high rotor speed — up to 4000 rpm. We made different cooling for stator and rotor of 200 kW motor. For the decrease of cooling power, stator had ambient temperature (300 K). The rotor was placed in a rotating cryostat for cooling of 2G HTS excitation coils. In this regard, the air gap of HTS motor was increased for placing thermal insulation in the cryostat. Increased air gap demanded excitation winding magnetomotive force increase. For these purposes the number of double-pancake HTS coils was increased up to 3 on one pole.

The stator of 200 kW HTS motor was cooled by water. This feature allows one to increase of stator current density if necessary.

Main parameters of 200 kW HTS motor are shown in Table 1. The general view of the motor is shown in figure 1.
Figure 1. The 200 kW 2G HTS motor on the test bench.

Table 1. Main parameters of 200 kW synchronous 2G HTS motor.

| List of Parameters                          | Identification | Value |
|---------------------------------------------|----------------|-------|
| Nominal Output Power (kW)                   | P              | 200   |
| Phase voltage (V)                           | U              | 450   |
| Nominal Speed (rpm)                         | n              | 1500  |
| Maximal Speed (rpm)                         | n_{max}       | 4000  |
| Nominal moment (N·m)                        | M             | 1300  |
| Maximal moment (N·m)                        | M_{max}       | 2600  |
| Phase number                                | m             | 3     |
| Pole number                                 | p             | 6     |
| Nominal current (A)                         | I             | 165   |
| Nominal stator current density (A/mm²)      | J             | 5     |
| Inner diameter of stator (mm)               | D             | 340   |
| Active light (mm)                           | L             | 220   |
| Material of stator winding                  | –             | Cu    |
| Operating temperature of stator winding (K) | T             | ~300  |
| Material of field-coils                     | –             | HTS 2G tape |
| Operating temperature of field-coils (K)    | T_{FC}        | 77    |
| Nominal current in field-coils (A)          | I_{FC}        | 40    |
| Number of turns per one pole                | w_{FC}        | 252   |
| Operating Power factor                      | cos \phi      | 0.95 – 0.99 |
| Full load efficiency (%)                    | \eta           | 96.3  |

2.3. The rotor of the 200 kW motor with 2G HTS field coils

The rotor of 200 kW HTS motor consists of 5 main parts: HTS field coils, rotating cryostat, rotor yoke, shaft and liquid nitrogen supply for the HTS coil area.

The HTS field coils are located on the rotor yoke directly. They are made of 2G HTS tape AMSC (100 A, 77 K, self-field). On each pole there are 3 double pancake coils with total number of turns 34x6 = 204. The HTS tape is wound directly on the pole core through the electric insulating material. Application of different compounds and epoxy resin for HTS coils led to decreasing of critical currents [2, 3]. Kapton was used for the isolation of HTS
tapes from each other. There were 6 excitation coils on the rotor. They created magnetic field in the gap (7 mm) up to 1.2 Tesla. General view of the rotor with HTS coils is shown on figure 2.

The authors used the rotating cryostat for thermal insulation of 2G HTS field coils. It consisted of structural materials and superinsulation "Cryogel-Z” [10]. There was no vacuum in the cryostat, and that greatly simplifies the design and increases the simplicity of operation.

Rotating cryostat isolated the outer and the lateral sides and the inner surface of the rotor from the external environment. Cores and the yoke of the rotor were cooled along with HTS coils steel. So we had even more stored "cooled power" or thermal capacity in metal parts of rotor. This provide greater thermal stability of 2G HTS coils, especially in case of possible accidents of cryogenic supply system.

The cryogenic cooling system consisted of tubes and channels through which the cryogenic liquid enters directly into six HTS coils. It was able to operate both in open and closed circuits (closed-loop).

The cryogenic liquid was supplied through the inner tube of the holes rotor shaft, followed through six radial channels, supplied directly to the HTS coils, flows along the coils, returns to the inside of the outlet tube and went out of the rotor. Inlet and outlet channels were arranged concentrically. In the outlet channel there were wires for powering of the HTS coils.

Cryogenic liquid fitting was stationary, and other parts of the cooling system rotated with the rotor. Sealing was achieved by using special cryogenic seals. The constructive scheme of the 200 kW HTS motor is shown in figure 3.

The cooling system of the 200 kW HTS rotor was designed for operations at the temperature range of 65 – 77 K. However, it is able to operate at lower temperatures.

2.4. The stator of the 200 kW HTS motor

The stator of the electric motor is traditional design with three-phase copper winding. It did not contain the cryogenic cooling and could be cooled by two ways. The first way is traditional air convection cooling, the second one is – water cooling. In this case the nominal output power of 200 kW HTS motor could be increased up to 900 kW. For this purpose a special channels for water circulation was made in the stator housing. The stator current density was calculated for operation in case of air cooling only (see Table 1). Water cooling allowed to manage the losses in the copper winding and magnetic core more efficiently. This reduced the thermal flow inside in the cold rotor.

The use of separate rotor (cryogenic) and stator (water of air) cooling allowed one to decrease demands for the rotor bearings. In such case traditional bearings could be used, because the temperature in the bearings is above 0 Celsius.

3. Experimental study of the 200 kW HTS motor

All experimental studies of the 200 kW HTS motor were divided into several stages. The first stage
was — HTS coils testing directly after manufacture, the second one — rotor testing in the static mode, and the third one — the motor testing directly. The first and 2nd stages reached the final stage at the time of publications.

3.1. Testing of 2G HTS coils
Study of the 2G HTS coils (first stage) showed that current is slightly greater than the calculated values, ranging from 46 A to 53 A, depending on the coil. This proved the high cooling quality. During tests the coils were tested only with the steel core, i.e. in open magnetic circuit. All HTS field coils were manufactured and tested at the Institute for High Energy Physics (Protvino).

3.2. The rotor cooling process of the 200 kW HTS motor
The second stage of testing started after the assembling of the rotor of the 200 kW HTS motor. During the tests the authors solved the following tasks: determining the time required for the primary cooling of HTS coils and determining the necessary amount of liquid nitrogen for that. Checking the operation of the cryostat and determining of temperature of its outer surface in critical areas (air gap, bearings, slip rings etc.) took place. The results of the experiment are shown in Figure 4. The graphs represent the temperature distribution on the cryostat external surfaces. All measurements were performed using temperature sensors with low thermal inertia.

![Figure 4. Rotor cryostat outer surfaces temperatures.](image)

The primary cooling time was 42 minutes. During this time about 50 liters of liquid nitrogen were used. The average consumption of LN2 by repeated cooling ranged from 1 to 4 liters per hour. During the initial cooling from 300 K down to 77 K — consumption was about 1 liter per minute.

The liquid nitrogen supply system showed good thermal stability (see. the time-line during the break for lunch). The high degree of protection against system failures of cryogenic cooling was confirmed experimentally.

Checking of the bearings showed that they maintained their performance even at a temperature of minus 46 Celsius.

Also during the testing of the cryostat the control input of the current supply in the HTS field coils was made. The current was limited to 35 A and the speed of the current inputting was lower 1 A/sec for safety reasons. This was done in order to keep the HTS coils for further testing of the 200 kW motor itself. The HTS coils may be damaged due overvoltage when inputting current or burned out due to overcurrent.

3.3. Testing of 200 kW HTS motor
Experimental study of 200 kW synchronous motor with 2G HTS field coils were carried out at the test bench of Research Institute of Electromechanics (Istra).

Main output characteristics of 200 kW HTS motor are shown in figure 5.

The output power of HTS motor is 212 kW at nominal stator current (165 A), power factor and self motor efficiency (without cooling) are about 1. Current density in the stator winding does not exceed the calculated value (5 A/mm²).

No-load characteristics (E-I) in the generator mode were measured beside the shown overload regime characteristics (1.5 of nominal power).

Provided tests showed that the 200 kW motor with 2G HTS field coils operated stably and thus technical solutions were completely proven. It means that proposed design may successfully applied for more powerful electrical machines.

![Figure 5. The main output characteristics of the 200 kW HTS motor.](image)

4. Perspectives and future applications
The project team consider the installation of the HTS motor to the “Tatneft” oil pumping station and running additional test series in 2017.

The authors plan to create a whole range of such HTS motors in the power range from 200 to 2000 kW. Now the authors consider solutions for HTS electric propulsion systems for large scale applications.

5. Conclusion
At Moscow Aviation Institute based "Center of Cryogenic electrical machines and devices" the 200 kW synchronous motor with 2G HTS field coils have been designed and produced. Initial testing of the novel type motor was successful.

Acknowledgments
The reported study was funded by RSF according to the research project № 17-19-01269.

References
[1] Dezhin D, Ilyasov R, Kozub S, Kovalev K and Verzhbitsky L 2014 J. Phys.: Conf. Ser. 507 032011
[2] Kovalev L K, Kovalev K L, koneev S M, Penkin V, Poltavets V, Ilyasov R, Dezhin D 2010 Electrical machines and devices based on bulk high temperature superconductors (Moscow: Fizmatlit) p 394
[3] N V Bykovsky, S S Fetisov, A A Nosov, V V Zubko and V S Vysotsky 2014 *J. Phys.: Conf. Ser.* **507** 022001
[4] Tixador P, Simon F, Daffix H and Delelise M 1999 "150-kW experimental superconducting permanent magnet motor" *IEEE Trans. Appl. Supercond.* **9** 58–61
[5] Oswald B, Best K-J, Maier T, Soell M and H C Freyhardt 2004 *Superconductivity and its Applications Supercond. Sci. Technol.* **17** 445–449
[6] M Miki, B Felder, K Tsuzuki, M Izumi and H Hayakawa 2010 *J. Phys.: Conf. Ser.* **234** 032039
[7] R-Musenich, V Calvelli, S Farinon, W J Burger and R Battiston 2014 *J. Phys.: Conf. Ser.* **507** 032033
[8] Figueira P, Pronto A G, Vilhena N and Pina J M 2014 *J. Phys.: Conf. Ser.* **507** 032015
[9] Tsibulnikova M R, Pogharnitskaya O V and Strelnikova A B 2015 *IOP Conf. Ser.: Earth Environ. Sci.* **24** 012032
[10]  [http://www.aerogel.com/products-and-solutions/cryogel-z/](http://www.aerogel.com/products-and-solutions/cryogel-z/)