Development and test of an axial flux type PM synchronous motor with liquid nitrogen cooled HTS armature windings

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Abstract. We developed an axial gap permanent magnet type superconducting synchronous motor cooled by liquid nitrogen (LN₂). The motor includes 8 poles and 6 armature windings. The armature windings are made from BSCCO wire operated at the temperature level between 66K~70K. The design of the rated output is 400kW at 250rpm. Because HTS wires produce AC loss, there are few motors developed with a superconducting armature winding. In a large capacity motor, HTS windings need to be connected in parallel way. However, the parallel connection causes different current flowing to each HTS winding. To solve this problem, we connected a current distributor to the motor. As a result, not only the current difference can be suppressed, but also the current of each winding can be adjusted freely. The low frequency and less flux penetrating HTS wire because of current distributor contribute to low AC loss. This motor is an axial gap rotating-field one, the cooling parts are fixed. This directly leads to simple cooling system. The motor is also brushless. This paper presents the structure, the analysis of the motor and the tests.

1. Introduction
In pursuit of small size, light weight and high efficiency of rotating machines, studies on application of superconductivity to rotating machines have been performing world-wide. However, the high cost and the large cooling equipments make it hard to obtain the expected benefits. With the advent of high temperature superconducting (HTS) wires, especially the high critical current and long length BSCCO and YBCO wires and the reduced cost cooling system provide a chance to achieve HTS machines’ marked advantages over conventional ones.

The dimension of the rotating machine is generally decided by flux density in air gap and ampere conductor of armatures. Most of developed superconducting machines employed superconducting wire in field to obtain high air-gap flux density to achieve small size. These motors mainly employed an radial air-gap rotating field construction [1][2].
However, this kind of machines cannot be applied to commercial use. The drawbacks are summarized as follows:

- The cooling system for both armature windings and field windings are necessary.
- The rotary joint for conducting coolant to rotating parts is necessary due to the rotating cryostat.
- The excitation equipments are necessary as the conventional machines which employ windings in field.

These necessary equipments make it hard to build small size machines, which is the main obstacle to superconducting machines application.

To solve these problems, we have proposed a high temperature superconducting motor (HTSM) construction with superconducting armatures and permanent magnets [3]. This motor is an axial-gap rotating field type, operating at 66K-70K. It aimed at increasing ampere conductors to build a smaller and higher efficiency motor compared to conventional PM motors and HTS motors.

Based on this construction, we developed a new HTS motor of 400kW. In this paper, we present the design, finite element method (FEM) analysis and the tests of this motor.

2. Design and fabrication of the 400kW HTS machine

2.1. Overview

The cross-section view of the motor is shown in figure 1 and the specifications are described in table 1. This motor consists of two 8-pole fields making of permanent magnets and one armature assembly which includes six HTS windings made using BSCCO wire. The fixed armature winding is arranged between two field windings. The outer diameter including housing is 1220mm and the length of the motor is 806mm. The rated output of this motor is 400kW at 250rpm.

To construct a reduced size machine, the conventional HTS machines normally employ superconducting wire in field to increase magnetic loading. In this motor, we approach this target by using HTS armature windings to increase electrical loading.

2.2. Characteristics of the BSCCO wire

Figure 2 shows the relation of flux density and critical current of BSCCO wire at different temperatures. In figure (a), the flux direction is parallel to wire face while in (b) the flux is perpendicular to the wire. The employed wire has 120A critical current in self-field at 77K. The measured data are supplied by wire developer. The wire in the motor is operated at sub-cooled liquid nitrogen (66K to 70K) to obtain larger current.

2.3. Details of the armature components

The armature composes of six iron-cored HTS windings which form 3 phases by two coils per phase. Each winding contains 14 double pancake coils. The ends of the winding experience stronger perpendicular component magnetic flux than the middle part, so the DPC which arranged at two ends are located proper space between pancake coil. Because the spaces among DPC can make sure coils are fully cooled. All the coils are connected in a parallel way because of the large current of HTS coils.

Because of the low resistance of the HTS coils, even small different EMF of each coil could cause much different value of current flowing to coils. Employing some resistor or more inverters may fix this problem, but they cause many other problems such as high cost, large space also low efficiency. It is also difficult to dislocate windings just like in a transform to solve this problem. In this motor, we proposed to use a new device called current distributor. It can not only suppress the differences among coil currents, but also can adjust the current flowing to each coil at any given value. Thus, the current that flows to each coil can be operated easily in regard to different critical currents.
The critical current of employed BSCCO wire is defined as the flowing current when the voltage of 1cm-long wire reaches to 1 V. In other words, wire voltage increases significantly when the voltage of 1cm-long wire is 1 V. This value was verified by the test in our previous developed machine HTSM. It is not a wise decision to design a motor around the critical current even taken the temperature arise through motor operation into account, so the design was carried out at voltage arise slowly part which have 80% load factor (the ratio of operating current to the critical current). The load factor of each coil is adjusted by the current distributor to keep the same value.

In this motor, the HTS wire is exposed on changing field, thereby AC losses generating. Generally, AC loss of HTS wire is decided by the volume of wire, the normal component of penetrating flux and the flux frequency. Iron cores are applied to armature windings to prevent flux to penetrating coils and the low frequency 16.7 Hz is chosen to minimize AC loss. Besides, applying iron cores can also prevent the force to act on coil and minimize leakage flux. Laminated iron cores are employed and put at the outside of the cryostat to reduce eddy current loss.
2.4. Detail of the field components
Each field consists of 8 Nd permanent magnets which can produce and keep high magnetic field and an iron back yoke. However, the main component of this kind permanent magnet contains iron. It would cause eddy current when the permanent magnet is applied to changing field. To prevent eddy current loss, one permanent magnet is fabricated with several insulated permanent magnets. Between the soft magnetic iron back yoke and eight permanent magnets, magnetic steel shields are employed to reduce eddy current of the back yoke.

Unlike in a conventional HTS machine, permanent magnets rotating field construction avoids slip ring, brushes and excitation equipments.

2.5. Cooling system
Liquid nitrogen is applied to cooling system. It is cheaper and easier to be handled than frequently used liquid neon and helium gas. LN2 is sub-cooled by Stirling refrigerator then transferred to HTS windings through circulating pumps. The fixed HTS windings make the whole cooling system simple since the rotary joint for conducting coolant are not necessary. The cryostat, making of FRP which is a kind of eddy current free, light and tough material, contains cooling layer and insulation layer.
3. Analysis
The electromagnetic field analyses were conducted by FEM. According to the analysis result, the torque is $1.53 \times 10^4 \text{N}\cdot\text{m}$. This is equal 400kW at 250rpm. Figure 3 shows the flux density of armature HTS windings. In plot (a), the flux direction is parallel to wire face while in plot (b) the flux direction is perpendicular to the wire face. The critical current and the critical magnetic field of wire are mainly determined by the perpendicular component flux penetrating wire. From the plot (b) it is known that two ends of winding experience higher flux than the middle part. As mentioned before, the current of coils can be adjusted by the current distributor to correspond different strength flux. The analysis results show that the load factors of DPC is almost 80%, which met the design goals that operating current can be adjusted at proper value against different critical currents.

Figure 4 shows the flux density of cross-section of armature iron core when the iron overlapped with permanent magnet. The armature coil has an average 1.15T flux density, which is a sufficient performance to meet HTSM design.

4. Result of motor tests
In this section, the trial motor tests are described and discussed. Figure 5 shows the photograph of the trial motor.

4.1. Electro motive force test
This test was carried out at various speeds and the results are shown in figure 6. The measured line to line EMF is 446V at 250rpm, which is the almost same with analysis results as shown in figure 6.

4.2. Four-quadrant operation
Figure 7 shows the operation result. The identity of speed detection and speed order shows the motor can be accelerated and decelerated smoothly.

4.3. Load test
The plot of torque versus armature current is presented at figure 8 showing good linearity. The load test was carried out when torque reached $1.40 \times 10^3 \text{N}\cdot\text{m}$, which is 365kW output power. Among the load test, the operating temperature almost kept constant, which showed the motor can be operated
Figure 7. Characteristic of the acceleration and deceleration of four quadrant drive distribution.

Figure 8. Result of the load test. (Characteristics of the current and torque).

stable under load. As we mentioned before, the analysis results show the load factors of each coil can be adjusted at proper value to make sure 400kW can be obtain. Beside, according to load test, the linear relation of current and torque and the stable operation demonstrated that our design goal can be achieved.

Furthermore, the torque density is 18300N·m/yl when only the volume of the motor is only taken into account, which is a high value compared to other HTS motors.

5. Conclusion
We developed an axial-gap permanent magnet synchronous motor with high power density at liquid nitrogen temperature. Dealing with the current drift which is a critical problem of superconducting wire due to low resistance, the current distributor was developed and applied successfully.

The successful development of this HTSM demonstrates the benefits of the construction that employ PM in field and apply HTS wire to armature windings.

In the next step, we will develop the same type machines aiming at larger output and practical applications. Another 400kW axial-gap PM HTS motor is being constructed focusing on high efficiency.

References
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