Development of Liquid Nitrogen-Cooled Full Superconducting Motor

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Ishikawajima-Harima Heavy Industries Co., Ltd. (IHI) released the world’s first liquid nitrogen-cooled superconducting motor in January 2005. In April IHI released the world’s first full superconducting motor. The process of the development of these and the technical breakthrough, and the features of each motor are discussed. The introduction of the large full superconducting motor that will be developed in the future are also described.

1. Introduction

In 2003, overseas manufacturers began to market their IPS (Integrated Power System) electric propulsion systems, including generator and power distribution system, to ship yards and ship owners in Japan. This is a total system equipped with multiple generators in place of the main engine used for the conventional mechanical propulsion system. Its generators (Fig. 1) supply power to both inboard loads and the electric propulsion system. Europeans have extensive experience in electric propulsion, but the manufacturers and ship yards in Japan lag in terms of technology and cost.

The problem of global warming is much talked about nowadays, and the movement to save energy and reduce CO2 is active. In the world of superconductivity, high-temperature superconductors were discovered in 1986 resulting in a superconductor boom, but the industrialization of the superconductor was hampered by the wall of mass-production. Recently, however, industrial products using superconducting wire have been actively developed thanks to the successful mass-production of bismuth superconducting wire. Our company started research to develop a superconducting motor to cope with both IPS and global warming.

In 2004, an organization to develop superconducting motors was established in our company, and the development of superconducting motors was started by an eight-organization joint development fortune learning team ---Ishikawajima-Harima Heavy Industries Co., Ltd.; Sumitomo Electric Industries, Inc.; Taiyo Nippon Sanso Corporation; Nakashima Propeller Co., Ltd.; Niigata Power Systems Co., Ltd.; Hitachi, Ltd.; University of Fukui; and Fuji Electric Systems Co., Ltd. --- (hereinafter called “8 Joint Team”) led by our company. In January 2005, the 8 Joint Team developed the world’s first liquid nitrogen-cooled superconducting motor with a motor capacity of kW class and released it together with a POD propulsion system incorporating the motor. In April 2005, it developed the world’s first full superconducting motor.

This paper introduces 12.5kW superconducting motor and 12.5kW full superconducting motor. The motor jointly developed by the 8 Joint Team is called “developed SC motor” and the motor released by the 8 Joint Team is called “released SC motor” or “full SC motor.”

2. Type of superconducting motors

We introduce the superconducting motors by briefly explaining the motor principle and classification. Main AC motors can be classified into induction motor and synchronous motor. The induction motor has not been made superconductive because the cooling method is difficult. The following explains the synchronous motor.

The synchronous motor is composed of field and armature. For the field, normally direct current is supplied to make an electromagnet or permanent magnet in some cases. For the armature, alternating current is supplied to make a rotating electric magnet. The motor is rotated by attraction and repulsion of both magnets of the field and armature.
2.1 Classification by structure
The synchronous motor is classified into a radial gap type and axial gap type depending on the arrangement of the field and armature against the rotating shaft. The synchronous motor normally used is the radial gap type because of easy production.

In the case of the superconducting motor with only the field made superconductive, both types are adequately efficient, but in the case of a full superconducting motor with both field and armature made superconductive, the axial type is better in terms of cooling-medium supply and power supply.

2.2 Classification by superconducting rotor
The motor is classified into two types depending on whether the rotor (rotating part) is made the field or armature. The rotating field type motor whose field is rotated, and the non-rotating field type (rotating armature type) is a motor whose armature is rotated.

The superconducting motor is normally of the rotating field type. The ordinary method is to supply cooling medium and power to the rotating part via the rotating shaft. Normally the field portion is made the rotating portion because a smaller-capacity power supply can be made compared with the armature. In the case of some small-capacity motors, power supply is made to the armature via the slip ring to facilitate the cooling-medium supply with the field fixed, but this case is rare.

2.3 Classification by superconducting coil
There are two types of coil that can be made superconductive: field type and armature type. The motor is classified into superconducting motor with the field made superconductive and superconducting motor with the armature made superconductive. If alternating current is supplied to the superconducting coil, hysteresis loss and eddy current loss occur, and the products of other companies are superconducting motors with the field made superconductive. The developed superconducting motor is a motor with both field and armature made superconductive and is called full superconducting motor (trademark registration applied for).

2.4 Classification by others
The superconducting motors are classified as follows by the type of cooling medium and wire.

(1) Classification by type of cooling medium
The superconducting coil is classified into 3 types by the type of cooling medium: liquid nitrogen, neon, and helium. Liquid oxygen and liquid hydrogen are also available, but they are omitted here because they are not practical.

In terms of both price (liquid nitrogen is 10 times cheaper than helium and neon is 10 times cheaper than that) and handling, including heat insulation, liquid nitrogen is superior. In the magnetic field, however, it remains problematic in that large current cannot be supplied to the superconducting coil, and so helium or neon is presently used except for the developed superconducting motor.

(2) Classification by superconducting wire
High-temperature superconductor and low-temperature superconductor are available, but here the high-temperature superconducting wire is considered.

As the high-temperature superconducting wire, bismuth type and yttrium type are available. Yttrium is superior in performance, but it has the problem of mass-production, and it is said that it will take 10 years for it to be put to practical use. Presently, the high-temperature superconducting wire means bismuth type wire.

Also developed are superconducting motors using bulk material instead of wire. Since the bulk material becomes a strong permanent magnet when cooled and magnetized, it is used for a motor without field control such as the permanent magnet motor (PM motor) used for the field portion. For a PM motor with large capacity, a large permanent magnet must be used, but the large strong magnet becomes difficult to handle.

3. Developed superconducting motor
We introduce the superconducting motor released in January 2005 (Fig. 2). It is the world’s first superconducting motor as kW class motor using liquid nitrogen as the cooling medium, and its main specifications are as follows.
Rated output: 12.5kW
Rotating speed: 100min⁻¹
Motor diameter: 600mm
Motor length: 400mm

The field coil is made superconductive and fixed, and the liquid nitrogen is supplied to the field coil directly from outside. For the armature coil, ordinary copper wire is used.

### 3.1 Technological breakthrough of superconducting motor

Since the bismuth type high-temperature superconducting wire used for superconducting motors in the world is weak against magnetic flux when the liquid nitrogen cooling temperature is near 77K, it is difficult to develop motors, and so some means were necessary for using it as the coil for motor.

The bismuth high-temperature superconducting wire has such a characteristic as to make flux opposite in direction to the surrounding flux on the wire surface using current essentially to be passed in order to prevent the surrounding flux from entering the wire (Fig. 3). For this reason, as the surrounding flux becomes strong, the wire tries to proportionally strengthen the reverse flux to prevent the surrounding flux from coming into its interior. But since the quantity of electrons inside is limited, the wire will use up the electrons in due course, and the electrons to supply current to the superconducting wire will be lost and the current will no more run. In short, this wire has such the fatal shortcoming that it cannot supply current to the superconducting wire in a strong magnetic field. For this reason, American manufacturers have coped with this problem by using neon gas and reducing the temperature to near 30K in developing motors. In this method, however, it is difficult to make motors small and light because the heat-insulating barrier of neon becomes large.

The 8 Joint Team made motors smaller and lighter by using liquid nitrogen as the cooling medium to reduce the heat-insulating barrier. The technological breakthrough was that we devised a technology to rotate the motor using the liquid nitrogen, which has so far been difficult to use as the cooling medium. This technology put the flux collector (FLC) in the coil (trade name registration for FLC was applied for). For the FLC, we used metal capable of supplying large flux. Figure 4 shows the effect of the FLC. If the FLC is inserted in the coil, the surrounding flux and the flux produced from the coil run through the FLC and no flux is applied to the coil, as shown in Fig. 4-(b).

Using the FLC made it possible to rotate the motor with liquid nitrogen used as the cooling medium. It is also a big
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merit that since the flux runs to the FLC, the motor torque is

(1) Induced voltage – rotating speed characteristic (Fig. 5)

This shows the relationship between voltage generated by rotating the superconducting motor with an external motor and the rotating speed. For each field current, an almost straight-line characteristic is obtained showing a constant-torque characteristic as a motor.

(2) Current – torque characteristic (Fig. 6)

This shows comparison between data measured with the rotor locked and data measured by rotating the rotor at 100 min⁻¹. Both sets of data show almost the same straight lines, and the expected characteristics were obtained.

(3) Efficiency characteristic (Fig. 7)

Table 1  Revolution deviation to the input signal

<table>
<thead>
<tr>
<th>Rotating speed commanded (min⁻¹)</th>
<th>Rotating speed detection (min⁻¹)</th>
<th>Speed deviation</th>
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<tbody>
<tr>
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applied to the FLC and not to the superconducting material.

3.2 Characteristics of superconducting motor

The characteristics of the superconducting motor are shown below.

Fig. 5  Characteristic of generator mode

Fig. 7  Characteristic of motor efficiency

Fig. 8  Vibration test data

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This shows data of efficiency characteristic by torque. When the field current is small at 15A, the efficiency is low, but setting the field current at the planned value of 30A obtains high efficiency. The characteristic at low load shows high efficiency up to a load of approximately 13%, and with a large-capacity motor, 99% efficiency can be expected.

(4) Speed deviation characteristic (Table 1)

This shows data of speed deviation against the command value of rotating speed. No oscilloscope data are shown, but it was confirmed that the speed response was sufficient.

(5) Leakage flux, noise, vibration

It was impossible to measure the leakage flux with the gauss meter. The noise was measured, but it was almost impossible to measure the difference from the background noise. The vibration was measured, but we did not find any problem.

4. Developed full superconducting motor

This section introduces the full superconducting motor released in April 2005 (Fig. 9). This is the world’s first full superconducting motor with all the coils including armature coil made superconductive, and its main specifications are shown below.

Rated output: 12.5kW
Rotating speed: 100 min⁻¹
Motor diameter: 400mm
Motor length: 450mm

In developing the full superconducting motor, it is necessary to make the armature superconductive. For this reason, the armature coil must be cooled with the cooling medium introduced from the shaft. To introduce the cooling medium from the shaft, the shaft end must be provided with a rotary joint (hereinafter called RJ). Figure 10 shows the rotary joint for introducing the cooling medium. The figure shows a method used with a superconducting motor of another company. If the RJ is provided, the structure becomes such as to cut off the cooling medium with the seal, thus making it necessary to conduct maintenance work on the RJ. For this reason, the reliability of the motor decreases.

Our company focused on a method that does not install the RJ
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or the structure to fix all the superconducting portions but instead developed a structure with an inductor inserted between field and armature (Fig. 11). This is the second technological breakthrough. This structure is such that the motor is rotated by the attraction and repulsion of the magnet working between the inductor magnetized with the field coil and the armature coil. Thus we completed the world’s first full superconducting motor with all the superconducting portions fixed.

5. Features of full superconducting motor and application for ship
The features of the full superconducting motor are as follows.
(1) Compactness and light weight (half or smaller than normal conduction motor + speed reducer)
(2) High efficiency (remarkable at low load)
(3) Almost no noise leak
(4) Almost no leakage flux
(5) Ordinary temperature on motor surface
(6) Cooling with liquid nitrogen
(7) All coils are made superconductive
(8) All coils are fixed
(9) Both ends of motor shaft are free (shaft is not equipped with the RJ required for cooling the superconducting wires)
In addition to the above features, the full superconducting motor can also be used as a ship motor. We conducted main tests for ship use on the 12.5kW superconducting motor and 12.5kW full superconducting motor in accordance with the provisions of JIS (for ship). As a result, we confirmed that they satisfied the requirements specified for ships. The test items conducted are shown below.
(1) Resonating test
(2) Vibration breakdown test
(3) Variable vibration breakdown test
(4) Crosswise direction inclination test (30 degrees)
(5) Longitudinal direction inclination test (10 degrees)
(6) Drop test (250mm high)

6. Conclusion
Based on the data obtained with the 12.5kW full superconducting motor, we are now developing a full superconducting motor of rated output 400kW and rotating speed of 250 min⁻¹. The 400kW motor is mainly used for a coasting vessel. Then we plan to develop larger motors such as 2,500kW and 12,500kW full superconducting motors. In the future it seems that the yttrium wire instead of bismuth wire will be the mainstream superconducting wire. It is said that yttrium wire makes it possible to pass current even through the magnetic field and the current density is considerably improved.
In line with the development of larger motors using the bismuth wire, the 8 Joint Team plans to develop motor members and structures to cope with future wire types in addition to investigating whether FLC is required when the yttrium wire is used, and intends to continuously hold the top position in the field of full superconducting motor.

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- References -
(1) Trademark registration 2005-080396, Trademark registration 2005-080397
(2) Trademark registration 2005-021357
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