Trial manufacture of liquid nitrogen cooling High Temperature Superconductivity Motor

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Abstract. We present a new high temperature superconductivity (HTS) synchronous motor using the liquid nitrogen as the refrigerant in this paper. This motor is designed to be used as the propulsion motor in ship. Because we use the liquid nitrogen as the refrigerant, it is possible to simplify the cooling equipments in the motor. And in our design, we apply the axial flux type of motor to simplify the cryostat of the HTS wires used to make the field coils. Here, the fields using the bismuth HTS wire for the HTS coils are fixed. Moreover, the cores used in the fields are separated from cryostat, and the armature applies the core-less structure. According to various the electromagnetic field analysis results, the new motor was designed and produced. The diameter of the motor is 650mm, and the width of the motor is 360mm. The motor’s rated output is 8.8kW at 100rpm, while the overload output is 44kW, and the maximum efficiency is 97.7%. Also, in order to further miniaturize the motor, other magnetic field analysis have been done when the high-current-density type HTS wire was used and the permendur was used instead of magnetic steel plates. In this case, the motor’s rated output is 12kW, and the overload output is 60kW.

1. Introduction
The purpose of this study is to realize the miniaturization of the motor and improve its efficiency. As one of the solution, we have proposed a new high temperature superconductivity synchronous motor (HTSM) cooled by liquid nitrogen. There is already the report on liquid nitrogen or liquid air cooling high temperature superconductivity generator [1]. This generator was a radial flux type, and bismuth HTS wires which are comparatively easy to obtain today have been used for the field coils. Permissible current density of these wires is not high, in case of being cooled by liquid nitrogen if...
density of magnetic flux penetrating to them is not low. In order to solve this problem, field cores were used in this generator. HTS wires were wound about the cores. Both of the wires and cores were put into a cryostat. Since the cores were being cooled together with HTS coils, the cooling loss increased. There were armature cores too, and the coils were made of copper wires. A cryostat rotates together because the field rotates in this generator. In this case, since the size of the cryostat was big, this generator's miniaturization was impeded. Moreover, the cooling system was of the same complexity as the conventional system, since there is a flow of refrigerator between fixed part and rotated part.

To solve these problems, we propose a new HTSM cooled by liquid nitrogen of higher performance. In this motor too, cores and bismuth HTS wires are used at the field. The differences between the generator reported in Ref. [1] and this motor are shown next. A) The field is fixed. B) The axial flux type is applied. C) Field cores exist outside the cryostat. D) There are no cores in the armature. By applying this method, it became possible to miniaturize the cryostat and simplify the cooling system. Moreover, torque ripple is reduced because of no armature cores. This paper describes the design, the electromagnetic field analysis result, and the experiment result of the new HTSM cooled by liquid nitrogen.

2. Design and electromagnetic field analysis

We designed a HTSM cooled by liquid nitrogen whose rated output is 8.8kW (overload output: 44kW) at 100rpm as a model of ship propulsion motor. In this motor, field coils are made of HTS wires. A schematic drawing of the designed motor is shown in Fig.1.

Applied wires in the field are bismuth HTS wires, and Fig.2 and Fig.3 show the relation of magnetic flux density and current at different temperatures. In Fig.2, the magnetic flux penetrates parallel to wire, and in Fig.3, the magnetic flux penetrates normal to wire. Both of figures are actual measurements of applied wires. In these figures, the current which can pass through the wire depends on the temperature and the density of magnetic flux penetrating to it. To keep the current flowing continuously in the wire, the density of magnetic flux penetrating to the wire has to be limited to be as small as possible especially when the wire is cooled by the liquid nitrogen.

Therefore, liquid nitrogen is cooled down to 66K specially to make current increase. And, cores are placed in the center of HTS coils to make density of magnetic flux which penetrates the coils low. To simplify cooling system, the field is fixed and the armature rotates. Furthermore we adopt the axial flux type of motor to simplify structure of the cryostat. An armature which has 6 coils is placed in motor’s center, and there is one field of 8 poles on each side. The cores exist outside the cryostat, and they are connected with the back-yoke. Since there are cores outside the cryostat, the loss by cooling cores is zero. Moreover the cores are wound cores made of magnetic steel plates to reduce the eddy-current loss. The field coils are put into a Fibreglass Reinforced Plastic (FRP) cryostat. FRP is light and strong, with no eddy-current loss. The electric power is supplied to each phase coils through a slip-ring and brushes because the armature is rotating. The armature consists of pancake coils made of copper wire, and there are no cores in order to reduce torque ripple.

Fig.1. A schematic drawing of HTSM

Fig.2. Relation of current and magnetic flux density at different temperatures (parallel direction)

Fig.3. Relation of current and magnetic flux density at different temperatures (normal direction)
Based on the design, we have done electromagnetic field analysis using finite element method. According to the result of various analysis, details of the motor satisfied our needs are shown as follows. The motor's torque is 840Nm, then the output is 8.8kW at 100rpm. The diameter of the motor is 650mm and the width is 360mm. Fig.4 presents a cross section of this motor. The field coils are 330-turn HTS wire (the width: 4.3mm, the thickness: 0.22mm). The inner diameter of field coils is 136mm, the outer diameter is 160mm. And the core's diameter is 96mm. The field current is 30A. The diameter of armature coils is 208mm, the 850-turn coils are made of φ2mm copper wires. The phase current in the armature is 30A and the current density is 5A/mm². 

Fig.5 presents the analysis result. This figure shows magnetic flux density distribution of part "A" on Fig.4, and the dark parts stand for the parts where magnetic flux density is high. Since the maximum magnetic flux density in the core is 1.8T, magnetic saturation does not occur. Moreover the maximum density of magnetic flux normal component penetrating to HTS coils is 0.29T, so it’s below the critical current according to Fig.3. Overload output of the motor is 44kW. Then the maximum density in the cores is 1.9T, the maximum density of magnetic flux normal component penetrating to HTS coils is 0.29T. Therefore magnetic saturation does not occur, and it is below the critical current.

3. Experiment result

We mention the experiment results in this section. At the same time, based on electromagnetic field analysis in Sec.2, the experiment results is compared with analysis results under the same condition. First, the experiment result of induced electromotive voltage is shown. Fig.6 shows the relation of rotational speed and induced electromotive voltage between U-V line. The solid line is experimental value, and the dot line is analysis value. The relation is proportional, furthermore the experimental value and analysis value are nearly the same. Fig.7 shows induced electromotive voltage's waveform when the rotational speed is 100rpm and the field current is 30A. Although the field and the armature have saliency, it is a smooth sine wave. There are round pancake coils in the armature, as a result torque ripples of the motor become smaller.

Next, the load experimental result at 100rpm and field current 30A is shown. The experiment has been done only up to 2.2kW owing to the limit of load equipment. Fig.8 shows the relation of armature current and torque. It is linear relation. Torque is 220Nm when armature current is 7.5A, so it is according with the result of analysis. Fig.9 shows the relation of torque and efficiency.
The maximum efficiency is 97.7%, and it remains high even torque increases over the maximum efficiency point. However, the cooling loss is not taken into account.

At last, the experimental result of acceleration and deceleration is shown in Fig.10. In this figure, we can see that acceleration and deceleration perform smoothly as speed command value and speed detection value are the same.

4. Design of further miniaturization

To get a higher performance motor, we have done electromagnetic field analysis when high current density type HTS wire (current density is 1.3 times) and permendur which is highly permeable material (saturation magnetic flux density is 1.5 times) are used. The permendur is applied for the material of the field cores. We set the armature current to be 30A (current density is 5A/mm²), and the field current to be 45A (1.5 times by using permendur). Fig.11 is the analysis result. In this figure, the maximum magnetic flux density in the core is 2.09T, it shows that magnetic saturation doesn't occur. The magnetic flux density of HTS coils in normal direction is 0.40T so it is below the critical current. The motor's torque is 1140Nm, then the output is 12kW at 100rpm.

Analysis result is shown as follows when the armature overload current is 150A. The highest magnetic flux density component in the core is 2.35T, therefore it is close to the magnetic saturation. The normal magnetic flux density of HTS coils is 0.5T, it is below the critical current due to high current density type HTS wire. The output is 60kW at 100rpm. Thus, this motor's rated output is 12kW and overload output is 60kW.

5. Conclusion

Although the experiment of rated output could not be done owing to the limit of load equipment, since the experiment value and the analysis value were nearly similar, the motor's performance is the same as the design. By using liquid nitrogen as the refrigerator, The cooling equipment is simplified from the case in which liquid neon or liquid helium is used. We have succeeded to miniaturize and simplify the cooling system, because the fixed field and the axial flux type were adopted and the field cores were put outside the cryostat. Since the cores are not cooled, the cooling loss decreases. This motor's torque ripple and iron loss are cut down by not using armature cores.

We have achieved the aim of proposing a new HTSM of high efficiency. And the experiment at rated output will be done in future. Additionally, a further research on a smaller motor with higher output is undergoing.

Reference

[1] M.K.Al-Mosawi, C.Beduz, K.Goddard, J.K.Sykulski, Y.Yang, B.Xu, K.S.Ship, R.Stoll, N.G.Stephen, “Design of a 100 kVA high temperature superconducting demonstration synchronous generator”, Physica C 372-376 (2002) 1539-1542