Motor structure and mechanical output density of IPM motor using bulk superconductors as magnetic field

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Abstract. Recently, means of transportation with electrical motors such as electric vehicles and ships are rapidly increasing. Various attempts have been made to reduce the size of the motors to increase the freedom of transport equipment system layouts and the energy efficiency of their transportation. Interior permanent magnet synchronous motors (IPMSMs) can realize higher torque than surface permanent magnet synchronous motors (SPMSMs) by using reluctance torque caused by magnetic saliency in addition to magnet torque. In comparison with SPMSMs, IPMSMs can have wide operation ranges by applying control methods such as maximum output control and field weakening control. Therefore, IPMSMs are expected to be used for a variety of application such as electric vehicles, ships and heavy equipment. By replacing permanent magnets with bulk superconductors in the rotors of IPMSMs, the magnet torque increases due to the stronger magnetic field of magnetized bulk superconductors. This leads to an increase in total torque density of the motors and contributes to motor size reduction. In this research, we propose an IPMSM with bulk superconductors with the goal of increasing the mechanical output density. In the proposed IPMSM, cooling space is left inside the rotor to cool the bulk superconductors to their superconducting state. Here, analysis based on finite element method was carried out to verify the utility of the proposed motor. First, the design of the motor with bulk superconductors and cooling space is discussed. It is shown that the total torque can be increased by adjusting the position of the bulk superconductor and modifying the structure of the flux barrier. The maximum total torque shown here was 22500 Nm. Then, the mechanical output density of the proposed IPMSM is compared with a conventional IPMSM. It is shown that the mechanical output density of the proposed IPMSM is 38% higher than the conventional IPMSM. Finally, the magnetic shielding effect, which might be a problem when using bulk superconductors, is discussed. By using electromagnetic analysis, it is shown that the external magnetic flux is weakened by the cooling space to several percent of the magnets’ surface and the effect of the shielding current is trivial.

1. Introduction
Recently, for the purpose of higher mechanical output and higher efficiency, interior permanent magnet synchronous motors (IPMSMs) are being used widely [1]. IPMSMs can realize higher torque than surface permanent magnet synchronous motors (SPMSMs) by using reluctance torque caused by magnetic saliency in addition to magnet torque [2]. Higher reluctance torque is realized by proper rotor design, which is essential in utilizing IPMSMs [3]. Also, IPMSMs have an advantage over SPMSMs in that they do not require protection tubes to prevent magnets from scattering. Furthermore, IPMSMs have broad operation ranges by applying control methods such as maximum output control.
and field weakening control [4]. Therefore, IPMSMs are expected to be used for a variety of application such as electric vehicles, heavy equipment and ships [5] [6].

In this research, we propose IPMSMs using bulk superconductors as field magnets instead of permanent magnets. The stronger magnetic field of magnetized bulk superconductors increases the magnet torque, leading to higher total torque, realizing higher mechanical output (torque × rotational speed) even at low rotational speed. To make use of this, transport equipment which require higher mechanical output, such as heavy equipment and ships, are assumed as the application of proposed IPMSMs.

In this paper, the motor structure of IPMSMs to fully utilize the bulk superconductors is discussed. In the discussion, necessary cooling spaces to cool the bulk superconductors below the critical temperature are considered, making the structure new and original. Then, mechanical output analysis was done to demonstrate the utility of bulk superconductors in IPMSMs by comparing the mechanical output density with conventional IPMSMs using permanent magnets. Finally, electromagnetic field analysis was done to reveal the electromagnetic phenomena occurring in the bulk superconductor in the IPMSM. The shielding current in bulk superconductors might decrease the magnet torque or increase the reluctance torque. The effect of the shielding current is investigated for further uses of bulk superconductors in motors.

2. Design of IPM motor using bulk superconductor

2.1. Designing method

Bulk superconductors can be used as strong magnetic flux sources [7]. By magnetizing the bulk superconductor stronger, the magnet torque increases. However, as the motor yoke causes magnetic flux saturation, there is a limit on the magnet torque. Therefore, we consider the design of IPMSMs to maximize the reluctance torque.

2.2. Motor structure

A basic motor structure is shown in figure 1, and the motor characteristics are shown in table 1, determined based on past research [8]. Electrical steel of 50A1000 is used for the yoke of the rotor and the stator. To cool the bulk superconductors, a cooling space is set in both sides of the bulk superconductors to flow the cryogen to cool the superconductors [9]. The space at the top/bottom side of the long side of bulk superconductors is 10 mm. The space is occupied by several millimeters of cryostat wall, support plate and evacuated space. Also, the bulk is supported by plates from both side of the space.

![Figure 1. IPMSM with bulk superconductor.](image)
Table 1. Motor specifications.

| Parameter              | Value       |
|------------------------|-------------|
| Outer diameter         | 1000 mm     |
| Gap length             | 8.3 mm      |
| Effective length       | 1530 mm     |
| Number of the poles    | 12          |
| Number of the slots    | 36          |
| Rotor diameter         | 784 mm      |
| Size of the bulk superconductor | Thickness 30 mm x Width 85.9 mm |
| Cooling space          | 10 mm       |
| Rotational speed       | 1900 rpm    |

2.3. *Method of analysis*

Torque analysis was carried out to find out the motor structures which realized high reluctance torque with bulk superconductors. Here, the distance of the bulk superconductors from the center of the motor and the shape of the flux barriers were changed. An air gap of 10 mm to cool the superconductors was considered in each case.

When deriving the total torque, the permeability of bulk superconductors was defined as $\mu_0$, the permeability of air. A current density of $6.3 \times 10^7 \text{ A/m}^2$ was applied to simulate a magnetization of 2.0 T. When deriving the reluctance torque, the permeability of bulk superconductors was defined as $\mu_0$ and no current density was applied. The permeability of the iron yoke was derived from the analysis of the total torque. The magnet torque was derived by subtracting the reluctance torque from the total torque.

2.4. *Position of the bulk superconductor*

Firstly, the flux barrier was fixed and the distance of the bulk superconductor from the center of the motor was varied from 311 mm to 326 mm. The total, the reluctance and the magnet torque of the IPMSMs in each case are shown in figure 2, figure 3 and figure 4, respectively.

![Figure 2. Total torque of the motors as a function of armature current phase.](image)
In the analysis, the current phase of the U-phase of the armature current was changed, and the time average of the torque is shown as the result. The standard value of this current phase was set as the current amplitude to obtain maximum torque. From the results, it is shown that when the distance of the bulk superconductors from the center of the motor is 326 mm, the total torque of the motor is maximized due to maximum reluctance torque. Although the maximum magnet torque is higher in 326 mm, the high reluctance torque lead 326 mm to surpass the total torque of the other motors.

2.5. Structure of the flux barrier
Secondly, the distance of the bulk superconductor from the center of the motor was fixed as 326 mm, and the shape of the flux barrier was varied as shown in figure 5. The total and reluctance torque of the IPMSM in each model are shown in figure 6.
Figure 6. Total and reluctance torque of the four models of motors.

From the result, it is shown that IPMSM with the rotor of Model 3 had the highest total torque. In this case, Model 3 showed the highest magnet torque. This is due to the curve, concentrating magnetic flux from the bulk superconductor to the edge of the curve, where the reaction with armature current is stronger. This leads to the highest total torque, although the reluctance torque is the lowest. Model 4 showed the highest reluctance torque due to the spread of the magnetic flux, leading to strong magnetic saliency. However, the spread of magnetic flux caused a large decrease of magnet torque and resulted in the lowest total torque. This shows that there is a potential for proposed IPMSMs to show higher total torque by changing the shape of flux barrier, affecting both the magnet torque and the reluctance torque.

3. Mechanical output density of IPM motor using bulk superconductor

3.1. Design of IPM motor using permanent magnet
Similar design of motors was carried out for IPMSMs with permanent magnets. As for permanent magnets, unlike bulk superconductors, cooling space is not needed, the air gap was filled with permanent magnets. So, the permanent magnets used in the analysis were larger than the bulk superconductors. The same rotor shape as the IPMSM with bulk superconductors was adopted. The designed IPMSM is shown in figure 7.
3.2. Comparison of mechanical output density

IPMSMs with bulk superconductors and with permanent magnets were compared by changing the effective length of the motor and aiming for 1000 kW with both motors. The bulk superconductors were magnetized with three current densities, listed in Table 2. The permanent magnets used for comparison were magnetized to 1.0 T.

Table 2. The current densities applied to bulk superconductors.

| Bulk   | Current density  | Magnetic flux density |
|--------|------------------|----------------------|
| Bulk 1 | $6.3 \times 10^7$ (A/m$^2$) | 2.0 T |
| Bulk 2 | $7.7 \times 10^7$ (A/m$^2$) | 2.5 T |
| Bulk 3 | $9.5 \times 10^7$ (A/m$^2$) | 3.0 T |

The mechanical outputs of the motors with different effective lengths are shown in Figure 8. The result shows that the IPMSM with Bulk 1 showed almost the same mechanical output as the permanent magnet machine. When the mechanical output is 1000 kW, the IPMSM with Bulk 3 can reduce the effective length of the motor to 71% against the permanent magnet motor. Finally, the output densities of the motors calculated using roughly-estimated motor masses are listed in Table 3. It is shown that the output density of the IPMSM with Bulk 3 is 38% higher than the conventional IPMSM.

Table 3. The mechanical output densities of the motors.

| Magnetic field | Output density |
|----------------|----------------|
| PM             | 0.47 kW/kg     |
| Bulk 1         | 0.48 kW/kg     |
| Bulk 2         | 0.56 kW/kg     |
| Bulk 3         | 0.65 kW/kg     |

4. Electromagnetic analysis of bulk superconductors

We analyzed the influence of the magnetic flux density from armature windings on the magnetized bulk superconductors. Superconductors have a nature to expel the external magnetic field [10]. This effect can be modeled with a shielding current flowing inside the superconductor negating the external magnetic field [11]. As bulk superconductors in IPMSMs are exposed to the external magnetic field generated by the armature current, the magnetization might be affected by the shielding effect. In this analysis, we considered the influence of the magnetic flux density of the armature windings on the bulk by comparing the maximal magnetic flux density of the magnetized bulk and the
magnetic flux density generated by the armature windings. Finally, the effect on the IPMSM is discussed.

The magnetic flux density of the IPMSM without the bulk superconductors is shown in figure 9. The magnetic flux density at the surface of the bulk superconductor is shown in figure 10, corresponding to the position shown in the red dotted line from A to B in figure 9. We considered the case that the maximal magnetic flux density in the center of the bulk was 2.0 T.

![Figure 9. Magnetic flux density of the IPMSM.](image)

![Figure 10. Magnetic flux density of the surface of the bulk superconductor.](image)

As shown in figure 9 and figure 10, the external magnetic field applied to the bulk superconductor was below 0.05 T when the magnetization of the bulk superconductor was 2.0 T. Also, the maximum magnetic flux density of the surface of the cooling space A-B was 1.0 T, which is 50% of the magnetization in the bulk.

Because of the existence of the cooling space for the bulk superconductor, the magnetic flux density from the armature windings, which influences the magnetized bulk superconductor, was severely weakened. This shows that the effect of the magnetic shielding effect of the bulk is small, if at all, and hardly affects the performance of the IPMSM.

5. Conclusion

In this paper, an IPMSM using bulk superconductors as field magnets was proposed. The motor was designed to maximize the reluctance torque, assuming the magnet torque to be compensated for with the magnetization of the bulk superconductors. Then, the mechanical output density of the IPMSM with bulk superconductors was compared with that of a conventional IPMSM with permanent magnets. It was shown that the proposed motor can fulfill the same mechanical output as the conventional motor with an effective length of 71%, showing an increase of mechanical output density depending on the magnetization. Finally, electromagnetic analysis was conducted, investigating the magnetic flux density generated on the surface of the bulk superconductor by the armature current. The result of the analysis was that the magnetic flux reaching to the bulk superconductor is very small due to the air gap made for the cooling. Therefore, it could be considered that the effect of the shielding effect of the bulk superconductor is trivial.

Further optimization is needed for the IPMSM structure by trying other arrangements of design. As with electromagnetic analysis, the magnetic shielding effect can be modelled with shielding current flowing on the surface of the bulk superconductor, leading to a deeper understanding of the electromagnetic phenomena occurring in the bulk superconductors used in the IPMSMs. This may lead to further utilization of bulk superconductors in electric motors.
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