Mechanical design of a synchronous rotating machines with Gd-Ba-Cu-O HTS bulk pole-field magnets operated by a pulsed-field magnetization with armature copper coils

H. Matsuzaki¹, Y. Kimura¹, I. Ohtani¹, E. Morita¹, H. Ogata¹, M. Izumi¹, T. Ida²
H. Sugimoto³, M. Miki⁴, M. Kitano⁴

¹Department of Electronic and Mechanical Engineering, Tokyo University of Marine Science and Technology, Koto-ku, Tokyo 135-8533, Japan, ²Department of Electronic Control Engineering, Hiroshima National College of Maritime Technology, Hiroshima 725-0231, Japan, ³Department of Electrical and Electronic Engineering, Fukui University, Fukui 910-8507, Japan and ⁴Kitano Seiki Co. Ltd., Ohta-ku, Tokyo 143-0024, Japan.
hmatsu@e.kaiyodai.ac.jp

Abstract. We studied a high-temperature superconducting (HTS) synchronous motor assembled with melt-textured Gd-Ba-Cu-O bulk pole-field magnets. The structure of a HTS motor is an axial gap type with neither brushes/slip rings nor iron core. The specific feature is that the rotor pole-field magnets of bulk are magnetized with pulsed current flow through vortex-type armature copper windings. The rotor pole bulks and armature coils are cooled down with liquid nitrogen. Cooling and magnetization of bulk pole field magnets are performed inside of the rotor. The trapped peak magnetic field of more than 0.5 T of the bulk magnets provided the motor performance of 3.1 kW with 720 rpm. In order to attain high output, single rotor plate with 8 bulks was substituted with a twinned rotor plates with 16 bulks together with triple layer armature units. We report on the test results and performance of the present twinned rotor-type HTS synchronous motor.

1. Introduction

Abstract. Recently, the electric ship propulsion system attracts much interest from the viewpoints of environmental protection, transportation efficiency in logistics as well as maneuverability. The small class diesel engines compose an integrated power system, which drives the propulsion motor and provides electric power. In this respect, a rotating synchronous machine is crucial because of high efficiency under partial load, since the propulsion output is proportional to the cubic of the speed.

A small-sized synchronous motor may provide a larger torque with employing high-temperature superconductor as pole-field magnet [1]. The HTS motor has many striking features, such as smaller, lighter weight, lower vibration, lower noise, higher energy density, and larger torque.

We studied a high-temperature superconducting synchronous motor with melt-textured Gd-Ba-Cu-O bulk magnets. The structure of a HTS synchronous motor is an axial gap type. The bulk magnets are magnetized without connecting current leads like in the HTS wire winding coils. We have conducted a pulsed field magnetization technique of HTS bulk with a pair of vortex-type copper armature coils [2,3]. Recently, we have designed a HTS bulk synchronous motor. The specific feature is that the rotor field
magnets of bulk Gd-Ba-Cu-O are magnetized with magnetic field by pulsed current flow through vortex-type armature copper windings after the zero-field cooling. The trapped peak field density was varied from 0.5 T to 1.0 T for the present pulsed magnetization technique inside of the motor. The trapped peak magnetic field of 0.5 T of the bulk magnets provided the motor performance of 3.1 kW with 720 rpm. [4]. An axial gap type motor provides an output as well as a torque easily according to the pile up magnetic field layer and the armature layer plate along the shaft without increasing slip rings and a brush. Therefore, in order to attain high output, single rotor plate with 8 bulks was substituted with a twinned rotor plates with 16 bulks together with triple layered armature units.

2. Structure of a motor with a twinned rotor plates
The structure of a HTS synchronous motor is an axial gap type without a brush. Each rotor consists of eight poles of HTS bulk magnets, and armatures of vortex-type copper windings consist of six poles. There is no iron core, which provides no iron loss.

The dimension of each armature coil was 84 mm in diameter and 19 mm thick, 10 layers of 20 turn windings with a 2 mm copper wire. Inductance of the armature coil is 9.8 mH. The bulk magnet, 60 mm in diameter and 19 mm thick, is the Gd-Ba-Cu-O bulk fabricated by the quench and melt growth method (QMG) which was produced by Nippon Steel Co. Ltd. Relative proportion of the QMG is GdBa$_2$Cu$_3$O$_{6.9}$ 70.9 wt.%, Gd$_2$BaCuO$_5$ 19.2 wt.%, Ag 9.4 wt.%, Pt 0.5 wt.% in normal composition.

The major components of rotating parts are shown in Fig. 1. Single rotor plate with 8-pole field bulk magnets is sandwiched between the fixed armature plates. Each armature plate is composed of six vortex-type copper windings. The rotor components and the armature coils of vortex-type copper windings are cooled down by liquid nitrogen supplied from a separate circulation. Liquid nitrogen is supplied to rotor through rotary-joint. It has capability of supplying refrigerant up to 800 rpm. The eight-pole HTS bulk pole field magnets are isolated thermally from the warm shaft and rotor enclosure as well as fixed 6 armature copper coils. Neither slip-rings nor brush exciter can be seen. The magnetization geometry is very practicable and can be applied to the design of rotating synchronous motors of axial-gap type, in which the armatures play a role of pulsed magnetization coil for the rotor HTS bulk field magnets. The present design is acceptable for ship and other kinds of propulsion systems for survivability for long life cycle operation, too. Cooling and magnetization of bulk are performed inside of the motor. The rotor with HTS bulks is not immersed into liquid nitrogen and rotates in vacuum. HTS bulk magnets magnetized by the pulsed field magnetization method by using a pair of the armature coils. The typical rise time of the pulsed field was about 5 ms -10 ms.

![Figure 1. Schematic illustration of the construction of a HTS motor and twinned rotor](image-url)
3. Experimental

3.1. Change the rotor and armature plate into the twinned rotor plate with 16 pole-field bulks
An axial gap-type motor can raise an output easily thanks to the alternating pile up pole-field rotor magnet layer and the armature layer plates in the direction of the motor shaft. As shown in Fig. 1, we substituted the twinned rotor plate with 16 bulk magnets into triple armature plates. Then we studied the characteristics of the HTS motor operation.

3.2. Experimental
First, liquid nitrogen is introduced and both rotor and stator are cooled down. Subsequently, pulsed field magnetization is performed with a pair of armature copper coil windings. The pole field bulk HTS magnets are magnetized inside the HTS motor. The geometry of the pulsed magnetization is shown in Fig. 2.
To eliminate the mechanical problem upon pulsed magnetization, we have developed a specified attachment. It is possible to do successive pulsed magnetizations without any mechanical damage.

4. Results and discussion

4.1. Twinned rotor type bulk HTS motor
The present HTS synchronous motor of twinned rotor type was designed for the output of 60 kW with 720 rpm. The radial dimension of the motor frame is 600 mm in diameter. The Gd-Ba-Cu-O HTS field magnets are mounted on a circle with 220 mm in diameter. Presently, the HTS motor achieved the output of 16 kW with 720 rpm. The average of trapped peak field density was around 0.35 T. The obtained characteristics are shown in Table 1.

| Parameters                  | Single rotor type | Twinned rotor type |
|-----------------------------|-------------------|--------------------|
| Motor type                  | Axial gap         | Axial gap          |
| Speed                       | 720 r/min         | 720 r/min          |
| No. of HTS rotor(s)         | 1                 | 2                  |
| No. of HTS bulks for rotor  | 8                 | 16                 |
| No. of armature units       | 2                 | 3                  |
| Average field density       | 0.56 T            | 0.35 T             |
| Motor output                | 10 kW             | 16 kW              |

4.2. Twinned rotor type and single rotor type machines
The output of twinned rotor type is 16 kW at 0.35 T. The considerable increase of output was achieved with a twinned rotor. The detailed results will be reported elsewhere. The present result is coming from a successful pulsed magnetization technique improved with a specific technique and mechanical design to
avoid a mechanical damage from the electromagnetic force generated upon a successive pulsed magnetization [5].

4.3. Trapped field distribution on the rotor pole-filed HTS bulks

Fig. 3 shows a representative pole-field distribution of rotor HTS pole magnets. When we applied a magnetization for bulk HTS, a conical shape of magnetic field density distribution is expected. However, there exists inhomogeneous field density distribution on each bulk. This is coming from a motion of flux during the pulsed magnetization process as indicated by Ida et al [3]. This may cause a substantial effect on the operating efficiency and output of the present type of HTS synchronous motor.

It is necessary to establish the efficient pulsed magnetization technique of the HTS bulk field magnet with armature coils. The disorder and/or deficiency of the magnetic flux can be reduced with the following couple of strategies. First, in order to control the flux penetration into the bulk magnet, the typical rise time and coil size are changed. Second, in order to suppress flux motion inside the bulk magnet, two bulks are stacked misaligned. These kinds of studies are under progress [5,6].

![Figure 3. Trapped magnetic field distribution for 8 pole filed bulks on a rotor](image)

5. Summary

We studied an axial gap type high-temperature superconducting synchronous motor. The pole-field magnet rotor is composed of eight pole melt-textured Gd-Ba-Cu-O bulk magnets. In order to attain high output and torque, we developed a twinned rotor plate with 16 bulk magnets and assembled into 3 layered armature pulsed copper coil unit. The average of trapped peak field density 0.35 T of the bulk magnets is capable of the motor performance of 16 kW with 720 r/min. The twinned rotor type motor effectively increases the torque as well as the motor output comparing with single layer type.

6. Acknowledgement

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References

[1] I. Kalsi and S. Karon, Marine Engineering Systems, No. 76(2003)
[2] H. Sugimoto, Y. Hondou, S. Tsujii, Y. Akita, T. Ida, H. Matsuzaki, Y. Kimura, I. Ohtani, M. Izumi, M. Miki and M. Kitano, European Conference on Applied Superconductivity, (2003)
[3] T. Ida, H. Matsuzaki, Y. Akita, M. Izumi, H. Sugimoto, Y. Hondou, Y. Kimura, N. Sakai, S. Nariki, I. Hirabayashi, M. Miki, M. Murakami, M. Kitano, Physica C 412-414 (2004) 638.
[4] H. Matsuzaki, I. Ohtani, Y. Kimura, M. Izumi, T. Ida, H. Sugimoto, M. Miki, M. Kitano, IEEE Transactions on Applied Superconductivity, 15 (2005) 2222-2225.
[5] I. Ohtani, H. Matsuzaki, Y. Kimura, E. Morita, T. Ida, M. Izumi, M. Miki, M. Kitano, European Conference on Applied Superconductivity, (2005) submitted.
[6] Y. Kimura, H. Matsumoto, H. Fukai, N. Sakai, I. Hirabayashi, M. Izumi, M. Murakami, European Conference on Applied Superconductivity, (2005) submitted.