Double armature HTS bulk synchronous machine

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Abstract. In many high-temperature superconducting (HTS) rotating machines of radial flux type, the magnetic field from one side surface of the field pole is employed facing the armature winding. However, both side surfaces of the field pole can be effectively utilised to face the armature windings. Thus, we have applied the double armature structure in which both inner and outer armature rotors sandwiched the field pole stator in the HTS synchronous generator. We introduce the first step design and the electromagnetic study of the double armature synchronous machine for tidal current power generation. The double armatures with copper winding were adopted with a field pole composed of the HTS bulks. The power and the torque density were calculated with a low speed that depends on a 500 kW contra-rotating turbine design. In this paper, we comparatively studied three electromagnetic designs in which (1) a permanent magnet was used for the field pole, (2) the HTS bulk was employed as the field pole and (3) the field pole HTS bulk was arranged at an angle in the x-y plane, reducing torque ripple due to torque consistency and tilting of the HTS bulk plate. A generator model consistent with the input mechanical torque of the turbine was obtained from the analysis of compatibility with the 500 kW class tidal current power generation.

1. Introduction
The effective utilization of renewable energy is attracting attention due to the progress of global warming. Marine energy is one of the renewable energies that have domestic production resources. Unlike wind power and sunlight, marine energy has the advantages of being less affected by the weather and having a seawater density about 850 times higher than the air density. However, in order to use marine energy for generators, it is necessary to consider the impact on the environment and reduce the impact on marine organisms, so we aim to increase the efficiency and reduce the size of the tidal turbine generator. To achieve this, a contra-rotating turbine with different speeds and a generator that matches its torque is suitable. As a solution to this problem, we studied the high-temperature superconducting (HTS) bulk synchronous machine that introduced the double armature structure that was directly connected to contra-rotating turbines [1-3].

2. System configuration
The contra-rotating turbine was assumed with different speeds of reversal [4]. As a design example, the following mechanical conditions for a turbine were given. The rated flow velocity is 2.5 m/s. The front turbine torque is 251 kNm and the rear turbine torque is 188 kNm. The power generation capacity is 500 kW (generator outlet output), and the rotor diameter is 14.5 m [4].
Figure 1 shows a schematic diagram of a 500 kW class contra-rotating turbine. The turbine and the generator are directly connected without a speed-up gear. Figure 2 shows a cross-sectional view of the connection between the turbine and the armature of the generator shown in figure 1. In figure 2, the green part indicates the front turbine base integrated into the inner armature, and the blue part shows the rear turbine integrated into the outer armature.

3. Generator configuration

Table 1 shows the generator design specifications. The input torques from the front and the rear turbines have been optimized to 251 kNm and 188 kNm, respectively, and the total output power is 518 kW [4]. These values were obtained by a group of NMRI as a part of their study of the representative tidal turbine of a different speed contra-rotating type under a tidal speed of 2.5 m/s [4]. The above issues mean that the front turbine torque of 251 kNm should be equal to the inner generator torque that appeared in the inner armature thanks to the HTS bulk stator and the rear turbine torque of 188 kNm should be equal to the outer generator torque appeared in the outer armature and the HTS bulk stator. This is the requirement to fulfill the continuous rotating operation with a power generation of neither acceleration nor retardation. Figure 3 shows a part of the cross-section of the double armature rotors and the HTS bulk field pole stator of the designed synchronous generator. The HTS bulks are arranged as a field pole module between the contra-rotating armatures. The dimension of a single piece of bulk material is 50 mm x 50 mm x 20 mm thick and one field pole module is composed of 3 x 20 pieces. Thanks to a suitable choice of the magnetization technique for this field pole module, as a radial flux machine, the trapped magnetic field contributes to the power generation at both outer and inner armature windings. The armature winding is composed of either concentrated windings or distributed windings. In this work, we adopted distributed windings. The armature current is 3 kA. In terms of current density, 1.875 A / mm² is flowing. The operating conditions of the armature winding are assumed to be at room temperature.

The specification of the double armature HTS bulk synchronous machine is shown in Table 1. Regarding the rotation speed, the speed values in Table 1 were entered in the analysis software as the time for one lap. As the actual number you entered, 0 ms front side is 0 degrees, 360 degrees in 4918 ms, the rear side was made to 6593 ms in 0 ms, 360 degrees 0 degrees. The tooth material uses alloy steel with special physical properties. The density is 7.75 g/cm³.
Table 1. Specification of the double armature HTS bulk synchronous machine.

| Specification               | Value                                      |
|-----------------------------|--------------------------------------------|
| Speed [min⁻¹]               | 12.2 (Front), 9.1 (Rear) [4]               |
| Generator diameter [m]      | 2                                          |
| Rotor                       | Armature winding (Copper)                  |
| Stator/Field pole           | HTS bulk (GdB₄₂Ca₃Cu₇₋₂)                   |
| Maximum air gap [mm]        | 15                                         |
| Number of poles             | 16                                         |
| Teeth                       | M600 - 50A                                 |

Figure 3. Generator structure with the contra-rotating armatures and field poles of bulk HTS.

4. Analysis methods

The magnetic field distribution, the maximum torque, and the maximum output calculated based on the specification in Table 1 were compared with those using the permanent magnet (PM) of Nd-Fe-B for the field pole of the model of the synchronous machine. In the model of the machine by using PM, the analysis was performed with the field pole of a single PM plate of 150 mm x 1000 mm x 20 mm, which is the equivalent dimension of the HTS field pole module. The HTS bulk field pole was assumed to be magnetized up to 6 T.

Subsequently, the magnetic field distribution, the maximum torque, the maximum output, and the maximum torque ripple were calculated with the design where the pieces of HTS bulk from the field pole module were tilted in the x-y plane as shown in figure 4 (b). In this analysis, the HTS bulk is tilted 5 degrees for comparison. The tilt of the HTS bulk is arranged by tilting the HTS bulk body.
5. Analysis results

5.1. Comparison with the model by using the field pole of PM

Figure 5 shows the result of the magnetic field distribution when the HTS bulk (a) and the PM (b) are used to form the field poles. While a magnetic field of 6 T was trapped on the HTS bulk surface, a magnetic field of 2.5 T was confirmed at the bottom of the armature as shown in figure 5(a). On the other hand, when the PM was used as the field pole, the magnetic field was at most 0.2 T on the surface and the bottom edge of the armature across the air gap as shown in figure 5(b). A higher magnetic field could be obtained at the bottom of the armature than the PM while the HTS bulk was used as the field pole. Therefore, the advantage of using HTS bulk was obtained from the viewpoint of magnetic field distribution.

Figure 6 is a graph of the torque as a function of time for the HTS bulk (a) and the substituted by PMs (b). Table 2 shows the maximum torque and maximum output of each armature. As a result, the total output was 468 kW when the HTS bulk was used for the field pole and 96 kW when the PM was used. The inner armature torque was higher than the outer armature torque. It was confirmed that the input mechanical torque of the front turbine matches the torque of the inner armature, and the input mechanical torque of the rear turbine matches the torque of the outer armature. Thus, we obtained a generator model with a double armature structure that matches the torque of the two turbines input machines of the 500 kW class double contra-rotating turbine type tidal current power generation.

The reason why the torque of the inner armature is larger than the torque of the outer armature is thought to be that the distance between the armature windings in the inner armature is narrow and the divergence of the magnetic field is smaller than that of the outer armature, so the torque is larger thanks to high current density with the inner armature volume.
Figure 6. Calculated torque as a function of time for the HTS bulks (a) and the substituted by PMs (b).

Table 2. Calculated torque and power of contra-rotating bulk HTS generator and the reference values from the alternative model of the field poles composed of PM.

|                  | Outer armature | Inner armature |
|------------------|----------------|----------------|
| Maximum torque   |                |                |
| [kNm] HTS bulk   | 179            | 233            |
| PM               | 32             | 52             |
| Maximum power    |                |                |
| [kW] HTS bulk    | 171            | 297            |
| PM               | 30             | 66             |

5.2. Comparison with tilting superconducting bulk magnet

Figure 7 shows the magnetic field distributions when the HTS bulk tilted 5 degrees are used for the field poles. When the HTS bulk placed on a flat surface was used as the field pole, a magnetic field of 2.5 T was confirmed at the bottom of the armature when 6 T was magnetized on the surface of the HTS bulk as shown in figure 5(a). Alternatively, a magnetic field of 2.5 T was confirmed at the bottom of the armature when 6 T was magnetized on the surface of the HTS bulk as shown in figure 7 when the HTS bulk tilted 5 degrees was used as the field pole. No difference could be confirmed by comparing the magnetic field distributions between the calculation with the inclination and without inclination of the HTS bulks. Therefore, it was found that the merit of tilting the HTS bulk cannot be confirmed from the viewpoint of the magnetic field distribution.

Figure 7. Calculated magnetic field distribution around field pole HTS bulk tilted 5 degrees in the x-y plane.
Figure 8 is a graph of the torque as a function of time for the HTS bulk (a) horizontal in the x-y plane and the HTS bulk (b) tilted 5 degrees in the x-y plane. Table 3 shows the maximum torque, the maximum output and the maximum torque ripple of each armature. The total output was 468 kW when the HTS bulk placed horizontally in the x-y plane in figure 7 was used for the field pole and 466 kW when the HTS bulk tilted 5 degrees in the x-y plane was used. The maximum torque ripple with the inner armature increased by 8.6 kNm, but that of the outer armature showed a decrease of 24 kNm. Although the torque ripple of the inner armature has increased, it was confirmed that the torque ripple was reduced overall. In the total output, it was found that the output was maintained although there was a difference of 2 kW. Therefore, when the HTS bulk was tilted, the torque ripple could be reduced without impairing output.

![Figure 8](image)

**Figure 8.** Calculated torque as a function of time for the HTS bulk (a) horizontal in the x-y plane and the HTS bulk (b) tilted 5 degrees in the x-y plane.

|                  | Outer armature | Inner armature |
|------------------|----------------|----------------|
|                  | 0°             | 5°             | 0°             | 5°             |
| Maximum torque   | 179            | 169            | 233            | 239            |
| [kNm]            |                |                |                |                |
| Maximum power    | 171            | 161            | 297            | 305            |
| [kW]             |                |                |                |                |
| Maximum torque ripple | 52.6  | 28.6            | 33.0            | 41.6            |
| [kNm]            |                |                |                |                |

6. Conclusion
We obtained a generator model with the double armature structure that matches the torques of the two turbine input machines of the 500 kW class double contra-rotating turbine type tidal current power generation. Furthermore, it was confirmed that the torque ripple of the outer armature was improved. Previous studies have shown that the trapped magnetic flux is stable under synchronous operation when the HTS bulk material is used as the field pole [4]. Based on the research results on magnetizing technology and cooling, we will verify the feasibility of the system by prototyping a reduced model of the generator.
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