Optimal Design of a MW Class SCSG for a Tidal Current Power Generation System

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Abstract – A superconducting synchronous generator (SCSG) can be expected to decrease the size and weight compared to conventional tidal current generators. This paper proposes an optimal design of a 2 MW class SCSG for a tidal current power generation system. The proposed optimal design of the SCSG will reduce the length of the high-temperature superconducting wire as well as the weight and volume of the SCSG. The 3D finite element method is used to analyze the magnetic field distribution. The optimized 2 MW SCSG is compared with a 2 MW conventional generator. As the optimized SCSG is more compact and lighter than a conventional generator, it will be efficiently applied to practical tidal power systems.

Keywords: High-temperature superconductor, Superconducting generator, Tidal current power generation system

1. Introduction

Tidal currents are attractive sources of renewable energy due to their predictability and high energy density, in general. The density of water is 840 times higher than the density of air and hence, a greater amount of power can be harvested from a smaller domain than wind turbines [1, 2].

Tidal current turbines can be classified into geared and gearless types. A gearless turbine has a higher efficiency, as well as lower maintenance costs than the geared type. However, due to its larger size and rotating speed, it becomes less efficient at generating power [3]. A gearless type superconducting synchronous generator (SCSG) is proposed as a tidal current power generation system because the SCSG has a high torque and a simplified mechanical structure [4, 5].

This paper presents an optimal design of a 2 MW class SCSG for a tidal current power generation system by optimizing the method using a 3D Finite Element Method (FEM) program. The 3D FEM program is used to analyze the magnetic field distribution, and the 3D CAD program shows the detailed structure and calculates the weight of the SCSG. This optimal method offers a simple and systematic approach to optimizing the design for performance, quality, and cost. The design's purpose is to reduce the length of the High-Temperature Superconducting (HTS) wire, as well as the weight and volume of the SCSG to ensure a low-cost tidal current power generation system. The optimized 2 MW SCSG is compared with a 2 MW conventional generator from the perspective of the weight and volume of the generator in order to demonstrate the

most efficient design for the MW class tidal current turbine.

As a result, the optimized design of the gearless SCSG turbine is more efficient, lighter, and more compact than the conventional generator. Therefore, the mechanical stress and construction costs associated with the tidal current power generation system can be reduced. The optimized design of the SCSG can be effectively utilized to develop MW class tidal current power generation systems.

2. Overview of a Tidal Current Turbine

Tidal current resources can be analogized to energy extraction from wind. The kinetic energy in a water channel is proportional to the cube of the velocity of the water passing through the cross section of that channel. The energy is calculated by Eq. (1).

$$E = \frac{1}{2} \rho A V^3 \quad (1)$$

where, ρ is the density of sea-water (kg/m^3), A is the cross sectional area of the channel (m^2), and V is the flow velocity perpendicular to the cross section of the channel (m/s). However, a tidal current turbine can only harness a fraction of this power due to losses, so Eq. (1) is modified to Eq. (2).

$$E = \frac{1}{2} \rho C_p A V^3 \quad (2)$$

where, C_p is known as the power coefficient and is essentially the percentage of power that can be extracted from the fluid current and takes into account losses due to Betz's law [5, 6].

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(a) Rotor radius depending on the rated power

(b) Rotating speed depending on the rated power

Fig. 1. The rotor radius and rated rotating speed of the SCSG

For the conceptual design of a 2 MW class gearless-type SCSG, the design specifications of 2 MW class conventional tidal current turbines should be defined. The rotor radius (R) and rated rotating speed (RPM) of a tidal current turbine are calculated by Eqs. (3) and (4).

$$R = \sqrt{\frac{2 \times P}{\pi \times C_p \times \rho \times V_{tide}^3}} \quad (3)$$

$$RPM = \frac{30 \times \omega_{blade}}{\pi} = \frac{60 \times \lambda \times V_{tide}}{2 \times \pi \times R} \quad (4)$$

where, the C_p and ρ are 0.48 and 1,025 kg/m³, respectively [3]. Fig. 1 shows the rotor radius and rated rotating speed of a tidal current turbine depending on the rated power.

When the rated power of a tidal current turbine increases, the rotor radius grows to get more power from tidal energy. The rotor radius of the 2 MW class tidal current turbines is 13 m, and the rated rotating speed is 11 rpm at flow velocity of 2.5 m/s.

Compared to the wind turbine at the same capacity, the rotor radius is significantly decreased by the high density of water. Conversely, the generator radius is increased to generate the same torque when the rotating speed is slower than the wind turbine.

Fig. 2 shows the layout of a conventional tidal current turbine.

Fig. 2. Layout of a 2 MW class tidal current turbine

3. Optimal Design of a SCSG for Tidal Current Turbines

3.1 Fundamental structure of the SCSG

In order to operate the SCSG with full variable speed, the generator is connected to the power grid through a full scale frequency converter. The frequency converter is composed of a generator side rectifier, a DC link, and a grid side inverter. Fig. 3 shows the schematic diagram of the SCSG.

Fig. 3. Schematic diagram of the gearless type SCSG

The SCSG is composed of the HTS rotor coil, rotor body, vacuum vessel, stator coil, stator teeth, and magnetic shield. Fig. 4 illustrates the configuration of the SCSG. The rotor poles consist of a racetrack-type double pancake coil (DPC) using an HTS wire. The HTS wire of the rotor coil is coated with long, flat conductor tape with a thickness of 0.1 mm and width of 4 mm. The rotor body, vacuum shield, and stator teeth consist of nonmagnetic material to prevent iron loss. Laminated silicon steel is used at the magnetic shield. The SCSG is not equipped with a damper winding. In the case of the SCSG being connected to a frequency converter, which provides a variable stator frequency according to the actual rotor speed, no relative movement between the stator and rotor field exists. The copper stator winding has double-layered and distributed three-phase winding [7-10].

(a) Whole shape of the SCSG

(b) 1/28 model of the SCSG

Fig. 4. Configuration of the SCSG

3.2 Design procedure of the optimization method

Here, the 2 MW class SCSG is designed based on the optimization procedure, suggested in Fig. 5. Three major factors of the SCSG are investigated in this paper: the length of the HTS wire, the weight, and the volume. The four control parameters are selected, including the number of poles, the number of DPC layers, and the turns of the HTS field coil and the stator coil.

Initially, the number of rotor poles of the generator is adjusted to reduce its diameter to less than 6.0 m. The next step is to change the number of DPC layers, and HTS field coil and stator coil turns to generate 2 MW output power. The HTS field current of the generator is gauged by a perpendicular magnetic field – the critical current curve of HTS wire. Finally, the generator can be specifically designed by changing the axial length of the HTS coil to achieve a minimum volume and weight. The HTS field coil turns are controlled to generate rated power because the electromotive force is transformed by changing the axial length.

3.3 Optimal design of the 2 MW SCSG for tidal current turbines

In the 2 MW class tidal current turbines, the rotor radius and rated rotating speed are 13 m and 11 rpm, respectively, at a flow velocity of 2.5 m/s. The density of water is 1,025 kg/m³. The water density is 840 times higher than the

Fig. 5. Optimal design procedure for the tidal current SCSG

Table 1. Basic specifications of the designed 2 MW SCSG

Items	Value
Rated power	2 MW
Rated line to line voltage	690 V
Rated armature current	1,673 A
Rated rotation speed	11 rpm
Rated torque	1.74 MNm
Number of poles	28
Number of stator coils/phases/poles	2
Rated frequency	2.56 Hz

Table 2. Detail specifications of the designed 2 MW SCSG

Items	Value
Operating temperature	20 K
DPC turns	840
Stator coil turns	6
Number of DPC layers	5
Operating current of DPC	135 A
Outer radius of generator	4,631 m
Optimized axial length	400 m

density of air. The line-to-line voltage of the generator is 690 V. Table 1 represents the specifications of the 2 MW SCSG for tidal current turbines. Table 2 indicates the detail specifications of the optimized 2 MW SCSG for tidal current turbine.

Fig. 6 shows the comparative analysis results of the designed 2 MW class SCSG according to the optimal design procedure in terms of the weight and volume of the generator and total length of HTS wires. In the case of 400 mm axial length, the weight and volume of the generator, as well as the total length of the HTS wire are the smallest SCSG.

Fig. 6. Comparative analysis results of the designed 2 MW SCSG according to the axial length

4. Analysis Results and Discussion

4.1 3D FEM analysis results of the optimized 2 MW SCSG

Fig. 7 shows the magnetic field distribution for the 1/28 model of the optimized SCSG. The maximum magnetic field is 5.82 T. The HTS wire is influenced by the perpendicular magnetic field because the HTS wire has a tape-like shape. Therefore, the operating current is selected according to the value of the perpendicular magnetic field.

Fig. 7. Magnetic field distribution of the 2 MW SCSG

Fig. 8 shows the perpendicular magnetic field of the optimized 2 MW SCSG. The perpendicular magnetic field is 4.6 T. The measurement position of the perpendicular

Fig. 8. Perpendicular magnetic field of the 2 MW SCSG

(a) Output voltage of the optimal designed SCSG

(b) Output current of the optimal designed SCSG

Fig. 9. Output voltage and current of the designed 1/28 model

magnetic field is also given in Fig. 8. The operating current of the HTS wire, applying 80% of the rated current for safety margin, is 135 A.

The generated output voltage and current of the 1/28 model of the 2 MW SCSG is illustrated in Fig. 9. The voltage and current are 14.23 V and 1,673 A, respectively.

4.2 Comparative analysis with a conventional generator

The optimized SCSG has a total diameter of 4,631 mm, and the axial length of the DPC is 400 mm. The volume

and weight of the generator are 16.35 m³ and 52.7 tons, respectively. The total length of the HTS wire is shortest at 171.32 km. The active weights of the SCSG and the PMSG are similar. However, inactive weight of the SCSG including the torque disk and generator frame is much lighter than the PMSG because the volume of the SCSG is smaller than that of the PMSG. As a result, the total weight of the optimized 2 MW SCSG is less than the 2 MW PMSG.

5. Conclusion

This paper presented an optimal design of a 2 MW class SCSG for a tidal current power generation system. An optimizing procedure was used to reduce the length of the HTS wire as well as the weight and volume of the 2 MW SCSG. Then the SCSG was redesigned considering the axial length of the DPC. The magnetic field distribution was analyzed by the 3D FEM. As a result, the volume and weight of the 2 MW SCSG for tidal current turbines were 16.35 m³ and 52.7 tons, respectively.

The results showed that the optimized 2 MW SCSG could be about two to three times smaller than a 2 MW PMSG. The mechanical stress and the construction costs were reduced because the weight of the support structure was decreased. The optimized design of the SCSG can be effectively utilized to develop MW class tidal current power generation systems.

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