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Study on Homopolar Superconducting Synchronous Motors for Ship Propulsion Application

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Abstract-- **Superconducting synchronous motors compared with conventional motors can reduce the motor size and enhance the motor efficiency for low-speed and high torque applications under the space constraints for propulsion system. Especially, homopolar superconducting synchronous motors (HSSMs) need less superconductor and lower magnetic flux density in superconductor field coil than air-cored superconducting synchronous motors (ASSMs). In addition, mechanical structure is more simplified and stability is increased because the superconductor field coil of HSSMs is not rotated in operation. In this paper, we present the outline of HSSMs including structure, characteristics and operational principles with the conceptual design of 5MW HSSM.**

1. INTRODUCTION

Recently, conventional motors, such as induction and permanent magnet synchronous motors, have been applied to ship propulsion applications [1]. However, the development of motors to satisfy low-speed and high torque is difficult because of the constraints for space in the propulsion system and low motor efficiency [2]. Accordingly, it is necessary that study on superconducting synchronous motor to reduce motor size and enhance motor efficiency [3].

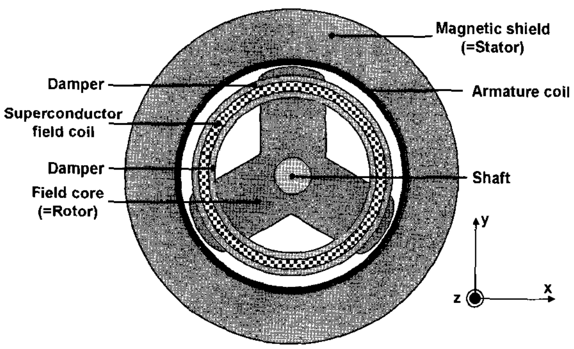
In order to develop low-speed and high torque motors, air-cored superconducting synchronous motors (ASSMs) have been developed. ASSMs can increase the motor efficiency but they raise the production costs due to increase of superconductor resulting from magneto-motive force (MMF) loss. On the other hand, homopolar superconducting synchronous motors (HSSMs) can be reduced superconductor because rotor consisted of magnetic materials [4]. In addition, mechanical stability of HSSMs is higher than that of ASSMs since superconductor field coil does not rotate in operation. However, increase in volume and reactance of HSSMs compared with ASSMs is expected. To develop HSSMs having low-speed and high torque for ship propulsion applications, the structure, characteristics and operational principles of HSSMs are researched. In addition, the conceptual design of 5MW HSSM is presented in this paper.

2. THE OUTLINE OF HOMOPOLAR SYNCHRONOUS MOTOR

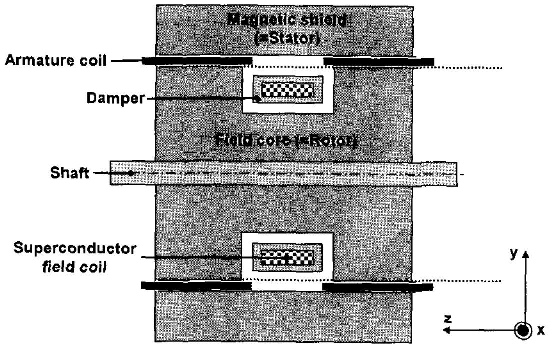
2.1. Structure

Fig. 1 (a) and (b) show the vertical and cross section of HSSM having six poles, respectively. Dampers are located between the two salient parts of field core and they do not rotate in operation. Superconductor field coil is wound by solenoid shape.

Field core is made of magnetic materials. In addition, MMF which is generated from superconductor field coil is very high. Therefore, carbon steel is used as a magnetic material for the field core because carbon steel can get higher flux quantity than silicon steel under the high MMF condition.



(a) Vertical section



(b) Cross section

Fig. 1. The configuration of HSSM.

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2.2. Characteristics

Homopolar superconducting synchronous motors (HSSMs), which superconductor is applied to the field coil, have several kinds of merits compared with ASSMs.

i) Superconductor field coil does not rotate in operation.
ii) Quench effect by magnetic field in superconductor field coils is decreased since flux entirely passes through field core which is made of magnetic materials.
iii) The quantity of superconductor is decreased because rotor consisted of magnetic materials.
iv) Effective air-gap length is decreased because dampers are located between the two salient parts.
v) Mechanical stability is enhanced because superconductor filed coil is fixed.
vi) System volume of HSSMs including motor and cooling system is reduced.

On the other hand, motor volume and weight are increased due to the magnetic saturation in the rotor. In addition, reactance which is related with number of turns per phase is increased but it is not a big problem at the low-speed applications.

2.3. Operational principles

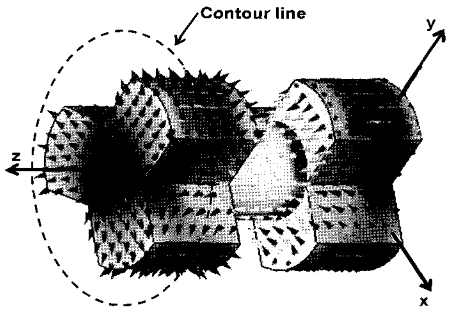
Fig. 2 (a) shows the flux distribution and Fig. 2 (b) shows the air-gap flux density under the no-load condition. The two salient parts in the rotor are respectively induced to N and S pole because superconductor field coil is excited by DC current. Because of the sharp difference of HSSMs compared with conventional motors, the distribution of air-gap flux density is not alternated. For example, if the N pole in the salient part is located at the center of armature coil, flux linkages in the armature coil have maximum values. On the contrary, flux linkages between the two N poles have minimum values. Accordingly, driving frequency of HSSMs is written as

$$f = \frac{PN}{60} \quad [Hz] \qquad (1)$$

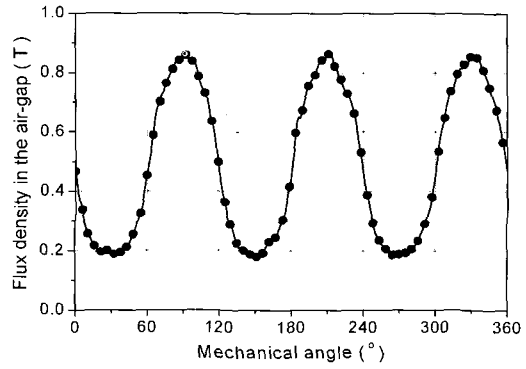
where P is the number of salient part and N is the driving speed of HSSMs.

In order to explain the winding distribution and connection method of armature coil, the example of six poles and nine slots with concentrated windings is shown in Fig. 3. It is assumption that the rotor rotates clock wise (CW) at the A view. And then, the wound direction of armature winding is indicated by (+) and (-).

Flux distribution under no-load condition and the rotating direction of rotor are shown in Fig. 3 (a). Fig. 3 (b) and (c) show the winding distribution of armature coil based on rotating direction of the rotor. The two salient parts, which are shown in Fig. 3 (a), function as the N pole and S pole, respectively. Each armature coil at the N and S pole wounds in the opposite direction and it is coupled by series. Briefly, if the number of turns per phase is 1 at the each N and S pole, it of whole motor is 2.

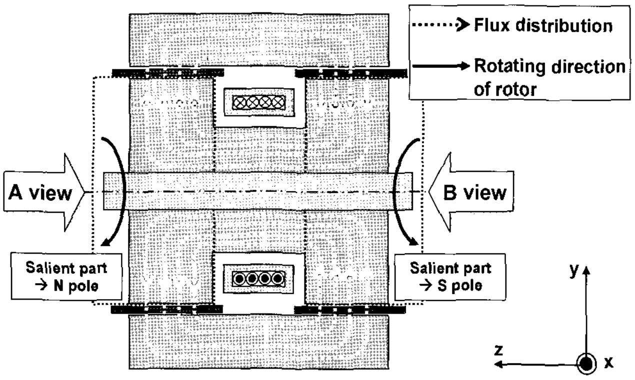


(a) 3D flux distribution

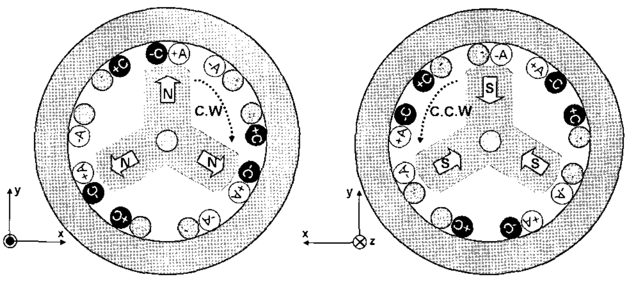


(b) The distribution of air-gap flux density

Fig. 2. The characteristics under no-load condition.



(a) Flux distribution under no-load condition and the rotating direction of rotor



(b) A view (c) B view

Fig. 3. Winding distribution of armature coil.

3. CONCEPTUAL DESIGN OF 5MW

The design procedures to perform the conceptual design of 5MW HSSM by 3D commercial program are described. Finally, the characteristics between HSSM and ASSM are compared.

3.1. Objective function

As the objective function of conceptual design, calculation process of flux quantity per pole is as follow.

Firstly, air-gap flux density at the center of the salient parts along the z direction as shown in Fig. 2 (a) is calculated. Secondly, fast Fourier transform (FFT) is performed and total harmonic distortion (THD) is analyzed. Finally, flux per pole in consideration of only the fundamental component is calculated by equation (2).

Objective function :

$$\Phi = \frac{e}{4.44 \times k_p \times k_d \times N_{ph} \times f} \tag{2}$$

Subject to :

$$\Phi \geq 0.214 mWb \tag{3}$$

Constraint condition :

$$THD \leq 10 \ \% \tag{4}$$

where e is RMS value of phase Back-EMF, k_p is the short pitch factor, k_d is the distribution factor, N_{ph} is the number of turns per phase and f is the driving frequency of motor.

3.2. Design variables

Several design variables are shown in Fig. 4. In addition, magnetic materials and the shape of superconductor field coil are analyzed in the design procedures.

3.3. Design procedures

Design procedures are shown in Fig. 5 and they are divided into six steps. Although THD of air-gap flux density is an important factor for the flux per pole, it is not entirely considered in design procedures due to complexity of conceptual design. Therefore, the design of salient shaped is only performed in initial design. And then, THD of air-gap flux density has about 10 %. Explanation for each step is simply as below.

Step1) Based on ASSM model designed by 2D FEA, initial design of HSSM is performed under the same volume. At this time thickness of magnetic shield is 0.28 m which is the same as that of HSSM.

Step2) Under the same MMF which is generated from superconductor field coil, air-gap flux density according to change the diameter of field coil, such as Fig. 4 (a), is analyzed.

Step3) After the position of superconductor field coil is decided, the variation of flux per pole according to the change of the shape of field core, which is shown in Fig. 4 (b), will be analyzed.

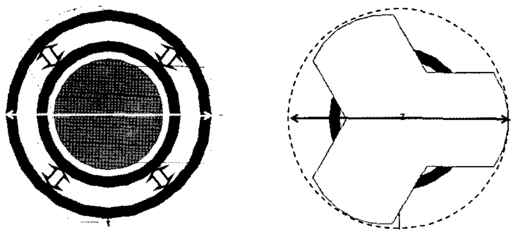
Step4) Magnetic materials and MMF by superconductor field coil are changed, respectively.

Step5) In order to increase the flux quantity per pole by increasing the area per pole under the same magnetic saturation, rotor diameter, height of salient parts, and turn number of superconductor field coil are increased.

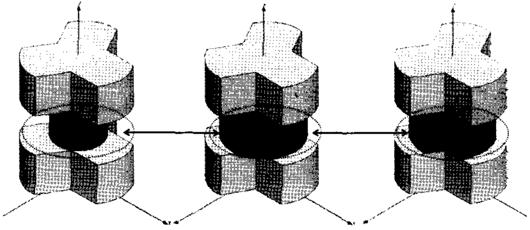
Step6) In order to reduce the degree of magnetic saturation at the magnetic shield, the thickness of magnetic shield is increased.

3.4. Design of 5MW HSSM

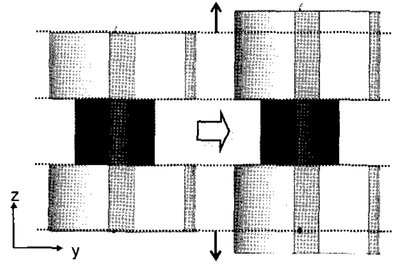
The specifications of 5MW ASSM through 2D FEA is shown in Table 1 and conceptual design of HSSM based on Table 1 was performed. Before initial design, it is assumption that number of turns per slot of 5MW HSSM is six because increase of number of turns per phase is not a big problem at the low speed. In initial design, mechanical air-gap length takes into number of turns per slot and diameter of armature coil consideration. Armature winding to increase the winding factor is distributed by the full pitch in the distribution winding and then winding factor is 1. So, the value of objective function in 5MW HSSM design is 240 mWb.



(a) Diameter of field coil (b) Rotor diameter



(c) Shape of field core



(d) Height of salient parts

Fig. 4. Design variables.

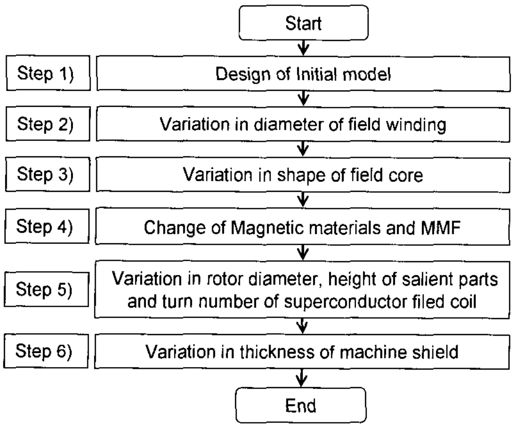


Fig. 5. Design procedures.

TABLE I
THE SPECIFICATIONS OF 5MW ASSM.

Capacity	5 MW
Terminal voltage (V)	6600
Speed (rpm)	230
Number of pole and slot	6 / 72
Number of turns per phase	120
(Number of turns per slot)	(5)
Efficiency (%)	95

Fig. 6 shows the flux per pole according to the change of the height of salient parts and the turn number of superconductor field coil based on the result of design procedures from step 1) to step 5) in Fig. 5. When the number of turns of field coil is 14,000 turns and height of salient parts is 0.49 m, flux per pole has 220 mWb, which occupies about 91 % for goal of objective function. The degree of magnetic saturation was analyzed by increasing the thickness of magnetic shield because maximum flux density in magnetic shield has 1.8 T.

Table 2 shows the comparison of characteristics between ASSM and HSSM. Although volume and weight of HSSM compared with ASSM are increased, the quantities of superconductor field coil of HSSM are reduced.

4. DISCUSSIONS

This paper presents the outline and conceptual design of HSSMs which apply to low-speed and high torque for ship propulsion applications.

Superconducting synchronous motors compared with conventional motors can reduce motor size and enhance efficiency. In superconducting synchronous motor, ASSMs are more expensive than HSSMs because the quantity of superconductor is increased and the price of superconductor is even more expensive than core materials. In order to apply to ship propulsion system, constraints ~~for~~ such as space, price and other design specifications should be more investigated.

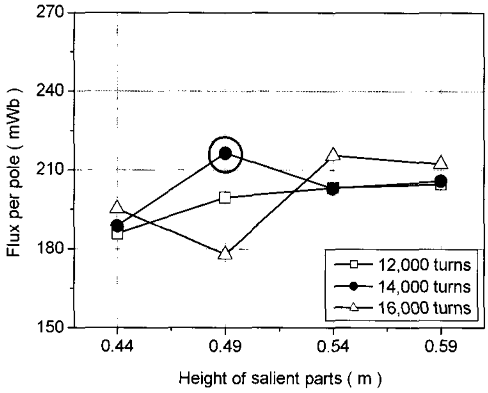


Fig. 6. Flux per pole according to the change of the height of salient parts and turn number of field winding (Rotor diameter is 1.296m).

TABLE II
THE COMPARISON OF ASSM AND HSSM.

	ASSM	HSSM	Comparison with ASSM
Capacity	5MW		
Analysis method	2D FEA	3D FEA	-
External diameter (m)	1.747	2.500	140 %
Stack length (m)	1.315	1.415	107 %
Number of turns per phase	120	288	-
Number of turns of superconductor field coil	40,272	14,000	-
Maximum flux density in the shield (T)	1.2		-
Volume (m^3)	3.15	6.95	220 %
Weight (Kg)	18,000	44,000	240 %
Superconductor quantity (Km)	100	50	50 %

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