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Conceptual Design of a 10 HP Homopolar Motor with Superconducting Windings

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Abstract-- **Superconducting motor has a lot of benefits from high power density for ship propulsions, so a number of research project are in progress worldwide. Despite of all the benefits, there is always a difficulty of cryo-moving part for conventional air-core superconducting synchronous motors. In order to get rid of this moving cryogenic part, we propose a homopolar superconducting synchronous motor, which has high temperature superconducting armature and field coils. The rotor is supposed to be made of iron only and excited by the stationary HTS field coils. The stationary field coils make the cooling system simple and easy to realize because there is no cryo-moving part. A design result of a 10 hp homopolar synchronous motor is presented in this paper. The self and mutual inductance of the motor having the size of air gap as variable parameter are calculated by a 3-dimemsional finite element method. The value of design variables such as the dimension of a motor and the number of turns, etc. is decided by performing the coordinate transformation of the calculated inductance. The operating frequency is supposed to be below 5 Hz for low rotating speed which is needed for a purpose of ship propulsion. Low frequency also has the benefit of low AC losses.**

1. INTRODUCTION

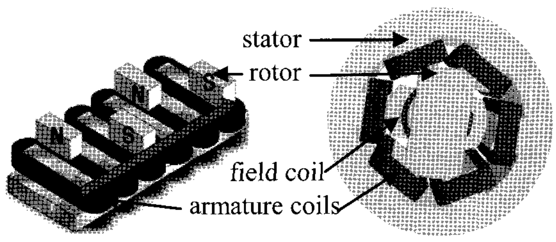
The high-temperature superconducting (HTS) power device has lower weight and volume, higher efficiency as well as environment-friendly in larger scale application. The practical adaptation of the superconducting motor with low speed and high torque for large scale ship propulsion has many advantages such as high efficiency, small size and low weight due to high current density and magnetic field intensity as using the superconducting wire for field winding and armature winding. A fully HTS motor having both the field winding and the armature winding with superconducting wire is difficult to do machining due to a property of HTS wire with a thin tape shape and the cooling for making the wire a superconducting state. In previous work by other researchers, the motor of an axial type was proposed [1], also a motor of a homopolar type was proposed [2-4]. But it is not a fully superconducting motor because the field winding part uses a superconducting wire and the armature winding part uses a normal conductor. Also, the superconducting synchronous motor has difficulties such as cooling and current lead because the field winding is located at a rotor and rotated during operation [5].

In the present research, we propose a fully HTS homopolar motor by mixing a synchronous motor with a linear motor. The synchronous motor is similar to the armature winding was applied to the linear motor. The armature winding of a racetrack type is locating at a stator, and the field winding generating the magnetic field flowing in a rotor is located at not a rotor but a stator portion. So, the motor has firm structure and advantage in cooling, etc. The motor designed with structure having less change of magnetic resistance has less noise and vibration due to small torque ripple.

2. THE OUTLINE OF HOMOPOLAR MOTOR

2.1. Structure

The stator of a homopolar motor as shown in Fig. 1(a) is linear motor's operating principle. Fig. 1(b) shows the structure of a homopolar motor which an operating principle of a linear motor is applied. A rotor becomes a homopolar electromagnet when an electric current flows to the field winding corresponding to a permanent magnet of a linear motor, and a motor gets to rotate as the electric current applies to the armature winding.



(a) Linear motor's operating principle (b) Homopolar motor structure

Fig. 1. Structure of Homopolar motor.

We adapt the armature winding as the racetrack shape coils of concentrated winding not distributed winding generally used in synchronous motor because it is suited for used superconducting wire (that is to say, YBCO coated conductor). The rotor winding is solenoid shape and placed at outside of the rotor iron in center region of rotor axis, and

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is structurally firm because it is fixed such as the stator instead of rotating with a rotor. Operating temperature is 77 K, will be cooled by liquid nitrogen. The specifications of the HTS conductors are shown in Table I.

TABLE I
SPECIFICATIONS OF THE HTS CONDUCTORS.

SPEC	12 mm	4 mm
Critical Current @ 77 K	240	80
Widths	12 mm	4 mm
Thickness	0.1 mm	0.1 mm
Manufacturing Company	SuperPower	SuperPower Sunam

2.2. Characteristics

The designed homopolar motor has the following characteristics different from a conventional motor or the other superconducting motor.

i) It is a fully superconducting AC motor that the rotor winding and stator winding are designed with a superconducting wire.
ii) Structure is simple and steady because the rotor winding doesn't rotate during the operation of a motor.
iii) It generates low noise and vibration with small torque ripple because the change of magnetic resistance is small.

2.3. Equations

The self and mutual inductance of the homopolar motor is calculated by the finite element method. OPERA 3D was used to obtain the inductance as a commercial FEM tool. As the change of inductance is very small, the inductance can be shown as a constant as in equation (1).

$$Labc = \begin{bmatrix} L_s & M \\ M^T & L_r \end{bmatrix} \tag{1}$$

$$= \begin{bmatrix} L_s & -M & -M & M_r\cos\theta \\ -M & L_s & -M & M_r\cos(\theta-\frac{2}{3}\pi) \\ -M & -M & L_s & M_r\cos(\theta-\frac{4}{3}\pi) \\ M_r\cos\theta & M_r\cos(\theta-\frac{2}{3}\pi) & M_r\cos(\theta-\frac{4}{3}\pi) & L_r \end{bmatrix}$$

Here, L_s is the self-inductance of the armature winding, M being mutual inductance between armature windings. L_r is the self inductance of the rotor winding, M_r being mutual inductance between stator winding and rotor winding.

The reactance can be expressed as in equation (2). The reactance is proportional to square of the number of turns of armature winding and frequency, and is inversely proportion to magnetic resistance.

$$X_s = \omega(L_s + M) = \omega\frac{N_s^2}{\Re} \tag{2}$$

Here, ω being angular frequency, N_s being the number of turns of stator winding, and $\Re$ is magnetic resistance. The equation (3) shows counter electromotive force.

$$E = V - R_a I_a - jX_s I_a \tag{3}$$

Here, V is input voltage, R_a being input resistance, I_a being input current, and X_s is the reactance of equation (2).

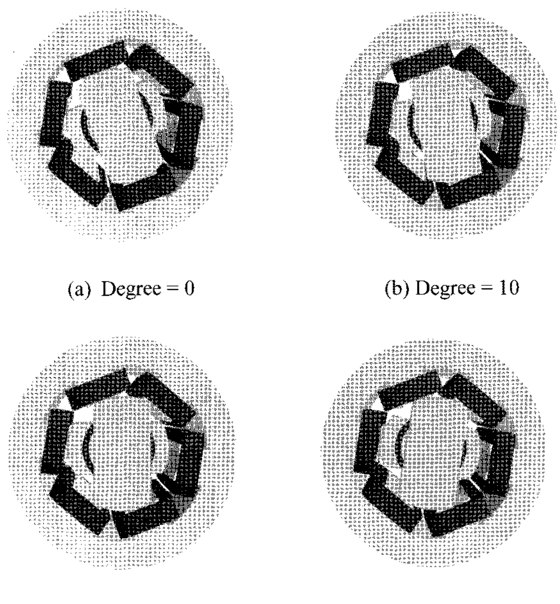
The equation (4) expresses the counter electromotive force with field winding and armature winding, etc. which are design variables.

$$E = \frac{\omega M_{af}}{\sqrt{2}} I_f = \frac{\omega}{\sqrt{2}}\frac{N_s N_r}{\Re} I_f \tag{4}$$

Here, M_{af} is the mutual inductance between field winding and armature winding, N_r being the number of turns of rotor winding, and I_f being the current applied to field winding.

3. DESIGN OF HOMOPOLAR MOTOR

Fig. 2 shows a homopolar motor according to the angle between the stator and the rotor. The constant area of a rotor is made to be always coincident with the area of a stator to reduce the variation of magnetic resistance. Fig. 3 is a figure spreading in a plane of a rotor and a stator for easy understanding. We can see that the 2/3 area of the rotor is coincident with a stator in any angle. Actually, the change of magnetic resistance can occur due to a design error and magnetic leakage, etc. Table II shows an initial model. The initial model was designed by using the YBCO coated conductor with the width of 12 mm as superconducting wire. While setting air gap size as a design variable, the self and mutual inductance of the homopolar motor can be calculated by the finite element method. The design order is as follows.



(a) Degree = 0 (b) Degree = 10

(c) Degree = 20 (d) Degree = 30

Fig. 2. Shape of homopolar motor according to angle between the stator and the rotor.

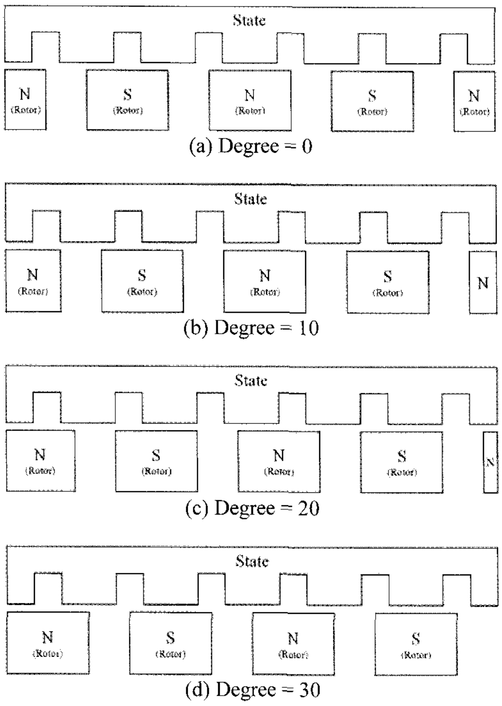


Fig. 3. A straight line motion of homopolar motor state and rotor.

1. Decision of an initial model of a homopolar motor.
2. Calculation of self and mutual inductance of a homopolar motor by using the finite element method.
3. Decision of the number of turns of N_s and N_r from reactance and counter electromotive force.
4. Calculation of magnetic flux density of a stator and a rotor of a homopolar motor by using calculated N_s and N_r.
5. Calculation of dimensions and wire consumption amount, etc. of a homopolar motor by using calculated magnetic flux density.

The design orders from 2 to 5 were repeated by using the YBCO coated conductor with the width of 4 mm. The number of turns of armature winding, the number of turns of field winding, outer diameter of a rotor, outer diameter of a stator and required wire amount in each case were calculated while varying air gap size as design variable from 1 mm to 15 mm. Using FEM to calculate the inductance of the angle and curve fitting in MATLAB program. Fig. 4 ~ 6 are the result of initial model. Fig. 4 and Fig. 5 show self and mutual inductances of the stator coil, respectively. Fig. 6 shows a mutual inductance between stator coil and rotor coil.

TABLE II
INITIAL MODEL.

	Stator	Rotor
Type	Racetrack type	Solenoid
Number of turns in winding	600	20
Inner diameter	200 mm	
Outer diameter	400 mm	190 mm
Length	400 mm	400 mm
Input current	140 A	200 A
Width of HTS	12 mm	12 mm
Material	Silicon Steel	Silicon Steel
Air gap	5 mm	5 mm

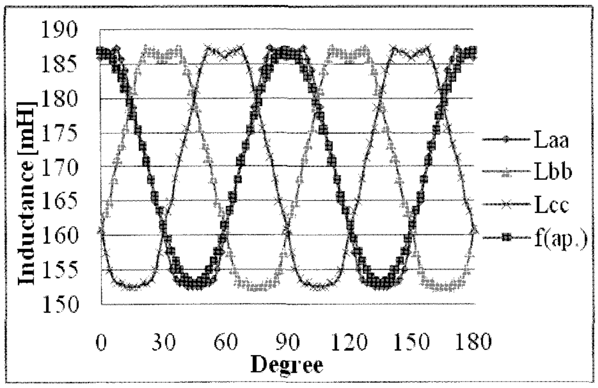


Fig. 4. Self inductance of state coil(f(ap.): Approximation function).

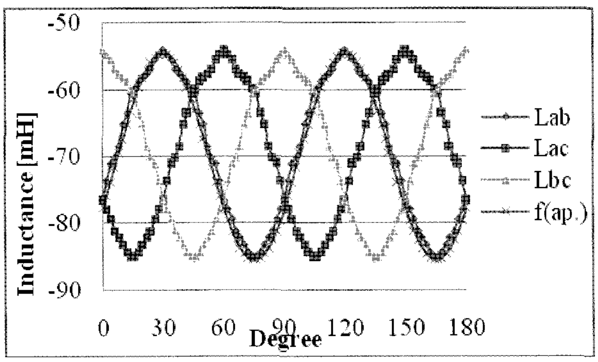


Fig. 5. Mutual inductance of state coils(f(ap.): Approximation function).

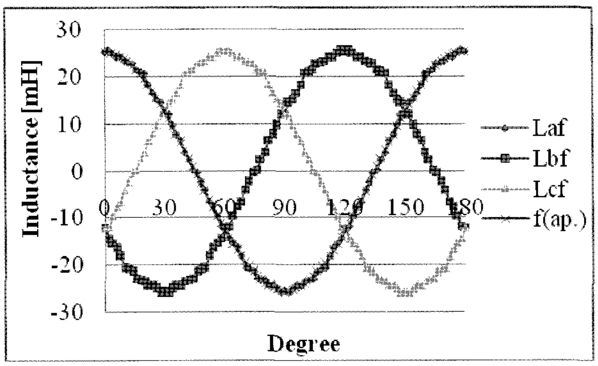


Fig. 6. Mutual inductance of state coils and rotor coil(f(ap.): Approximation function).

Fig. 7 shows the analysis result by using FEM. Fig. 7(a) is the magnetic flux density as a color zone, and Fig. 7(b) is the vector expression of magnetic flux density.

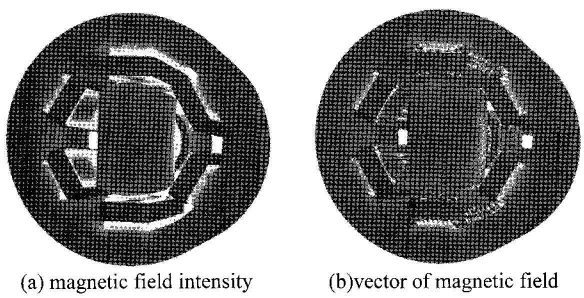


Fig. 7. Analysis result of homopolar motor using the finite element method.

The calculated values of the number of turns of armature winding, the number of turns of field winding, outer diameter of a stator, and wire requirement according to air gap size are shown in Table III to Table VII. As shown in the results, the wire requirement increases as larger the air gap because of smaller the magneto-motive force. The outer diameter of the rotor and total diameter of a motor increase as the rotor is saturated by small turns of field winding due to the low magnetic resistance. If the air gap increases, the outer diameter of a motor decreases, and if the air gap becomes larger than 10 [mm], the outer diameter of a motor again increases. Maximum flux density 1.6 T results that exceed the design parameters were changed. Table VIII shows designed dimensions and specification of a homopolar motor of 10 HP.

TABLE III
DESIGN VALUE(AIR GAP : 1 mm).

X_{spu}	0.5	0.7	0.8	0.9	1
N_s	24	28	30	32	34
N_r	103	87	83	81	80
OD of Stator	787	770	775	787	803
Length of HTS wire	306	302	310	323	338

TABLE IV
DESIGN VALUE(AIR GAP : 7 mm).

X_{spu}	0.5	0.7	0.8	0.9	1
Ns	48	57	61	64	67
Nr	450	381	363	355	352
OD of Stator	736	699	689	686	685
Length of HTS wire	982	896	891	901	920

TABLE V
DESIGN VALUE(AIR GAP : 10 mm).

Xspu	0.5	0.7	0.8	0.9	1
Ns	60	71	76	80	85
Nr	486	410	391	383	380
OD of Stator	705	670	662	659	659
Length of HTS wire	1076	1001	1006	1024	1062

TABLE VI
DESIGN VALUE(AIR GAP : 12 mm).

Xspu	0.5	0.7	0.8	0.9	1
Ns	75	88	94	100	106
Nr	690	583	556	545	539
OD of Stator	730	691	681	677	676
Length of HTS wire	1579	1422	1413	1437	1477

TABLE VII
DESIGN VALUE(AIR GAP : 15 mm).

Xspu	0.5	0.7	0.8	0.9	1
Ns	69	81	87	92	97
Nr	561	475	452	443	439
OD of Stator	713	676	667	663	662
Length of HTS wire	1279	1179	1181	1205	1236

TABLE VIII
SPEC OF 10 HP HOMOPOLAR MOTOR.

	State	Rotor
Type	Racetrack type	Solenoid
Number of turns in winding	662	76
Inner diameter	462 mm	
Outer diameter	662 mm	442 mm
Length	400 mm	400 mm
Input current	60 A	60 A
Input voltage	51.8 V	
Width of HTS wire	4 mm	4 mm

4. CONCLUSION

This present aimed to design a HTS homopolar motor of 10 HP as fully superconducting machine using a superconducting wire both the field winding and the armature winding. The armature winding was proposed by applying a linear motor and a synchronous motor. As the field winding is placed at a stator and is not rotated during the operation of the motor, its structure is simple and firm. We obtain the designed results such as the number of turns of armature winding and field winding, outer diameter of a stator and wire requirement according to air gap size. Many of the results were determined by the minimum volume of homopolar motor.

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