Modeling and Prototype Experiments for a New High-Thrust, Low-Speed Permanent Magnet Synchronous Motor

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Abstract — **Fully integrated electric propulsion systems are gaining popularity in both commercial and military sectors. Propulsion motor manufacturers are investigating new direct drive solutions for use in electric ships. These applications require motors with high torque output at low speeds. Such requirements were the motivation for the design of a new PMSM with a novel topology. This paper describes the efficient model used to for high thrust at low speed. Also, to compare the theoretical result, the authors had an experiment on the characteristic of the suggested motor. Finally, analytical calculation of the cogging torque and the method to decrease that are suggested.**

Keywords— **permanent magnet synchronous motor (PMSM), transverse flux machine (TFM), tunnel actuator (TA), cogging torque**

I. INTRODUCTION

Just as the commercial automotive, aerospace, and railway industries have been affected by rising fuel costs, the marine industry has recently endeavored to create more fuel-efficient, cost-effective drive systems. During the last 15-20 years, fully electrified propulsion (EP) systems have been gaining popularity and capturing most of the market growth in sectors such as cruise ships, passenger ferries, oil and gas transport vessels, and merchant and special order ships [1,2].

Several different types of motors are currently in use or have been proposed for application in ship propulsion. We took particular interest in a Permanent Magnet Synchronous Motor (PMSM) solution because of the possibility of higher thrust, less complicated design, and lower maintenance.

Due to the short pole pitch characteristic of certain types of PMSM designs, these machines can have high torque at low speeds, which is particularly beneficial in a marine application. Transverse Flux Motor(TFM) designs have short pole pitch and high torque characteristics, but TFM are plagued by low power factor [3]. In order to improve on previous designs, we developed a theoretical model of a transverse flux PMSM and subsequently built and tested the prototype of a new design. We also adapted the basic flux path idea present in the Tunnel Actuator(TA), a linear PMSM produced by Hitachi, to perform in a rotary application. Also, in order to decrease cogging torque that has a negative effect on PMSM's behavior, we suggested the techniques to reduce cogging torque. Finally, to compare the theoretical result, we had an experiment on the characteristic of suggested motor.

II. FUNDAMENTALS OF NEW MOTOR DESIGN

The transverse flux machine takes advantage of a 3-D flux path to increase torque production without having to trade off between electrical or magnetic loading as with radial and axial flux machines. But, the TFM described by Weh, et. al. and later improvements on that design have such complex manufacturing requirements that they are impractical for industrial production[4]. This complex design can be seen in Fig.1. Ultimately, the low power factor characteristic of transverse flux machines becomes an obstacle against this type of machine attaining a high real power to volume ratio [3]. For example, Rolls-Royce Ltd. manufactured a TFM for marine propulsion that was capable of large thrust but had power factor ratings of less than 0.7 [6].

When examining the field of direct drives for another motor with a similar flux path configuration but a high power factor, we found Hitachi's Tunnel Actuator for linear drive applications [5]. This drive has the advantages of easy assembly, thin permanent magnet and high resultant permeability and a magnetic flux path that is transverse. The TA suffered from large leakage flux due to the close position of the armature poles and the configuration of the flux path in alternating poles. We thought that by placing only poles with flux in the same direction next to each other and spacing them further apart to increase magnetic isolation. The following sections will show the details of new direct drive design.

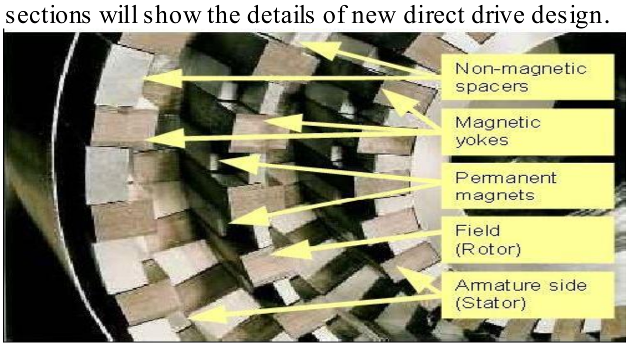

Fig. 1. Transverse Flux Machine[7]

A. The Model

The basic unit of our model was one pole of the machine. One pole consists of a stator C-core. The winding is wrapped around the back of the C, and the permanent magnets on the rotor are accelerated through the air gap to generate thrust. An illustration of the one-pole model is in Fig. 2. The input to the model is the armature current I_0. B_a is the armature flux and B_f is the flux contributed by the field magnets. As I_0 changes, the polarity of B_a also fluctuates, which pulls the alternating polarity magnets through the air gap, creating thrust. The movement of the magnets through the armature flux field also induces an internal EMF.

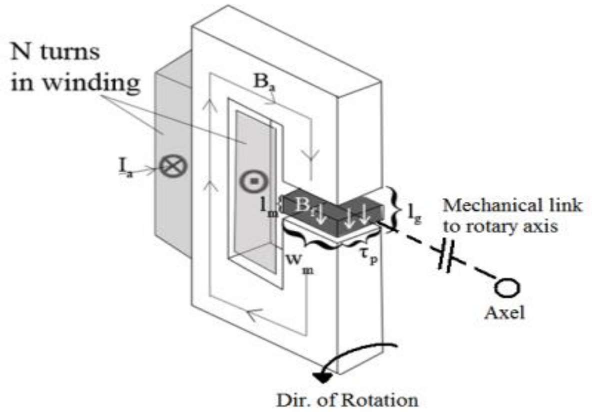

Fig. 2. One-pole model diagram[7]

Fig. 3 shows how the rotor would be propelled through the consecutive air gaps of several poles connected in phase by their armature winding. The self-induced voltage and thrust contributed by each pole would be superimposed to create the total contribution of one phase. The phases of the machine could then be connected to the operator's convenience. The C-cores of each phase would be placed at balanced angular separation around the axel to create the outer radius of the machine.

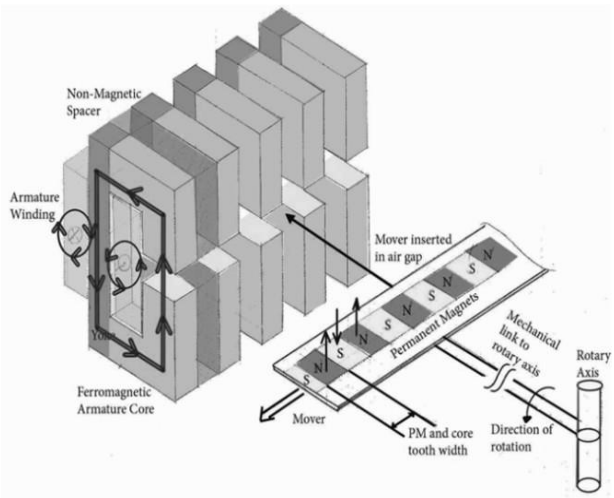

Fig. 3. Flux path through C-core and rotor[7]

B. Creation of the prototype and test bench

The prototype design was created by taking a number of unit model C-cores and arranging them radially to create a full stator. In Fig. 4, this idea is drawn up with 3-phases and 4 stator cores per phase. In the actual prototype, only 2 cores were used per phase. The rotor was constructed in a similar fashion by placing alternating polarity magnets on a rotor backing at a set angular separation. In the prototype, there were 36 permanent magnets, thus 18 pole pairs.

It is important to note that because the flux lines in adjacent stator cores of the same phase point in the same direction and there is a large physical separation between phases, we expected negligible leakage flux.

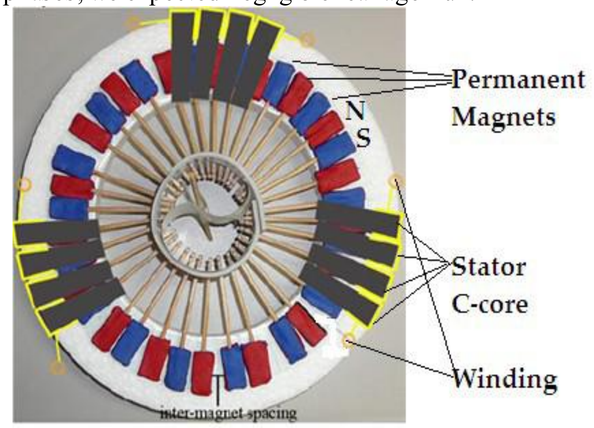

Fig. 4. The illustration of the prototype motor model[7]

Fig. 5, 6 is detailed parts of the prototype motor and the full test bench involved directly connecting a PMSM load motor to the prototype. The prototype was driven directly in generator mode. The prototype was connected to an inverter to be controlled for dynamic testing. This test bench accurately represents the typical case of an industrial client, where the motor supplier will have only general knowledge about the loading conditions applied to their product [7].

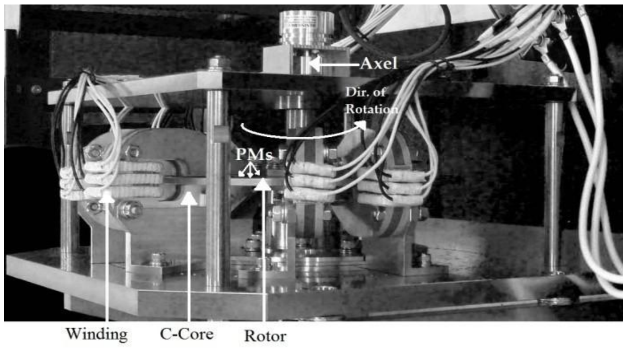

Fig. 5. Detailed parts of the prototype motor[7]

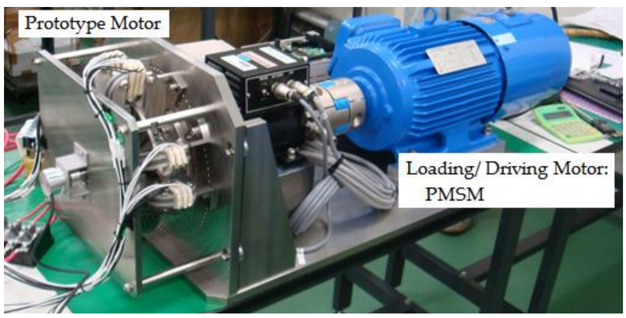

Fig. 6. A full version of the prototype motor model[7]

C. Experiment and comparison of theoretical and empirical data

In order to verify that our design would behave as characteristics we has calculated, experiments measuring the fundamental characteristics of the prototype motor were preformed and compared with theoretical data. Table I shows the theoretical and empirical values for the efficiency, power factor, torque, and force density of the prototype etc.

TABLE I
COMPARISON OF THEORETICAL AND EMPIRICAL DATA

Variable	Theoretical Value	Empirical Value
Winding resistance R_u	0.319 [Ω]	0.72 [Ω]
Self-inductance L_u	0.433 [mH]	2.91 [mH]
Self-induced voltage V_{rms}	3.25 [V]	4.94 [V]
Output P	31.0 [W]	59.3 [W]*
Torque T	2.69 [Nm]	5.15 [Nm]*
Power factor $Cos\theta$	0.99	0.98*
Efficiency η	0.76	0.63*
Force density D	39.9 [kN/m^2]	38 [kN/m^2] *
Frequency f	33 [Hz]	33 [Hz] *

*values are estimated based on empirical values for R_u, L_u, V_{rms}

In experiment, we considered 1phase-2core to measure the fundamental characteristics of the prototype motor. By open circuit test and adding dc, ac to armature coil, we can measure winding resistance, self-inductance, self-induced voltage.

However, *values are estimated based on empirical values R_u,, L_u,, V_{rms} by equations that we used to calculate theoretical data because the prototype motor could not be rotated as synchronous motor mode.

III. COGGING TORQUE MINIMIZATION

As we mentioned in previous section, the prototype motor could not rotate as a synchronous motor mode when having an experiment. We thought the reason that prototype motor did not rotate in the synchronous speed could be the cogging torque.

Cogging torque is caused by the reluctance change between the stator teeth and magnet poles on the rotor, this is an inherent characteristic of PMSM. Cogging torque cause excessive noise and harmful vibration to the machine itself, and in many serious cases, a mechanical resonant may occur so that serious destruction is caused. In many applications, cogging torque has become one important design specifications and consideration issues of PMSM. Consequently, the cogging torque calculation and reduction method will be discussed in this section.

A. Analytical Cogging Torque Calculation Method and Analysis

There are many methods to reduce the cogging torque such as Energy method, Virtual work method, Maxwell tensor method etc [8]. Based on the energy method, the cogging torque can be calculated from the energy variation with the angle of rotation. In order to simplify calculation of the cogging torque, we have considered one pole-one core in the prototype model. The basic concept is considered without the leakage flux as illustrated Fig. 7.

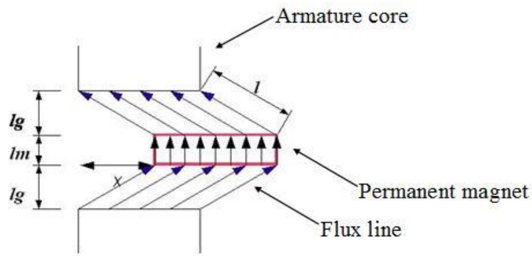

Fig. 7. Flux line in the air gap

In Fig. 7, l_g is the air gap length excepted magnet's height l_m, l is the flux line length between magnet and armature core and x is the length away from the initial position that magnet was below armature core vertically. Considering that magnet is in the initial position, the reluctance R_0 and flux density B_0 in the air gap are followed respectively;

$$R_0 = 2\frac{l_g}{\mu_0 S} + \frac{l_m}{\mu_0 S} \tag{1}$$

$$B_0 = \frac{H_c l_m}{R_0 S} = \frac{\mu_0 H_c l_m}{2(l_g + l_m)} \tag{2}$$

μ_0 is permeability of the air gap, H_c is the coercivity of magnet and S is the surface area of magnet. Considering that magnet is in x away from the initial position, the reluctance R_x and flux density B_{g_x} in the air gap are followed respectively;

$$R_x = 2\frac{\sqrt{x^2 + l_g^2}}{\mu_0 S} + \frac{l_m}{\mu_0 S} \tag{3}$$

$$B_{g\_x} = \frac{H_c l_m}{R_x S} = \frac{\mu_0 H_c l_m}{2\sqrt{x^2 + l_g^2} + l_m} \tag{4}$$

The total magnetic co-energy U_t in the air gap is followed as;

$$U_t = U_a + U_b = \frac{B_0^2}{2\mu_0} V_m + 2\frac{B_{g\_x}^2}{2\mu_0} V_g \tag{5}$$

U_a is the magnetic co-energy in the air gap when magnet is in the initial position. U_b is the magnetic co-energy in the gap at x away from the initial position. V_m, V_g are the volume of magnet and air gap.

Therefore, the cogging torque F can be calculated as follows;

$$F = \frac{\partial U_t}{\partial x} = -4\mu_0 d w_p l_g H_c^2 l_m^2 \frac{x}{\sqrt{x^2 + l^2}\,(\sqrt{x^2 + l_g^2} + l_m)^3} \tag{6}$$

In (6), w_p is the width of magnet and d is the length of magnet.

B. The Method to Reduce Cogging Torque

According to different applications and considerations of technical and economical factors, various cogging torque reduction method can be employed, including Slot or magnet skewing, Magnet pole shape optimization and Stator slot opening width optimization etc [8]. In particular, skewing has been well recognized as a practical technique to reduce cogging torque of PMSM.

In this paper, we calculated the cogging torque as a function of skewing angle of the magnets. Considering the skewing, the cogging torque is expressed as (7).

$$F = -\frac{4\mu_0 w_p l_g \left(H_c l_m \cos\theta\right)^2}{d\theta} \cdot \frac{2xd\theta + l_m\{A-B\}}{\{2B+l_m\}^2\{2A+l_m\}^2}$$

$$A = \sqrt{\left(x+\frac{1}{2}d\theta\right)^2 + l_g^2}\ ,\ B = \sqrt{\left(x-\frac{1}{2}d\theta\right)^2 + l_g^2} \qquad (7)$$

Considering the geometric structure, we decided the skew angle θ as 4 degree. Fig. 8 is the cogging torque according to variation of skew angle. When not considering skewing, the cogging torque was 51N and its peak value was at 0.6mm from the initial position. In 4 degree, although it was not eliminated perfectly, the cogging torque was 28N and its peak value was at 1.8mm from the initial position. The cogging torque decreased to almost half by skewing.

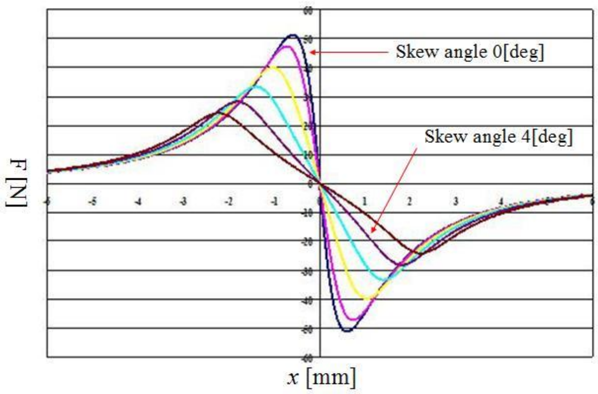

Fig. 8. Cogging torque per a pole depending on skew angle

IV. CONCLUSION

This paper proposed a new evolution in the development of the transverse flux type permanent magnet motor. A new idea for a low-speed, high-torque permanent magnet motor was proposed. We reviewed the initial transverse flux concept and two adaptations of the TFM topology.

In Section II, a new design of the proposed motor was described as a modification of the TFMs. It has a simple flux topology that allows for simplified linear modeling of the motor characteristics.

The fundamental measurements of the prototype's open circuit voltage armature impedance and self-induced voltage were completed in experiment. Also, the fundamental characteristics of the prototype motor were estimated analytically and compared with experiment values. However, some empirical values are estimated based on R_u, L_u, V_{rms} by equations that we have used to calculate theoretical data because the prototype motor could not be rotated as synchronous motor mode.

We thought the reason that prototype motor did not rotate in the synchronous speed could be cogging torque. In Section III, in order to solve the problem, cogging torque was calculated as a function of skewing angle of the magnets. By an appropriate skewing, the cogging torque can be reduced to half theoretically.

Our new model (the 2nd model) is being fabricated. In particular, the number of armature core, winding, pole and overall shape were changed in order to decrease the cogging torque and gain a higher torque than 1st model. Table II is a comparison of specifications of two test machines.

Also, after finishing the fabrication of the 2nd model, we will verify the calculated results and confirm the performance of this machine. We think that the 2nd model will have better performance than 1st model.

TABLE II

COMPARISON OF SPECIFICATIONS OF TWO TEST MACHINES

Variable	The 1st model	The 2nd model
Armature core number	6	18
Winding	84 [turns]	400[turns]
Pole number	36	38
Skew angle	0 [deg]	4 [deg]

Acknowledgement

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