A Novel Claw Pole Permanent Magnet Motor with SMC and Ferrite PM

Chengcheng Liu[1], Jianguo Zhu[2], Youhua Wang[1], Gang Lei [2], Youguang Guo[2], Xiaojing Liu[1]
[1] Province-Ministry Joint Key Laboratory of EFEAR, Hebei University of Technology, Tianjin, China
[2] School of Electrical, Mechanical and Mechatronic System, University of Technology, Sydney, Sydney, Australia
E-mail: Chengcheng.Liu@uts.edu.au

Abstract — This paper proposes a novel low-cost claw pole permanent magnet motor with soft magnetic composite (SMC) core and ferrite permanent magnet (PM). Since the ferrite PM is much cheaper than the rare earth PMs, the material cost of this motor can be reduced greatly. And the special spoke type rotor can make the ferrite PM produce very high air gap flux density in this motor. By using the SMC material, the claw pole stator and rotor core can be manufactured very easily. A 675 W 1.8 Nm claw pole motor is designed to replace the conventional permanent magnet synchronous motor (PMSM) in a refrigerator compressor. The finite element method (FEM) package ANSOFT and simplified magnetic network method are used to calculate the electromagnetic parameters of this motor. And the equivalent electric circuit is developed to predict the motor performance.

Index Terms—Low-cost claw pole permanent magnet motor, soft magnetic composite, ferrite permanent magnet, simplified magnetic network method.

I. Introduction

Soft magnetic composite (SMC) material is a relatively new soft magnetic material that has many advantages over the conventional silicon steels. The main advantages of SMC are its magnetic isotropy and powder metallurgy characteristic; various complex electromagnetic devices can be manufactured by this material. With the high production, low pressure in the molding, the manufacture cost of the motor with SMC core will be reduced greatly in a commercial production [1]. On the other hand, the disadvantages of SMC are that its permeability is quite low and its core loss is high at low frequencies. Hence, the motor with SMC core may not meet the high performance drive requirements such as the electrical vehicle drive system. These characteristics have determined that the motor with SMC core should be designed with the permanent magnet (PM) excitation and it should be utilized in the low-cost applications.

During last decades, various electrical motors with SMC core have been developed. Compared with other motor topologies, the torque density of claw pole/transverse flux motor is relatively higher. The claw pole/transverse flux motors are two successful examples in the SMC motors [2]-[4]. These motors with SMC core have all used the rare earth PMs to produce the PM flux linkage in the coil which make the material cost very high.

Among various permanent magnet materials, the ferrite PM is the cheapest one. However, the residual magnetic flux density of ferrite PM is very low, which is only 30% of that of the rare earth PMs. In order to replace the rare earth PM with ferrite PM in the permanent magnet synchronous motor (PMSM), the flux concentrating rotor is needed. Among the flux concentrating rotor topology, the spoke type is a famous one. Various researches have worked on improving the performance of the PMSM with ferrite PM during the last decades. In 2013, Kim *et al.* proposed a modified spoke type ferrite magnet motor. Compared with the traditional spoke type ferrite magnet motor, the main performances of this motor are improved except the efficiency [5]. In 2013, Petrov *et al.* analyzed the performance of an outer rotor PMSM with ferrite magnets, showing that the PMSM with ferrite magnet has lower performance than the PMSM with NdFeB, but higher performance than induction machines [6]. Furthermore, the ferrite PM can produce PM torque in the PMSM, and it can also be used to produce the PM torque in the synchronous reluctance motor [7].

TABLE I
Specifications of the Target Motor

Rated speed	3600 rpm
Rated torque	1.8 Nm
Rated power	675 W
Rated efficiency	80%
Maximum speed	7200 rpm
Minimum speed	1200 rpm
Maximum power	900 W
Supply voltage	230 V
Outer radius of the motor	55 mm
Axial length	60 mm

The aim of this paper is to propose a novel low cost claw pole motor (CPM) with SMC core and ferrite PM. A 675 W, 1.8 Nm motor is designed for replacing the PMSM with rare earth PM in the home applications. The requirements for the target motor are listed in Table I. Simplified equivalent magnetic network method (SEMNM) and finite element method (FEM) package ANSOFT are used to analyze the electromagnetic parameters of this motor.

II. Topology and Dimensions of the CPM with SMC Core and Ferrite PM

A. Topology

Fig. 1 shows the 3D view of one disk of the CPM. The complete CPM is composed of three disks that have 120 electrical degrees shift with each other. As shown in Fig. 1, the disk of CPM has a stator, several ferrite PMs, a rotor core and a shaft. As there are 12 ferrite PMs, the motor has 12 poles. In order to improve the motor performance, the special flux concentrating structure is used as shown in this figure. The concentrated global armature coil is located in the stator slot.

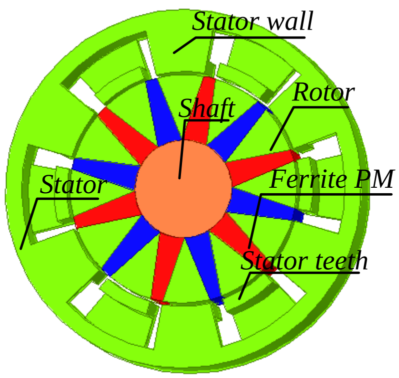

Fig. 1. Topology of the proposed motor

In this motor, all the effective magnetic parts are manufactured by the SMC - SOMALOY™ 500, specifically the stator teeth. The PMs are of the ferrite type and the residual flux density is 0.4 T and the coercive force is 300 kA/m.

B. *Dimensions of the motor*

Table II lists the major dimensions of the proposed motor. Considering that the permeability of SMC is quite low, increasing pole pairs will increase the magnetic reluctance of each part in the motor. On the other hand, increasing pole pairs in the claw pole motor will increase the flux leakages of the global winding. Finally, the number of pole pairs of this motor is chosen as 6. In this paper, the stator wall is defined as the part that connects the stator yoke and the stator teeth, as shown in Fig. 1.

TABLE II
DIMENSIONS OF THE CPM

Outer radius of the stator	55 mm
Inner radius of the stator	36 mm
Thickness of the stator yoke	5 mm
Thickness of the stator wall	5 mm
Height of the stator tooth	4 mm
Air gap length	1 mm
Out radius of the rotor	35 mm
Inner radius of the rotor	15 mm
Number of pole pairs	6
Axial length of the motor	60 mm
Number of coils per phase	80
Material of the stator and rotor	SOMALOY™ 500
Material of the PM	Ferrite magnet

III. SIMPLIFIED EQUIVALENT MAGNETIC NETWORK MODEL FOR THE PROPOSED MOTOR

SEMNM is a simple way to analyze the electromagnetic parameters of the CPM. Compared with the magnetic circuit method, the magnetic network can calculate the motor parameter more precisely. On the other hand, compared with the FEM, using the SEMNM can save much computational time.

A. *Basic electromagnetic parameters deduced by the SEMNM*

Fig. 2 illustrates the SEMNM model of this motor. In order to make the model precise, each ferrite PM is divided into two parts. In this model, the resistance represents the magnetic reluctance and the current source represents magnetic flux of the PM. R_{sy} represents the magnetic reluctance of stator yoke, R_{st} represents the magnetic reluctance of stator tooth, R_{gap} represents the magnetic reluctance of air gap, R_{rt1} and R_{rt2} represent the magnetic reluctance of rotor, and R_{pm1} and R_{pm2} represent the magnetic reluctance of permanent magnet. The PHI_{pm} represents the magnetic flux of permanent magnets. By analyzing the magnetic network model, the main flux of each part can be calculated. In this motor, the peak value of air gap flux is $1.16e^{-4}$ Wb, and the stator yoke flux is $5.8e^{-4}$ Wb. The flux density of air gap is 0.405 T, and the flux density of stator yoke is 0.58 T.

By using the current excitation in this model, the inductance L can be calculated by

$$L = \frac{\varphi_{I+PM} - \varphi_{PM}}{I} \tag{1}$$

where φ_{I+PM} is the flux linkage produced by the armature current and PM, and φ_{PM} the flux linkage produced by the PM only. The inductance is calculated as 2.3 mH

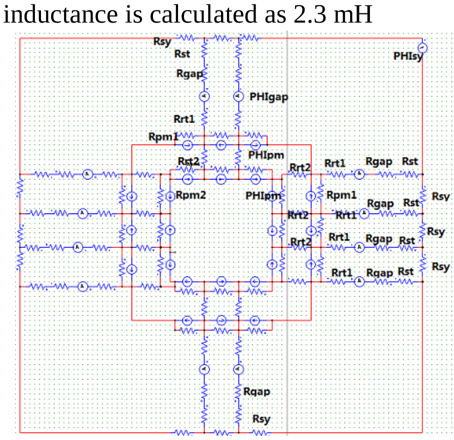

Fig. 2. Simplified magnetic network model for the motor

B. *Performance prediction by SEMNM*

In the PMSM, the electromagnetic torque is composed of two parts. One is the magnetic torque produced by the permanent magnet flux linkage and the other is the reluctance torque produced by the difference between the d-axis inductance and q-axis inductance. In this motor, the reluctance torque will be neglected. As the magnetic flux of the motor can be calculated by the SEMNM, the flux linkage per phase equals to the number of coil turns multiplied by the magnetic flux of each coil, and it can be represented as

$$\lambda_{pm} = k_l N_{coil} N_r \phi_{gap} \tag{2}$$

where λ_{pm} is the PM flux linkage per phase, k_l is the leakage coefficient, N_{coil} is the number of phase coil turns, N_r is the number of pole pairs, and Φ_{gap} is flux per coil. The back electromotive force (EMF) E_m can be expressed as

$$E_m = \omega_e \lambda_{pm} = N_r \omega_m \lambda_{pm} \tag{3}$$

where ω_e is the electrical angular speed, and ω_m is the mechanical angular speed. The electromagnetic power P_{em} can be expressed as

$$P_{em} = \frac{m}{2} E_m I_m \tag{4}$$

where is the number of phases.

The electromagnetic torque T_{em} can be expressed as

$$T_{em} = \frac{P_{em}}{\omega_m} = \frac{m}{2} N_r \lambda_{pm} I_m \tag{5}$$

The flux linkage of the phase coil is 0.028 Wb, and the no load back EMF of phase coil is 61.2 V at the rated speed of 3600 rpm. Hence, according to (5), the electromagnetic torque is 1.8 Nm at the rated current.

IV. Performance Validation by Finite Element Method

Though the simplified magnetic network method can predict the motor performance initially, the accurate performance should be validated by using the FEM package ANSOFT. In this part, all the parameters predicted by the magnetic network method will be validated by the ANSOFT. The flux density, flux linkage, back EMF and electromagnetic torque will be analyzed.

In the performance prediction by ANSOFT, the complete one disk FEM model is built and the nonlinear magnetization curve of SMC is considered.

A. *Flux density analysis*

Fig. 3 shows the air gap flux density at the radial direction. It can be seen that the maximum air gap flux density is 0.42 T. For comparison, in the simplified magnetic network model, the maximum air gap flux density is 0.405 T.

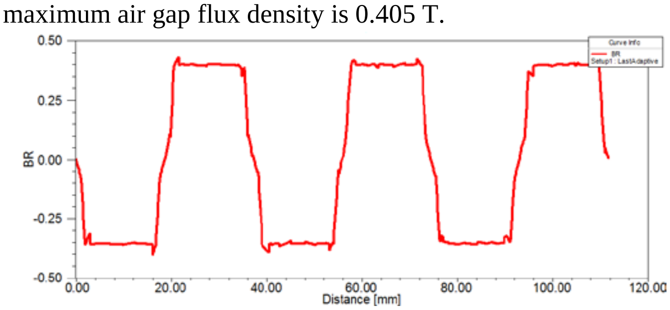

Fig. 3. Air gap flux density of the motor in the radial direction

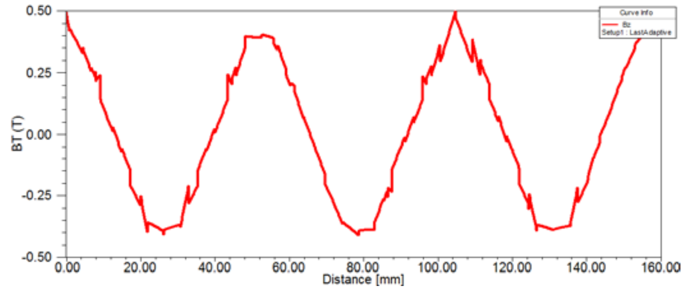

Fig. 4. Stator yoke flux density of the motor

Fig. 4 illustrates the flux density at the tangential direction in the stator yoke. It shows that the maximum flux density of the stator yoke at the no load is 0.5 T. For comparison, in the magnetic network method, the value is 0.58 T.

B. *Flux linkage and back EMF analysis*

EMF is produced in the armature coil as the rotor rotates. By differentiating the flux linkage, the phase back EMF can be calculated. Fig. 5 shows the flux linkage per phase winding of the motor against the time, and Fig. 6 shows the back EMF of the phase winding when the rotor rotates at 3600 rpm. It can be seen from the figure that the magnitude of the flux linkage is 0.0316 Wb, and the magnitude of the back EMF is 59 V. It can also be seen that the back EMF has many harmonics.

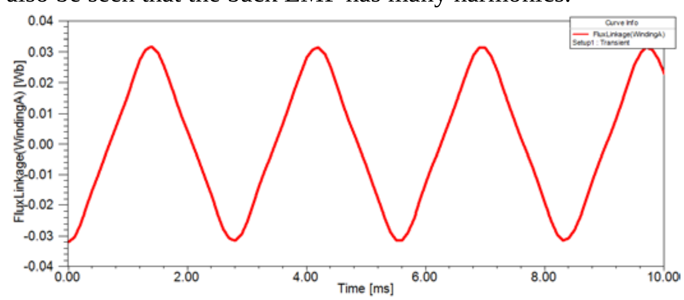

Fig. 5. Flux linkages of the motor

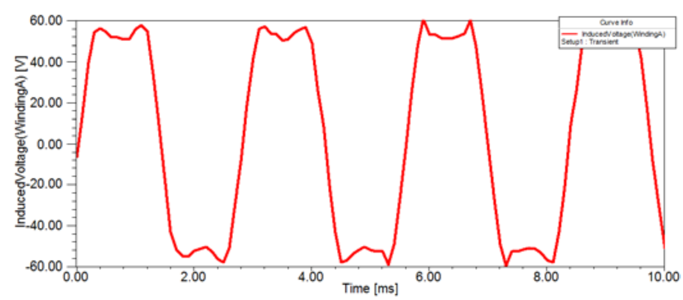

Fig. 6. Back EMF of the motor at the speed of 3600 rpm

V. Performance Prediction of The Motor

A. *Torque prediction*

In the performance prediction of a motor, the control method should be taken into consideration. In this paper, the condition that the d-axis current equals zero is applied. By using this control method, only the electromagnetic torque is worked out. Fig. 7 shows the equivalent electric circuit of this motor.

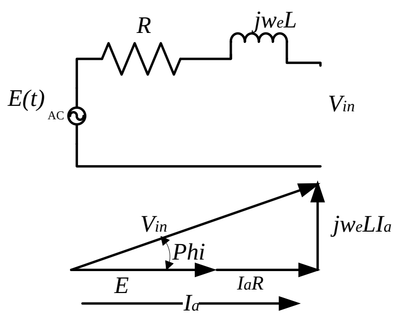

Fig. 7. Equivalent electric circuit of the motor

Based on this equivalent electrical circuit, the main relationships of the motor can be predicted by

$$V_{in} = \sqrt{(E + I_a R)^2 + (\omega_e L I_a)^2} \tag{6}$$

$$P_{in} = 3 V_{in} I_a \cos(Phi) \tag{7}$$

$$P_{out} = P_{in} - P_{core} - P_{copper} - P_{mech} \tag{8}$$

$$T_{out} = \frac{P_{out}}{\omega_r} \tag{9}$$

where V_{in} is the input voltage, E the back EMF, I_a the armature current, ω_e the electric angular frequency, L the inductance, R the resistance, *Phi* angle, P_{in} input power, P_{out} output power, P_{core} the core loss, P_{copper} the copper loss, P_{mech} the mechanical loss, T_{out} the output torque, and ω_r the mechanical angular speed.

The output torque is illustrated in Fig. 8. It only shows the output torque of a single disk of the motor. Therefore, the output torque of the motor should be multiplied by 3.

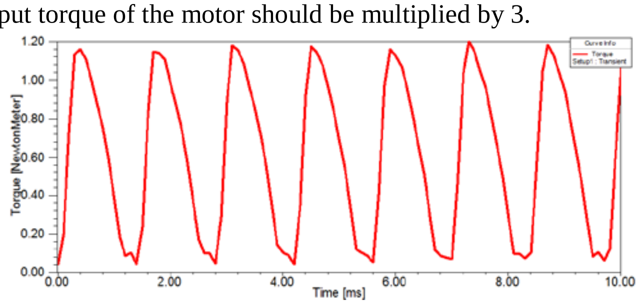

Fig. 8. Output torque of one disk with the phase current of 5A

B. Efficiency analysis

In the electric motor, the losses can be classified as core loss, copper loss and mechanical loss as expressed in (8). In the motor with SMC core, the core loss is the major part among these losses, and the mechanical loss is generally considered as 1% or 1.5% in the total output power. In the ANSOFT, the multi-frequency core loss curve is used to analyze the motor core loss. Its core loss of the single disk at the 3600 rpm is plotted in Fig. 9. The copper loss can be estimated by

$$P_{copper} = mRI_a^{\ 2} \tag{10}$$

where R is the resistance, which can be calculated by the resistance formula. The resistance of this motor is 0.396 ohm. Hence, the copper loss is 14.85 W. Then, the efficiency can be calculated by

$$\eta = \frac{P_{out}}{P_{out} + P_{mech} + P_{core} + P_{copper}} \tag{11}$$

The efficiency is calculated as 82% at the rated speed and rated power.

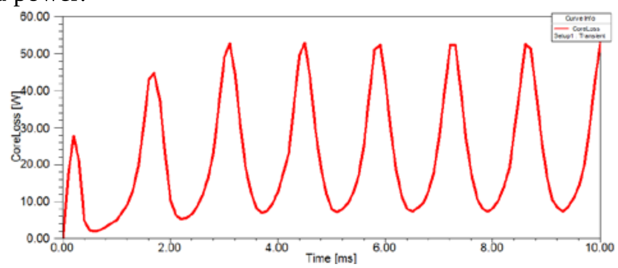

Fig. 9. Core loss prediction at the speed of 3600 rpm

The parameters of the CPM are listed in Table 3, which will be used to judge the motor performance.

TABLE III
BASIC PARAMETERS OF THE CPM

Inductance	2.3 mH
Resistance(phase)	0.396 ohm
PM flux linkage	0.0316 Wb
EMF constant (phase)	17.54 V/krpm
Torque constant	0.252 Nm/A

$$T_{em} = T_c I_a \tag{12}$$

$$E_m = E_c \omega_r \tag{13}$$

where T_{em} is the electromagnetic torque, T_c the torque constant, I_a armature current peak value, E_m the back EMF, E_c the EMF constant, and w_r the mechanical angular speed.

C. Cost evaluation

In the motor with SMC core and ferrite magnets, the material cost and manufacture cost can be reduced greatly. Furthermore, in a motor with SMC core, the material cost takes the major part. Consequently, only the material cost is considered in this paper. The material cost is based on following material prices. The coil is considered to be AUD $6 per kilogram, SMC is considered to be AUD $1 per kilogram, and ferrite magnet is considered to be AUD $2 per kilogram. The total materials cost of this motor is AUD $9.8.

VI. CONCLUSION

A novel claw pole PM motor with SMC core and ferrite PM is proposed and designed in this paper. By taking the PM flux concentrating rotor structure, the air gap flux density at the radial direction of this motor can reach 0.5 T. Therefore, the cheap ferrite PM can replace the rare earth PM in this CPM, and the material cost of this motor is only AUD $9.8. A 675 W 1.8 Nm CPM is designed and analyzed in this paper. With the help of SEMNM and FEM package ANSOFT, the magnetic parameters have been calculated. By applying the condition that the d-axis current equals 0, the output torque is predicted to be 1.8 Nm, and the efficiency is predicted to be 82%. It shows that this motor can meet the design targets.

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