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An Equivalent Circuit Model for Predicting Core Loss in a Claw Pole Permanent Magnet Motor with Soft Magnetic Composite Core

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Soft magnetic composite (SMC) materials and SMC electromagnetic devices have attracted strong research interest in the past decades. However, SMC devices have large core loss, which needs to be put into consideration even at the design stage. Effective and accurate prediction of core loss becomes crucial for design and optimization of high-performance motors with these materials. Equivalent circuit model is a widely used method for machine analysis, due to the advantages in fast calculation with clear physical mechanism. This paper presents an equivalent circuit model to predict core losses of a claw pole permanent magnet motor with an SMC stator core. All the parameters including core loss resistance in the equivalent circuit model are identified based on finite element method to achieve high accuracy, and the effectiveness of the parameters identification method is experimentally verified. The proposed equivalent circuit model can predict core loss and motor's performance efficiently both in no-load and loading conditions.

Index Terms—Soft magnetic composite materials, claw pole motor, core loss, equivalent circuit model, finite element method.

I. INTRODUCTION

Soft magnetic composite (SMC) material is formed by surface-insulated iron powder particles, and possesses a number of advantages, including isotropic magnetic and thermal properties, low eddy current loss and relatively low total core loss at medium and higher frequencies, net-shape fabrication process with smooth surface and good finish, and prospect of very low cost mass production [1]. Due to its powder nature and isotropic magnetic property, SMC material is suitable for construction of electrical machines of three-dimensional (3D) magnetic fluxes and complex structures, for which it is almost impossible or very difficult to use laminated steels. In the past decades, many investigations have been made to explore SMC material in different types of motor, such as claw pole motor [2], [3], transverse motor [4], [5], axial flux motor [6], [7], universal motor [8], [9] and so on. This paper will explore the equivalent circuit model for predicting core losses in a claw pole permanent magnet (PM) motor with SMC core.

There are three main types of loss in rotational electrical machines, namely the mechanical loss caused by the friction with air and between mechanical parts, the copper loss due to coil resistance, and the core loss caused by the variation of the magnetic flux in the core parts [10]. To be more specific, mechanical loss is related to the motor's rotating speed, and this is an uncontrollable component. In this research, we just discuss the electrical loss i.e. copper loss and core loss. The core loss can also be divided as three parts: hysteresis loss, eddy loss, and anomalous loss or excess loss. Generally, machines are designed for full-load operation where copper loss is dominant. Thus, core loss is usually neglected in equivalent circuit models [11]-[13]. However, core loss

gradually takes the dominance in the total machine power loss as the load decreases. Moreover, core loss is crucial for high-speed motors because the core loss may be the dominant component of power loss when motors operate in high frequency. Therefore, core loss needs to be precisely calculated for high performance design and good control strategies.

Equivalent circuit model is a widely used method for electrical machine analysis, because it provides good analysis results with fast calculation. Generally, in equivalent circuit model, the total core loss including hysteresis loss, eddy loss and anomalous loss is modeled as one resistance in parallel with the magnetizing branch. According to the past publications, the major researches estimate the parameters of electrical machines including the equivalent core loss resistances from standard machine characterization tests, namely the DC test, no-load test and locked-rotor test [14]-[21]. A small part of researches estimate the core loss resistance from tedious mathematical formulation, and these methods more or less rely on experimental tests or with specific conditions [22], [23].

In this paper, the identification method which is based on finite element method (FEM) is applied to calculate the parameters of equivalent circuit model, without motor characterization tests. Moreover, it is well known that core loss is not only caused by the fundamental but also by the higher harmonics presented in the flux density. Another advantage of this method is to take harmonic components into account when calculating the core loss by summing up contributions from each order of harmonic. Thus, the proposed equivalent core loss resistance identification method can give a rather good estimation of the core loss in the claw pole permanent magnet (PM) motor with SMC core. In addition, compared with other core loss calculation methods, such as FEM, the main advantage of using an equivalent circuit model to predicting core loss is that it can provide results with fast

calculation and clear physical mechanism. It is flexible with changing loading conditions changing and various operation conditions. Also, a comprehensive equivalent circuit model including core loss lays a solid foundation for advanced motor control strategies which help increase the efficiency of motor. Finally, the proposed equivalent circuit model can be easily extended to other similar machines.

II. STRUCTURE AND DIMENSIONS OF CLAW POLE PM MOTOR WITH SMC CORE

In order to investigate the performance of the material, a PM claw pole SMC motor prototype was designed and fabricated at University of Technology Sydney in 2005 [24]. This motor is of the outer rotor structure, and the structure of the claw pole SMC motor is shown in Fig. 1. The outer rotor consists of a mild steel case, three arrays of NdFeB magnets for three phases, and two aluminum end plates. Since the flux density in the yoke is almost constant, mild steel is used for the construction of rotor. The stator has three stacks with an angular shift of 120 electrical degrees from each other. Each stator phase has two pieces of SMC claw pole discs and a single concentrated coil, which is housed between two claw pole discs.

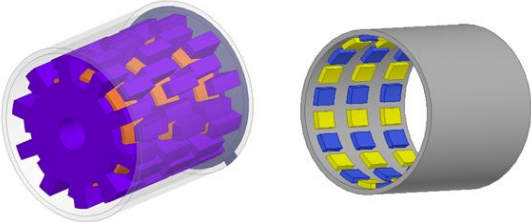


Fig. 1. The structure of the claw pole SMC motor

III. EQUIVALENT CIRCUIT MODEL FOR PREDICTING CORE LOSSES IN STEADY-STATE CONDITIONS

Using equivalent electric circuit is a common way to predict the motor performance in the area of electrical machine design and analysis. The machine is represented by lumped parameters such as rotational electromotive force (EMF), resistances and inductance. Taking phase A as an example, the electrical circuit equation for per-phase of claw pole PM motor can be written by the Kirchoff's voltage law as:

$$v_a = R_s i_a + d\lambda_a / dt \quad (1)$$

where v_a and i_a are the terminal voltage and phase current of the claw pole PM motor, R_s is the stator winding resistance, and λ_a the flux linkage of phase winding, which can be expressed in terms of the self and mutual inductances as following:

$$\lambda_a = \lambda_{aa} + \lambda_{ab} + \lambda_{ac} + \lambda_{af} = L_{aa} i_a + L_{ab} i_b + L_{ac} i_c + \lambda_{af} \quad (2)$$

where L_{aa} is the self-inductance of stator winding, L_{ab} and L_{ac} are the mutual inductances of stator windings, and λ_{af} is the flux linkage generated by permanent magnets.

Because of the independent magic circuit of each stack in the claw pole PM motor, the mutual inductances between phase windings, L_{ab} and L_{ac} , can be considered as zero. Furthermore, due to the small amount, the leakage inductance is also neglected in this analysis, so the above equation can be written as:

$$\lambda_a = L_{aa} i_a + \lambda_{af} = L_s i_a + \lambda_{af} \quad (3)$$

where $L_s = L_{aa}$ is known as the synchronous inductance of the claw pole PM motor.

Substituting the above expression of flux linkage into the circuit equation (1), one can obtain:

$$v_a = R_s i_a + L_s \frac{di_a}{dt} + \frac{d\lambda_{af}}{dt} \quad (4)$$

In steady state, (4) can be expressed in terms of voltage and current phasors as:

$$\mathbf{V}_a = \mathbf{E}_a + (R_s + j\omega L_s) \mathbf{I}_a = \mathbf{E}_a + (R_s + jX_s) \mathbf{I}_a \quad (5)$$

where $X_s = \omega L_s$ is known as the synchronous reactance, \mathbf{E}_a the induced back EMF, and ω the angular frequency.

When running in synchronous mode, according to (5), the claw pole PM motor's steady-state performance for a single-phase can be predicted by the equivalent circuit model as shown in Fig. 2. In order to predict core loss, a core loss resistance R_c is added, and the magnitude of core loss resistance does not remain constant within the operating frequency range. In the equivalent circuit model of electrical machine, the power consumed by the equivalent core loss resistance R_c represents the core loss in core material, while the power consumed by the stator winding resistance R_s simulates the copper loss of electrical machine. Although the general practice of mathematical model of core loss is to separate the total core loss into hysteresis loss, eddy loss, and anomalous loss or excess loss, in this proposed equivalent circuit model, the core loss is evaluated together and just one resistance is used to model the total core loss.

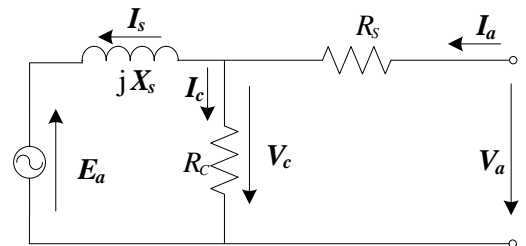


Fig. 2. Per-phase equivalent circuit including core losses

IV. PARAMETERS IDENTIFICATION OF EQUIVALENT ELECTRIC CIRCUIT

A. 3-D Magnetic Field Analysis

Considering the almost magnetic independence and

structural symmetry, only one pole pitch of one stack of the motor needs to be calculated. Fig. 3 illustrates the no-load magnetic flux density vector distribution. The major path of the PM flux is along one of the PMs – the main air gap – half of the SMC claw pole stator core disk – the stator yoke – another half of SMC claw pole stator core disk – main air gap – another PM and then – the mild steel rotor yoke to form a closed loop.

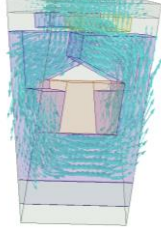


Fig. 3. Plots of magnetic flux density vectors

B. Back EMF

The flux waveform linking a stator phase winding produced by the rotor PMs can be calculated by rotating the rotor magnets for one pole pitch in steps. When the rotor rotates, the flux linking the stator winding varies and an EMF is induced. In this claw pole PM motor, the flux waveform is almost perfectly sinusoidal versus the rotor position. The induced stator EMF can be determined by:

$$E = 4.44 fN\phi_m \quad (6)$$

where f is the frequency of the induced stator EMF, N the number of turns of the stator winding, and ϕ_m the magnitude of the magnetic flux linking the stator winding. At 1800 rpm (300 Hz), $E=48.9\text{V}$, and the values of EMF are proportional to rotor speeds.

C. Winding Inductances

The behavior of an electrical circuit is governed by the incremental inductance rather than the secant inductance [25]. When considering the non-linear characteristic of the core material, which is the case for changing loading conditions, using the secant inductance to analyze the performance of electrical machines is less reasonable. Since the principle of FEM is based on the minimization of magnetic field energy, choosing energy method i.e. calculating the energy or co-energy stored in all the elements to evaluate inductances is considered as quite accurate. Thus, a modified incremental energy method for calculation of the phase winding incremental inductance of the claw pole motor is used [26]. However, in the case of PM machines, the magnetic field is generated not only by winding currents but also by permanent magnets, and the former one just accounts for a small account. According to the modified incremental energy method, the self-incremental inductance can be computed by:

$$L(\theta) = 2W_c(\Delta i, \theta)/(\Delta i)^2 \quad (7)$$

where W_c is the magnetic co-energy, Δi the current perturbation.

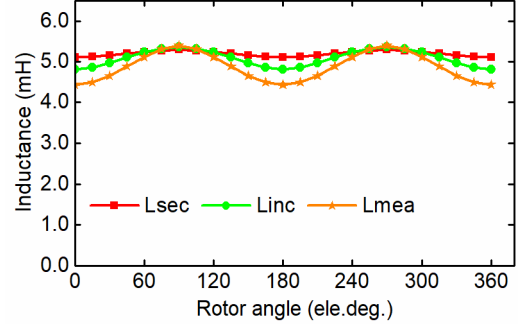


Fig. 4. Self-incremental, secant, and measured inductances

Fig. 4 shows the computed self-incremental inductance as well as the computed secant inductance and measured inductance of one phase winding at different rotor positions. Since the fluctuation of the values of inductances is not significant, for simplification, the phase winding inductance can be considered as a constant, e.g. the average value over a variation cycle. Therefore, the average value of a phase winding's self-inductance can be computed as $L=5.24\text{ mH}$. At the rated operational frequency 300 Hz, the synchronous reactance of the stator winding can be calculated as $X_s=2\pi f_1 L_s=9.88\ \Omega$.

D. Stator Winding Resistance

The stator winding resistance can be calculated by:

$$R = \rho l/A \quad (8)$$

where l is the total wire length, A the wire cross sectional area, and ρ the electrical resistivity of the stator winding.

At the rated winding temperature of 115 °C, representing a temperature rises of 75 °C above an ambient temperature of 40 °C, the resistance is calculated as 0.302 Ω.

E. Core Loss Resistance

As electrical machine rotates, the flux density locus at one position can be alternating (1D), two-dimensional (2D) or even 3D rotating with purely circular or elliptical patterns [27]. In general, the locus, calculated by 3-D magnetic field time-stepping FEM, in each element is an irregular loop in 3-D space, while other loops can be seen as special cases of the 3-D loop. Therefore, the core loss in an element can be computed as [27]:

$$P_k = P_{rk} R_{Bk} + (1 - R_{Bk})^2 P_{ak} \quad (9)$$

where P_{ak} is the alternating core loss, while P_{rk} the circular rotating core loss. B_{kmaj} and B_{kmin} are the major axes and minor axes of an elliptical flux density loci, and $R_{Bk} = B_{kmin}/B_{kmaj}$.

Furthermore, the total core loss in the SMC core can be computed by [28]:

$$P_t = \sum_{e=1}^{N_e} \sum_{k=0}^{\infty} [P_{rk} R_{Bk} + (1 - R_{Bk})^2 P_{ak}] \quad (10)$$

where N_e is the number of elements of the SMC core when performing the magnetic field FEM.

In no-load condition, the calculated core loss based on FEM of the motor at different speeds is illustrated in Table I.

TABLE I
CALCULATED CORE LOSS OF CLAW POLE PM MOTOR

Speed (rev/min)	Core Loss (W)
300	9.7
600	18.5
900	27.8
1200	38.5
1500	47.6
1800	56.5

The motor is assumed to operate in the optimum brushless DC mode, i.e. I_a in phase with E_a . The test rig of the claw pole PM motor is shown in Fig. 5. A printed circuit disc armature DC machine is connected via a torque transducer as the driver when the prototype is operated as a generator or the load when the prototype is operated as a motor.

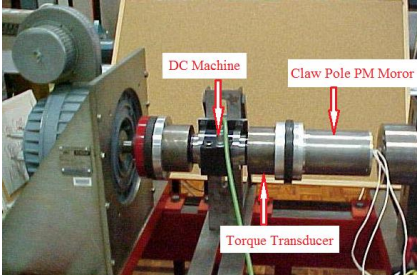


Fig. 5. Test rig of a claw pole PM motor

The core loss can be measured by separating the core loss from the mechanical loss. The calibrated DC motor is used as a prime mover to measure the core loss of the claw pole PM machine. The power feeding the DC motor would be the sum of core loss and mechanical loss (friction and windage) of both the DC motor and the claw pole PM motor. Subtracting the losses of the DC motor yields the core loss and mechanical loss of the claw pole PM motor alone. The mechanical loss of the claw pole PM motor is measured by replacing the stator of the claw pole PM motor with a wooden tube (to imitate the windage), and then repeating the previous test procedure. Therefore, the core loss of the claw pole PM motor is obtained by subtraction of the mechanical loss from the sum of the core loss and mechanical loss. The comparisons between measured core loss and calculated core loss based on FEM at different speeds in no-load steady-state conditions are shown in Fig. 6. The calculated core loss is about 7% lower than the measured, which may be caused by the measurement error and some addition loss ignored in calculation. The experimental results also suggest the effectiveness of the proposed core loss computation method, and the equivalent core loss resistance identification method based on the above calculation is

accurate. The details about how to estimate values of equivalent core loss resistances are shown below.

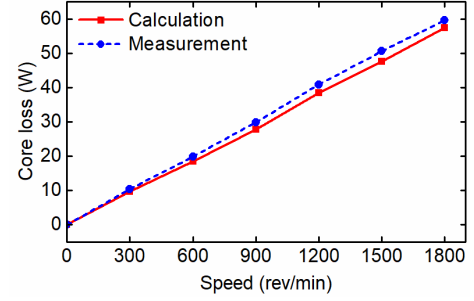


Fig. 6. Core loss measurement and calculation

According to Fig. 2, when the motor operates in no-load condition, I_a is considered as zero, then V_c and equivalent core loss resistance R_c can be calculated as:

$$V_c = E_a \quad (11)$$

$$R_c = 3V_c^2 / P_t \quad (12)$$

where V_c is the magnitude of the voltage across the core loss resistance, P_t the calculated core loss based on FEM.

The variation of core loss resistance R_c with respect to the motor speed is shown in Fig. 7. It is obvious that the values of R_c vary almost in proportional to the rotor speeds (frequencies). This agrees with the dominant hysteresis loss of SMC, which is proportional to the excitation frequency. Then, we can conclude an equation for calculating equivalent core loss resistance by curve-fitting as:

$$R_c = 0.0702n \quad (13)$$

where n is the rotor speed of claw pole PM motor.

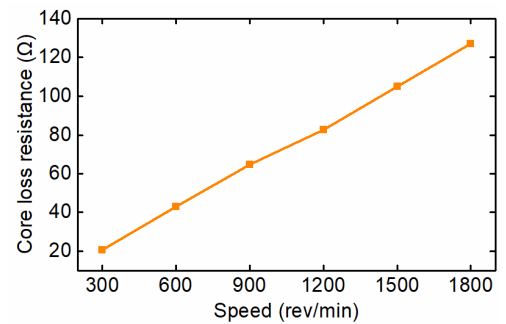


Fig. 7. Core loss resistance R_c with respect to motor speed

V. PERFORMANCE ANALYSIS BASED ON THE PROPOSED EQUIVALENT CIRCUIT MODEL

The motor is assumed to operate in the optimum brushless DC mode, i.e. I_s in phase with E_a , so that the electromagnetic power and torque can be obtained by:

$$P_{em} = 3E_a I_s \cos \varphi = 3E_a I_s \quad (14)$$

$$T_{em} = P_{em} / \omega \quad (15)$$

where φ is angle between phasors E_a and I_s , and in the optimum brushless DC mode, $\varphi=0$.

In this claw pole PM motor, the electromagnetic torque is a constant in the speed range as: $T_{em}=0.273$ Nm.

Since the armature reaction in SMC motor is quite small and it will not demagnetize the magnets, the calculated equivalent core loss resistance R_c by (13) can be used to predict core loss in loading conditions, i.e. phase current $I_a > 0$, then the core loss and copper loss can be predicted by:

$$V_c = E_a + jX_s I_s \quad (16a)$$

$$P_{core} = 3V_c^2 / R_c \quad (16b)$$

$$I_a = \frac{1}{R_c} E_a + (1+j\frac{X_s}{R_c}) I_s \quad (16c)$$

$$P_{copper} = 3I_a^2 R_s \quad (16d)$$

where V_c is the voltage across the core loss resistance, I_s the current through the synchronous inductance, and I_a the phase current of claw pole PM motor.

The output power, input power, and efficiency are calculated by:

$$P_{out} = P_{em} - P_{mech} \quad (17a)$$

$$P_{in} = P_{em} + P_{copper} + P_{core} \quad (17b)$$

$$\eta = P_{out} / P_{in} \times 100\% \quad (17c)$$

where P_{mech} is the mechanical loss including windage and friction. In this claw pole PM motor, mechanical loss is assumed as 3% of output power approximately.

The efficiency and output power of the claw pole motor with respect to the percent of rated speed are shown in Fig. 8. The output power is proportional to the percent of rated speed, while the efficiency of motor rises significantly in low speed range and goes up slightly in high speed range, and reaches 85% at the rated speed.

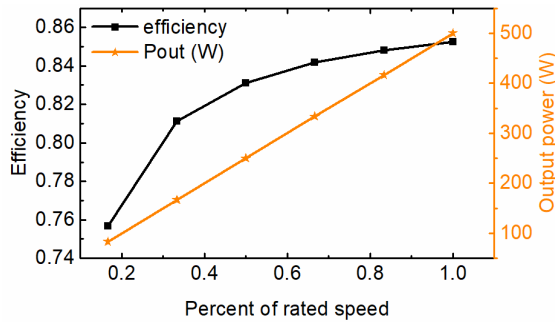


Fig. 8. Efficiency and output power with respect to the percent of rated speed

VI. CONCLUSION

This paper establishes the equivalent circuit model for predicting core loss in a claw pole PM motor with soft magnetic composite core. All the parameters within the equivalent circuit model including the core loss resistance are determined based on finite element method, which is efficient and accurate, particularly at the design stage. Experimental verification of the core loss of claw pole PM motor has indicated that the proposed parameter identification methods are practical and with good accuracy. Then this circuit model can be used to predict the core loss in both no-load and loading conditions, and the performance analysis has been done for a claw pole PM SMC motor based on the proposed equivalent circuit model. This approach can also be extended to other PM SMC motors.

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