A Permanent Magnet Synchronous Motor Model with Core Loss

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This paper presents an improved model of permanent magnet synchronous motors (PMSMs) considering core losses. The core losses of a surface mounted PMSM were measured at no-load and load, and the analysis on experimental results shows that the core losses in a PMSM can be attributed to the components produced by the rotor permanent magnets and the stator currents. The conventional equivalent circuit model of PMSM with core loss can account for the former but not the latter, and therefore, an additional core loss resistor is required to account for the additional core loss component due to the armature reaction. The nonlinear resistance for the no-load core loss is explained from the core loss model of magnetic materials. The method to determine these core loss resistances from the no-load and load tests is also presented. The relation between the core loss components and the corresponding resistors is clearly demonstrated by the analysis of experimental results.

Key Words: Permanent magnet synchronous motor model, Core loss

1. Introduction

The permanent magnet synchronous motor (PMSM) can be a serious competitor to the conventional DC and induction motors in servo applications due to its high power density, torque to current ratio, and efficiency. The model of PMSM is concerned by many researchers because it is important in motor performance analysis and drive system design. In addition, the performance of a PMSM drive system is considerably influenced by the accuracy of the model.

The core loss or iron loss, caused by the permanent magnet (PM) flux and armature reaction flux, is a significant component in the total loss of a PMSM, and thus, it can have a considerable effect on the PMSM modeling and performance prediction. This paper proposes a model of PMSM taking into account the stator core losses. No-load and load tests were carried out to determine the total core and mechanical loss of a PMSM, which was then separated by fitting the experimental results to their physical models. The relationship between the core loss resistor R_{c1} and the internal voltage V_i is estimated by the curve fitting of the no-load results. With the load test results, the conventional PMSM model is modified by adding an extra resistor, R_{c2}, to account for the effect of armature reaction on the core loss. The values of R_{c2} are determined by the analysis of the PMSM operational states. Finally, the modified equivalent circuit and the core loss mechanisms are discussed.

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2. Experimental Study of Core Losses in PMSM

The core losses of a surface mounted PMSM were measured with and without load. In order to obtain the core loss, some electrical and magnetic parameters of the motor, such as the magnetizing flux linkage produced by rotor PMs, stator winding resistance and inductances are required. Experiments are firstly conducted to measure these parameters.

The magnetizing flux linkage λ_m is obtained by measuring the phase voltage by the open circuit test, and the synchronous inductance L_{syn} is measured by the short circuit test. In order to find out the leakage inductance L_l, the mutual inductance, L_m, between different phases is measured by exciting one of the three phases of the motor. The experimental results are: λ_m= 0.118 Wb, L_{syn} = 12.8 mH, L_m = 3.29 mH. The stator winding resistances at various temperatures are measured by the V-A method in an environmental chamber. The relationships between the phase resistances and motor temperature are obtained as: R_U = 1.579(1+0.004033T), R_V = 1.584 (1+0.004017T), and R_W = 1.602(1+0.003946T), where T is the temperature in Celsius.

2.1 No-load test

The test system for measuring the core losses contains the PMSM and a DC motor coupled with a torque meter. The PMSM, as a generator, is driven by the DC motor at various speeds by adjusting the armature voltage of the DC motor. Through a power flow analysis, the following power balance equation can be obtained

$$P_{in} = P_{Cu} + P_c + P_{mech} + P_{out} \quad (1)$$

where the input power $P_{in} = T_m\omega_r$, T_m is the measured shaft torque, ω_r the angular speed, and the copper loss $P_{Cu} = \Sigma I^2 R$. Under no load, the output power $P_{out} = 0$, and therefore, the sum of the core loss P_c and mechanical loss P_{mech} can be obtained by $P_c+P_{mech} = P_{in}-P_{Cu}-P_{out}$. Fig. 1 shows the experimental result of (P_c+P_{mech}) versus rotor speed in rpm.

2.2. Load test

Further experiment is carried out to investigate the core loss of a PMSM operated as a generator with different load currents. The test system is similar to that for the no-load test. Various resistive loads, such as 20, 30, 40, 50, 60, 75, 90, and 110 Ω, are connected to the PMSM, respectively. The experimental results of mechanical and core losses at various loads are also illustrated in Fig. 1.

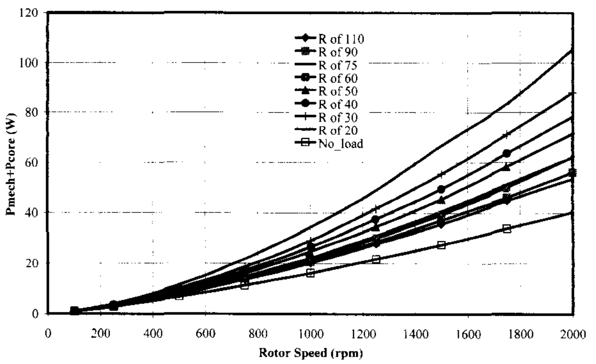

Fig. 1. (P_c+P_{mech}) measured by no-load and load tests

3. Conventional Core Loss Models

3.1 Core losses in magnetic materials

In a soft magnetic material, the total core loss P_c can be separated into hysteresis loss P_h and eddy current loss, which in practice can be calculated in terms of the classical eddy current loss, P_e, and the anomalous loss, P_a, and can be expressed as follows [1], [2].

$$P_c = P_h + P_e + P_a \quad (2)$$

Under the excitation of a circular rotating field in the steady state, it can be expressed as

$$P_c = P_{hr} + 2C_e(fB)^2 + C_a(fB)^{3/2} \quad (3)$$

where B is the peak value of the flux density vector, f the frequency, C_e and C_a are the coefficients which can be determined by experiment, and P_{hr} the rotational hysteresis loss.

3.2 Conventional model of PMSM with core losses

Among the power losses in a PMSM, the core loss P_c is a significant but difficult component to determine. Fig. 2 illustrates a per-phase equivalent circuit of PMSM commonly used to account for the core loss [3], [4].

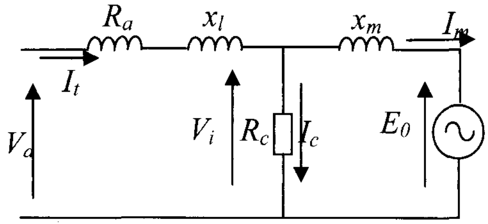

Fig. 2. Per-phase equivalent circuit with core loss

3.3 Curve fitting of experimental results under no-load condition

The mechanical loss and the core loss measured under no-load can be separated by the following method. The mechanical loss is generally a function of the rotor speed, and can be expressed as $P_{mech} = a_1\omega_r + a_2\omega_r^2 + a_3\omega_r^3$, where a_1, a_2, and a_3 are constant coefficients. The core loss, on the other hand, can be related to the internal voltage V_i, which is proportional to the product of frequency and magnetizing flux linkage, *i.e.* $f\lambda_m$, or fB since λ_m is proportional to B. Therefore, considering (3) and $P_{hr} = C_h f B^h$, where h is a constant, we have

$$P_c + P_{mech} = C_h f^{1-h} V_i^h + C_e V_i^2 + C_a V_i^{3/2} + a_1\omega_r + a_2\omega_r^2 + a_3\omega_r^3 \quad (4)$$

The coefficients in (4) can be determined by the least square curve fitting of the experimental results, and hence the mechanical and core losses can be mathematically separated. From the no-load test results in Fig. 1, these coefficients are determined as: $C_h = 1.00\times10^{-8}$, $h = 1.8$, $C_e = 1.582\times10^{-5}$, $C_a = 3.795\times10^{-2}$, $a_1 = 1.516\times10^{-1}$, $a_2 = 2.727\times10^{-5}$, and $a_3 = 6.075\times10^{-7}$. Fig. 3 plots the separated core and mechanical losses versus rotor speed.

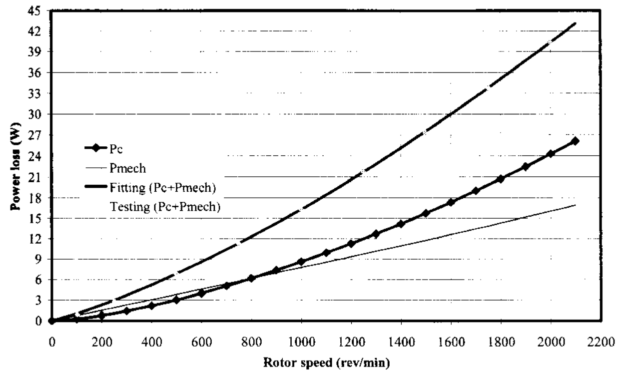

Fig. 3. Separation of no-load mechanical and core losses

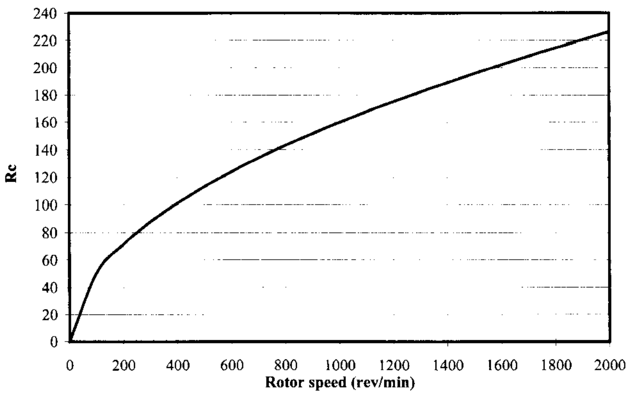

Fig. 4. Core loss resistance versus speed

The core loss resistor R_c is then calculated by

$$R_c = {3V_i^2}/{P_c} \tag{5}$$

using the core loss obtained by the loss separation procedure, and the result is plotted in Fig. 4.

Since the motor flux density and rotor speed are reflected by the internal voltage V_i under the no-load condition, R_c can be expressed as a function of V_i. As it varies significantly with respect to the flux density distribution in the motor, which affects V_i, the core loss resistance R_c cannot be regarded as a constant.

4. Core Loss Model of PMSM with Load

When the PMSM is loaded, the field distribution is distorted by the stator currents, which generate an extra component of core loss as illustrated by the experimental results in Fig. 1. To account for the core loss component due to stator currents, an extra resistor R_{c2} was added to the per-phase equivalent circuit, as shown in Fig. 5 [4].

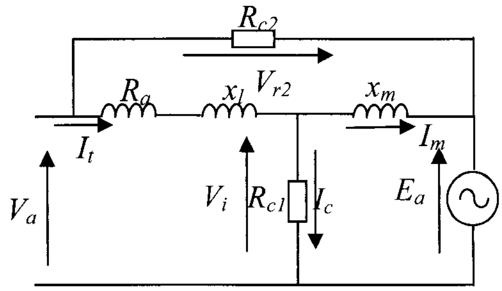

Fig. 5. Per-phase equivalent circuit considering core loss

In order to calculate the core loss resistor R_{c2}, the additional core loss component P_{c2} caused by armature reaction is obtained by subtracting the mechanical and core losses under no-load from those losses measured in the load testing. From the equivalent circuit shown in Fig. 5, we have

$$V_{r2} = E_a \cos\delta + jE_a \sin\delta - V_a \tag{6}$$

$$E_a = \omega\lambda_m \tag{7}$$

$$R_{c2} = {3V_{r2}^2}/{P_{c2}} \tag{8}$$

where $V_{r2} = V_a - E_a$ is the voltage across R_{c2}, ω the rotor speed in electrical rad/s, and δ the load angle. By neglecting the stator resistance, the load angle can be approximately estimated by

$$\sin\delta = \frac{P_{em}X_s}{3E_aV_a} \tag{9}$$

where P_{em} is the electromagnetic power obtained by subtracting the mechanical loss from the input power, and X_s the synchronous reactance.

Fig. 6 plots the additional core loss, P_{c2}, at different V_{r2} and rotor speeds, and Fig. 7 the calculated R_{c2} with respect to V_{r2} at different speeds. It is shown that both the additional core loss, P_{c2}, due to the armature reaction and the corresponding resistor, R_{c2}, are proportional to V_{r2} and independent of the rotor speeds.

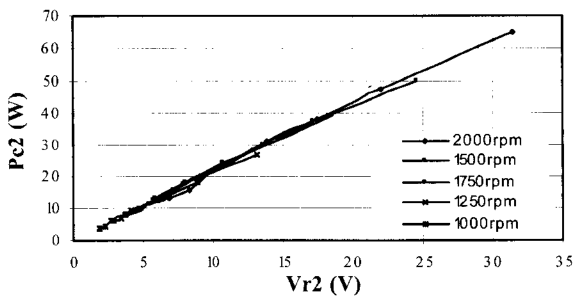

Fig. 6. Measured P_{c2} versus V_{r2} at different rotor speeds

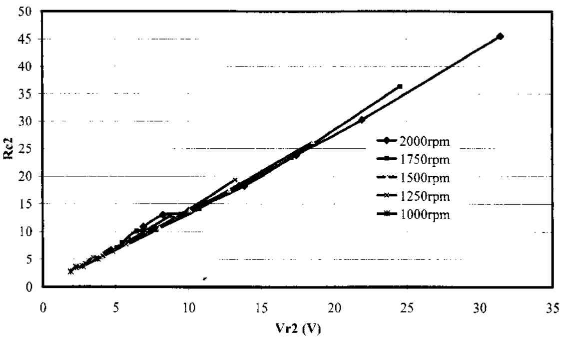

Fig. 7. R_{c2} versus V_{r2} at different rotor speeds

5. Discussion

In a PMSM, the total flux is composed of the fluxes produced by the rotor PMs and the stator currents. The finite element magnetic field analysis reveals that the magnetic field produced by the rotor PMs is distorted by the stator current flux, to some degree, and the distortion effects, such as saturation and demagnetization, vary with the stator current and rotor position. On the other hand, the load testing results show that the additional core losses caused by the stator flux cannot be simply represented by the variation of the internal voltage. This can also be observed from Figs. 6 and 7 as the variation of internal voltage, V_i, does not have effect on the additional core loss component and the corresponding resistance.

6. Conclusions

As revealed by the analysis of the experimental results of the no-load and load tests, the core loss in a PMSM can be attributed to the components produced by the rotor PMs (the no-load stator core loss) and the stator currents (the additional core loss component under load). The conventional equivalent circuit model of PMSM with core loss can account for the former but not the latter, and therefore, an additional core loss resistor is introduced to consider the addition core loss component due to the armature reaction. The nonlinear resistance for the no-load core loss is explained from the core loss model of magnetic materials. The method to determine these core loss resistances from the no-load and load tests is also presented. The relation between the core loss components and the corresponding resistances is demonstrated by the analysis of experimental results.

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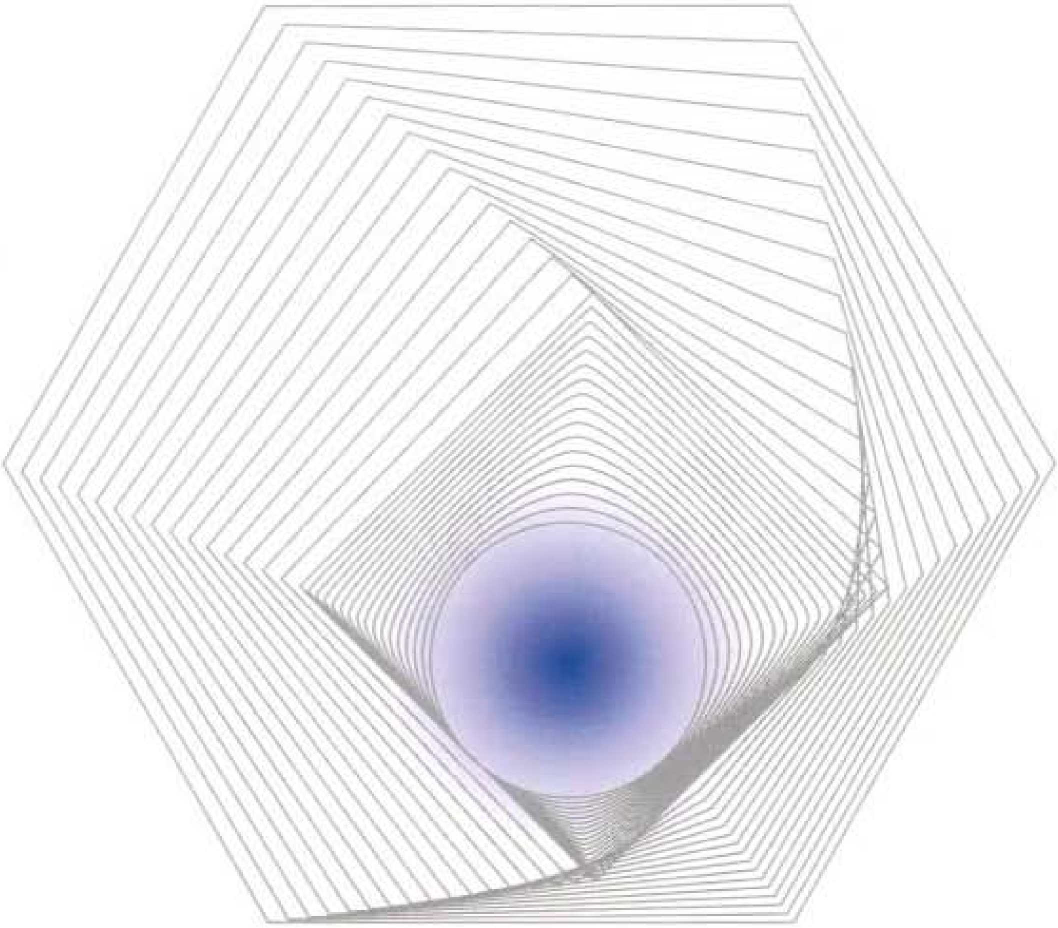

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