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The Maximum Efficiency Driving in IPMSM by Precise Estimation of Current Phase Angle

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Abstract – In this paper, the equivalent circuit for the efficiency calculation by precise estimation of the linkage flux, inductance and iron loss resistance was calculated accurately. In addition, the driving characteristics according to the current phase angle are analyzed and the maximum efficiency point is calculated. And then, analyzed and experimental values of the efficiency were compared. So, causes of error were expected to be vibration and noise by harmonic distortion of the voltage and current, and mechanical loss of dynamometer. In addition, the driving characteristics according to the current phase angle are analyzed and the maximum efficiency point is calculated.

Keywords: IPMSM, d, q-axis equivalent circuit, Iron loss resistance, Inductance

1. Introduction

IPMSM(Interior permanent magnet synchronous motor) offers a lot of advantages over the induction motor on the efficiency performance, control issue, etc. The recent progress in power electronic devices, rare earth PM (permanent magnet) material and motor control technology have allowed IPMSM to be widely used in various applications. Recently, much interest is paid to energy-saving technology for global protection of the circumstance of the earth. Improvement of efficiency for motors used in various applications is thus very important for the reason that motors swallow a large part of the electric energy consumed in the world nowadays [1, 2].

In the case of IPMSMs used for vehicles, because the voltage is very low, there are high current flows in comparison with industrial IPMSMs. Therefore, increasing efficiency is a very important research subject. Therefore, investigations of the maximum efficiency driving by current phase angle control are performed. Detailed estimation of the parameters of the IPMSM is required for this reason.

The characteristics of the IPMSM depend on the d, q-axis inductance. Therefore, accurate estimation of the d, q-axis inductance is very important. If the d, q-axis inductance and the iron loss resistance are precisely calculated, by using the equivalent circuit, the characteristics of the motor can be easily calculated.

The inductance test methods can be divided into two groups, tests that involve driving the rotor, Experiment for Rotate State(ERS), and tests that involve stopping the rotor, Experiment for Stop State(ESS). The ERS can be further divided into two methods, Current Vector Control Test(CVCT) and Generation Tests. Similarly, the ESS can be divided into two methods, Alternating Current Test (ACT) and Direct Current Test(DCT) [3, 4].

The efficiency of a motor was composed by input and output powers, however analysis and calculation were very difficult by using FEM(Finite Element Method) only. So, in this paper, the efficiency was calculated by d, q-axis equivalent circuit through the linkage flux, the inductance and the iron loss. Because, these non-linear parameters are mainly reason for precise computation of d, q-axis equivalent. The important parameters such as linkage flux, inductance and iron loss were verified by individual experiment. And then, the analyzed efficiency by d, q-axis equivalent circuit was verified the experiment.

2. Analysis model

Fig. 1 shows the core shape, division of elements and magnetic flux density in an analyzed model. Table 1 shows the motor specifications applied in this paper.

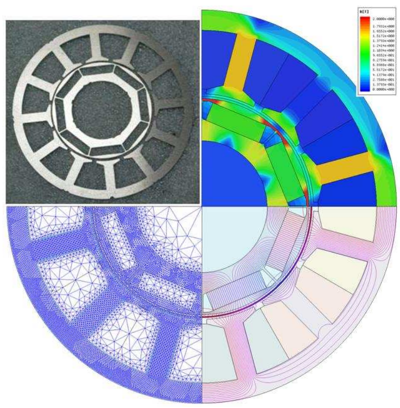

Fig. 1. Analysis model

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Table 1. The specifications of IPMSM

Item	Specification
Rated Speed (rpm)	3000
Rated Torque (Nm)	1.87
Pole/Slot	8/12
Air-gap Length (mm)	1
Winding Type	Concentrated winding
Br (T)	1.3
Stack Length (mm)	45
Stator Diameter (mm)	83.6
Resistance(ohm)@75˚C	0.0235

The motor used in this research has low-voltage and high-current characteristics because it is used inside vehicle. That is, it has different characteristics as compared with a general industrial motor. The turn of the stator winding is small in order to ensure that the back Electro-Motive-Force(EMF) is small. Therefore, because large diameter wire is used, the inductance is very small and large copper loss is generated.

3. L_d, L_q Equivalent Circuit of IPMSM

3.1 Equivalent circuit composition

$$i_{cd} = -\frac{\omega L_q i_{oq}}{R_c} \tag{1}$$

$$i_{cq} = \frac{\omega(\psi_a + L_d i_{od})}{R_c} \tag{2}$$

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_s \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1 + \frac{R_s}{R_c}\right) \begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} + \rho \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix}$$

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_a \end{bmatrix} \tag{4}$$

$$T = P_n \left\{ \psi_a i_{oq} + \left(L_d - L_q\right) i_{od} i_{oq} \right\} \tag{5}$$

$$W_c = R_s \left(i_d^2 + i_q^2 \right) \tag{6}$$

$$W_i = \frac{\omega^2 \left\{ \left(L_d i_{od} + \psi_a\right)^2 + \left(L_q i_{oq}\right)^2 \right\}}{R_c} \tag{7}$$

where i_d and i_q are the d, q-axis components of the armature current, i_{cd} and i_{cq} are the d, q-axis components of the iron loss current, v_d and v_q are the d, q-axis components of the terminal voltage, R_s is the armature winding resistance per phase, R_c is the iron-loss resistance, ψ_a is the flux linkage of PM per phase Root Mean Square(RMS), and L_d and L_q are the d, q-axis inductance [8].

The parameters required for the equivalent circuit composition are given in (1)~(7). W_c and W_i are the copper loss and iron loss [5, 9].

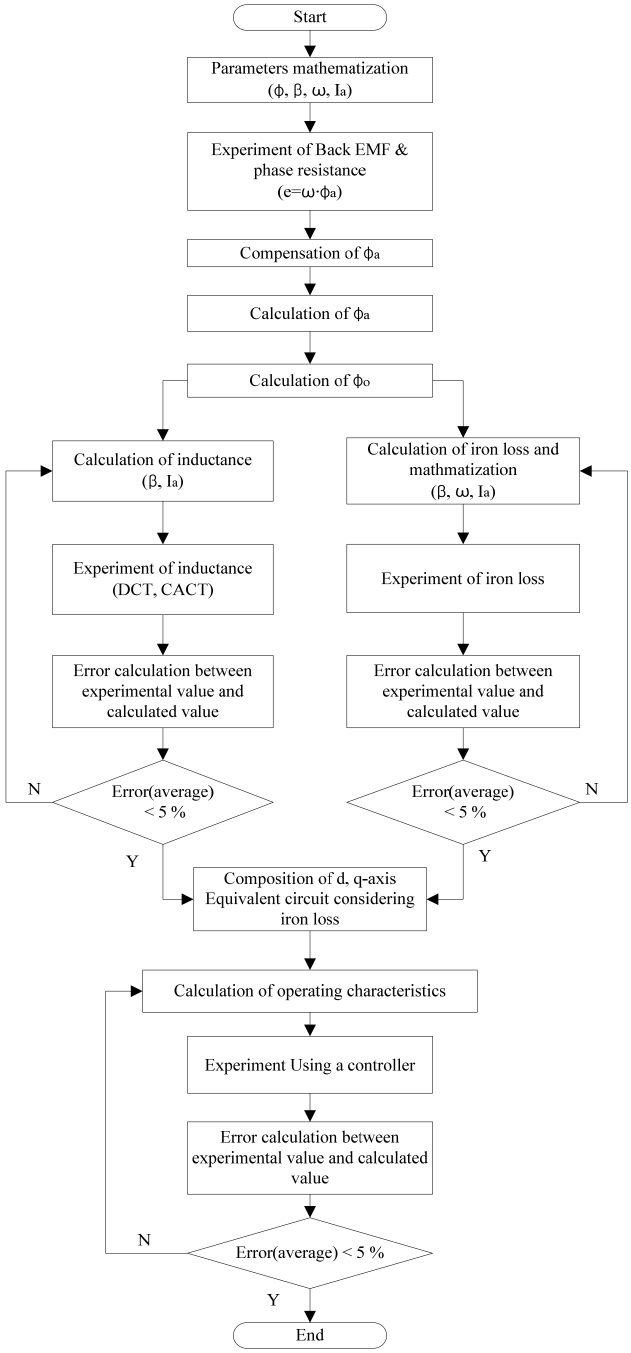

Fig. 2. Process of equivalent circuit composition

The major parameters calculation and verification process for efficiency calculation could be shown as Fig. 2. The inductance and iron loss had reliability when average error was fewer than 5%.

3.2 Calculation of the d, q-axis inductance

For verification of the d, q-axis inductance, two experimental methods were used. An iron loss is not generated in the DCT where the rotor is arrested. However, at current phase angles of 0° and 90° only, the inductance

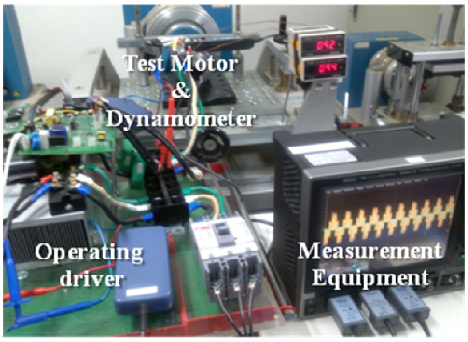

Fig. 3. CVCT experimental equipment

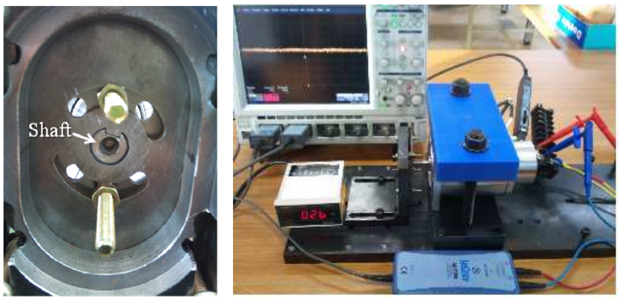

Fig. 4. DCT experimental equipment

calculation is available and the error is determined by the rotor alignment. Fig. 3 shows the experimental equipment of CVCT.

The CVCT in the driving state can calculate the inductance according to the change of the current phase angle. In addition, there is an advantage that separate equipment is not required for the inductance measurement besides the driver required for motoring. However, an error according to Pulse Width Modulation(PWM) drive of the controller is generated, due to consideration of the fundamental wave of the voltage and current [3, 4]. The average error of the inductance was as much as 2.92% for L_d and 4.5% for L_q. The experimental results of DCT at current phase angles of 0° and 90° are shown and very small error is obtained. In addition, regarding the d-axis error source, the magnetic circuit is relatively complicated and the lineup is more difficult than at the q-axis.

The average inductance was considered as average in torque calculation, because the controller needed fast response speed and operation speed. Fig. 5 shows inductance profile according to the current. The inductance was made by using CVCT and DCT. The inductance's propriety was verified through torque experiment according to current.

3.3 Estimation of the iron loss resistance

The iron loss is expressed as the iron loss resistance in the equivalent circuit. The stator was divided into 55 elements and the magnetic field of each region was analyzed. In addition, the iron loss data provided by the iron core manufacturer were re-arranged through the Curve Fitting Method(CFM) and the iron loss coefficient for the frequency was calculated in order to consider the change of the frequency [6]. The iron loss was calculated through a magnetic field behavior analysis [7, 10, 11].

Where k_h is the hysteresis loss coefficient, k_e is the eddy current loss coefficient, k_a is the abnormal eddy current loss coefficient, and f is frequency. The iron loss experiment device and the experimental results are shown in Fig. 6 and Table 2.

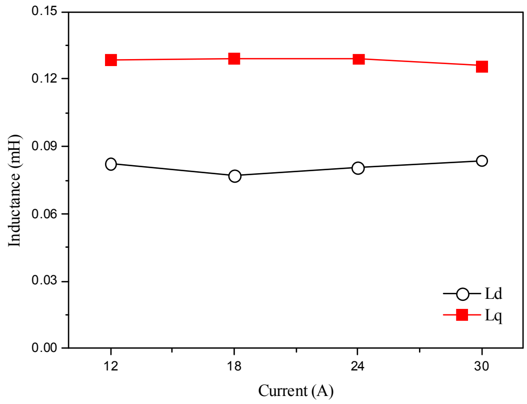

Fig. 5. The average of inductance according to current

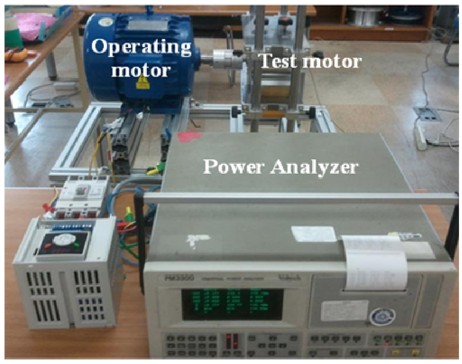

Fig. 6. The iron loss experiment equipment

Table 2. Iron loss of experimental and experimental values

(Hz)	W_h(W)	W_e(W)	W_a(W)	Wi(W)cal	Wi(W)exp
50	2.69	0.90	0.44	4.06	3.02
60	3.23	1.30	0.58	5.15	5.46
100	5.39	3.62	1.26	10.33	9.30
120	6.47	5.21	1.65	13.42	13.88
150	8.08	8.14	2.31	18.68	19.04
200	10.78	14.47	3.55	29.06	28.35
250	13.48	22.98	5.00	41.45	39.57
300	16.17	33.09	6.57	55.83	57.04

4. Calculation of Operating Characteristic and Experimental Results

For calculation of the inductance according to the current amplitude and phase angle change used the inductance, iron loss and linkage flux from the look-up table were applied.

According to the change of the current phase angle, by using the equivalent circuit in which the parameters of the motor are changed, the driving characteristic was calculated.

Fig. 7 shows efficiency characteristics according to

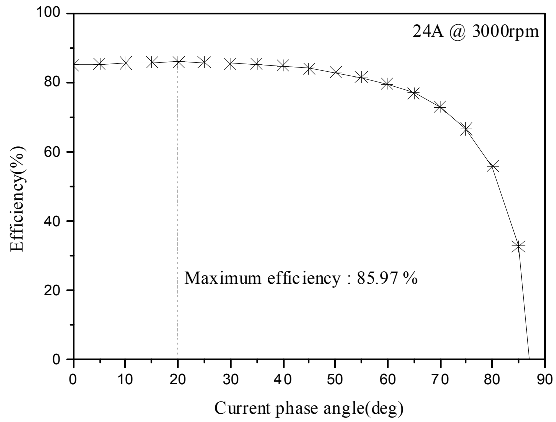

Fig. 7. Efficiency characteristics according to current phase angle

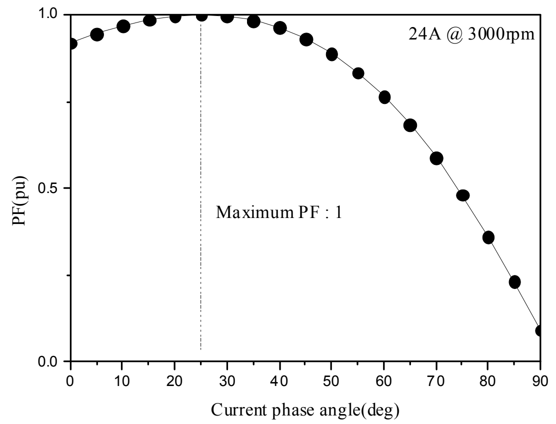

Fig. 8. Maximum power factor estimation

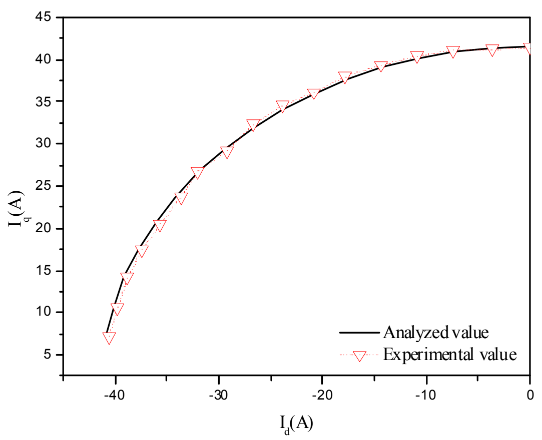

Fig. 9. d, q-axis current comparison of experimental value and calculated value

current phase angle. The maximum efficiency was 85.97 [%] at current phase angle 20°. The efficiency was decreased by current phase angle rising. Because a loss was decreased by current phase angle increasing, but output power was largely decreased too.

The power factor 1 was possible at current phase angle 25° like as Fig. 8. But, the current phase angle of maximum torque was 10°, so the choice of current phase angle is important.

Fig. 9 shows comparison of d, q-axis current. The analyzed value from equivalent circuit and experimental value were relatively collect.

The torque experimental results according to current phase angle are shown in Fig. 10. From the results, the maximum torque was generated at a current phase angle of 10° and the error of the theoretical value and experimental value was under 1% like as Fig. 10.

The torque experimental result according to current was shown in Fig. 11. The error was under 1%. So, output power characteristics have not error.

Fig. 12 is the voltage and current waveform measured at maximum efficiency driving. Fig. 13 shows distribution of measured voltage and current results.

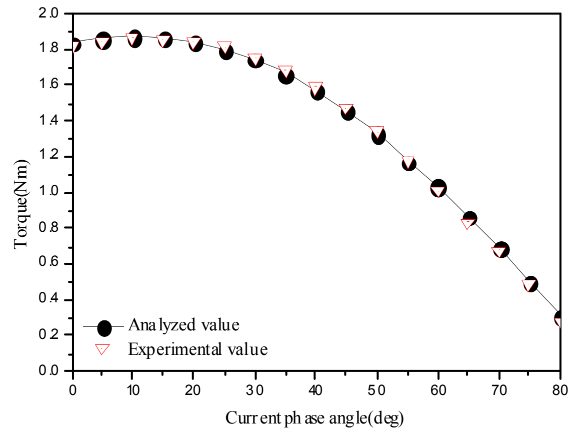

Fig. 10. Torque experimental result according to current phase angle

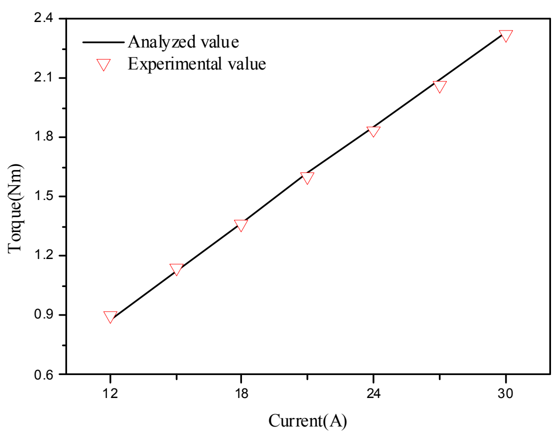

Fig. 11. Torque experimental result according to current

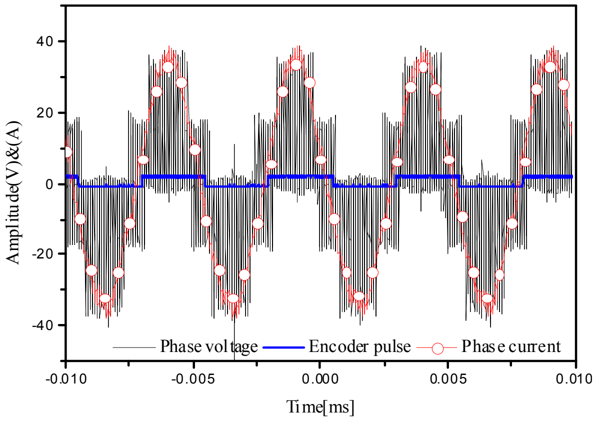

Fig. 12. Voltage and current waveform measured at maximum efficiency driving

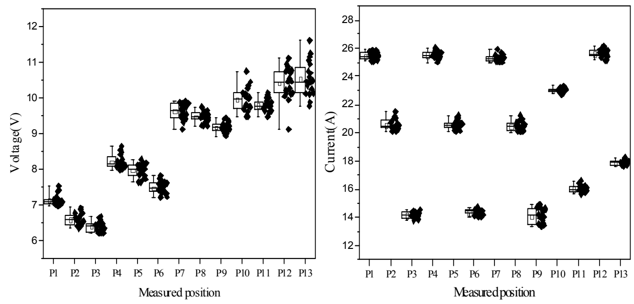

Fig. 13. The results of input voltage and current

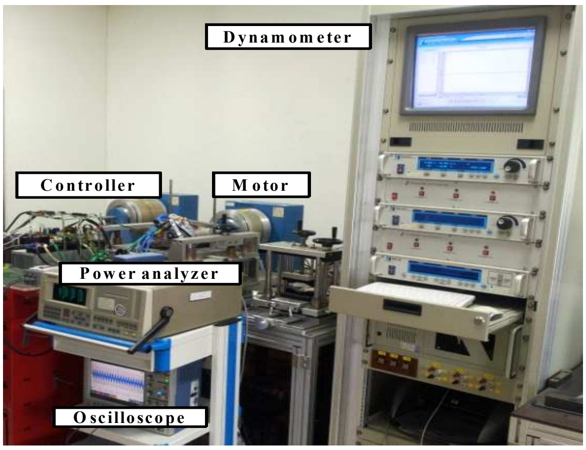

Fig. 14. Efficiency experiment equipment

Table 3. Experiment result of efficiency measurement

	Equivalent circuit value	Experimental value
Torque (Nm)	1.87	1.86
Current (A)	24.00	24.22
Voltage (V)	9.74	9.83
Copper loss(W)	40.60	41.35
Output power (W)	587.47	584.33
Input power (W)	701.58	694.39
Power factor (pu)	0.974	0.972
Efficiency (%)	85.97	84.15

The experiment equipment for the maximum efficiency measurement is shown in Fig. 14. The rated current was calculated in the equivalent circuit, and the input and output power were measured with a power analyzer at a fixed torque condition. In addition, the efficiency was measured and the theoretical values and experimental values were compared. Maximum efficiency driving is possible at a current phase angle of 20°. The experiment result of efficiency measurement was shown in Table 3.

The error between efficiency calculation and experimental values were 1.64%. The error was generated by a mechanical loss of dynamometer and measurement of input power. So, an input power was repeatedly measured, and representative value was chosen for reduction of error, like as Fig. 13. Accordingly, good results can be obtained. Also, the inductance and iron loss resistance were reliably calculated.

5. Conclusion

In this paper, the efficiency characteristics of motor were calculated by d, q-axis equivalent circuit. The equivalent circuit was composited by precise inductance, iron loss resistance and linkage flux.

The average of inductance was estimated by a complementation of CVCT and DCT method. And the iron loss resistance was calculated by CFM. Also power factor, efficiency and torque according to current phase angle were calculated for exactly output power.

Then, current vector controller was made, and the torque experiment was performed. As a result, a calculated torque has not error almost. The input power was repeatedly measured, and representative value was chosen for reduction of error.

Consequently, the error of efficiency measurement was 1.64%, because a mechanical loss of dynamometer and measurement were included. So, at measurement of input and output powers, a very small amount of loss was always presented. Therefore, in next paper, this error will correct.

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