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Performance Comparison between Saturation and Cross Saturation Effects in Interior Permanent-Magnet Synchronous Motor

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In a interior permanent magnet synchronous motor, although parameters of the d-q equivalent model fluctuate according to the proportion of magnetic saturation and flux distribution, for convenience, the influence of cross magnetic saturation is usually neglected in the d-q axis machine model, Therefore, in order to investigate the impacts of both the magnetic saturation and cross magnetic saturation, this paper proposes the analysis method with considering the cross magnetic saturation based on d-q axis equivalent model, and presents the performance comparison between magnetic saturation and cross magnetic saturation effects. These results are verified by the comparison between computed results and experimental results.

***Index Terms*—IPMSM, d-q axis equivalent model, Magnetic saturation, Cross magnetic saturation**

I. Introduction

RCENTLY, the Interior permanent magnet synchronous motor (IPMSM) is widely used in industrial applications, because that it has many advantages, such as robust structure, high efficiency, and high controllability [1],[2]. The high-performance operating of the IPMSM must be depending on the appropriate control strategies. Therefore, several control methods have been proposed in order to improve the performance of that. The algorithms widely used are the maximum torque-per-ampere (MTPA) control and the flux weakening control, and the groundwork for these motor controls is the two phase equivalent circuit model (d-q axis machine model). But, it needs to develop the appropriate control algorithms. And, for the more improvement of their performances, it is important to consider the magnetic nonlinearity of parameters in the IPMSM, because that the motor parameters of d-q axis machine model vary nonlinearly depending on operating condition, which is able to change the level of magnetic saturation and magnetic field distribution in the motor [2]-[4]. Therefore, the key of high-performance control is the motor parameters in d-q axis machine model. It is necessarily required to consider the magnetic nonlinearity when the machine is designed and analyzed. In order to analyze the performance of the IPMSM, previously, an equivalent magnetic circuit model of the IPMSM have been developed without directly including magnetic saturation and cross magnetic saturation effects [2]-[3]. Although d- and q-axis inductances are specially affected critically magnetic saturation according to the load current and the current angle, for convenience, the influence of cross magnetic saturation is usually neglected in the d-q axis machine model. The d- and q-axis inductances vary depending on the d- and q-axis current respectively. Moreover, the IPMSM has the cross magnetic saturation phenomenon according to the current vector control.

This paper is based on recent work that proposes the analysis method with considering the cross magnetic saturation in order to investigate the impacts of both the magnetic saturation and cross magnetic saturation in the d-q axis machine model. The performance comparison between magnetic saturation and cross magnetic saturation effects is presented, and these results are verified by the comparison between computed results and experimental results.

II. Model Description

A. D-Q Model of the IPMSM

The equivalent circuit analysis for the IPMSM is based on a rotate synchronous d-q reference frame, and frequently used to simulate performances of the IPMSM. The mathematical model of the equivalent circuit is given as follow the voltage equations and the steady-state Phasor diagram is shown in Fig. 1 [1]-[2].

$$\Psi_o = \begin{bmatrix} \Psi_{od} \\ \Psi_{oq} \end{bmatrix} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \Psi_a \\ 0 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s + pL_d & -\omega_s L_q \\ \omega_s L_d & R_s + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_s \Psi_a \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (2)$$

$$T = P_n \left\{ \Psi_a I_a \cos\beta + \tfrac{1}{2}(L_q - L_d) I_a^2 \sin 2\beta \right\} \quad (3)$$

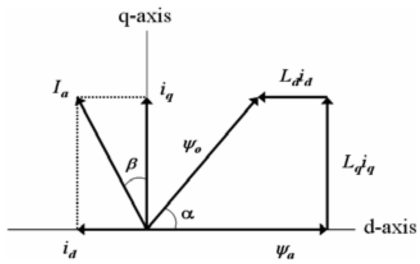


Fig. 1. Steady-state phasor diagram of the IPMSM.

Digital Object Identifier inserted by IEEE where, i_d, i_q = d- and q-axis component of armature current;

$I_a = \sqrt{3}\, I_e$;, I_e = phase armature current (rms);

v_d, v_q = d- and q-axis component of terminal voltage;

R_s = armature winding resistance per phase;

$\Psi_a = \sqrt{3}\ \Psi_f$;, Ψ_f = flux linkage peak of permanent magnet;

Ψ_o = total flux linkage included armature reaction;

L_d, L_q = d- and q-axis inductance;

P_n = pole pair;, p = differential operator (=d/dt);

ω_s = rotor speed in angular frequency;

α = phase difference between Ψ_a and Ψ_o ;

β = current angle;

B. Nonlinearity of parameters in d-q axis machine model

Magnetic saturation generally has a significant impact on the performance characteristics of the IPMSM. Inherently, the d-axis and q-axis inductances tend to be sensitive to magnetic saturation as the magnitude of i_d and i_q increases because of the saturation characteristics of the flux paths in the rotor. In particular, the q-axis inductance L_q tends to be much more sensitive to magnetic saturation. These characteristics are illustrated in Fig. 2 for a prototype IPMSM designed for a compressor application of air conditioner [2].

Additionally, the d-axis and q-axis inductances tend to be changeable to cross magnetic saturation according to the current phase β, which is determined by the operating condition in the IPMSM. These characteristics are identified by Fig. 1. In this paper, the d-axis and q-axis inductances considered with cross magnetic saturation are obtained directly by using armature linkage flux and magnet linkage flux, which are obtained from the finite element analysis (FEA). So, the d-axis and q-axis inductances according to the armature current vector are solved by using (3) and (4) [5].

$$i_d = -I_a \sin\beta\ ,\quad i_q = I_a \cos\beta \qquad (3)$$

$$L_d = \frac{\Psi_o \cos\alpha - \Psi_a}{i_d}\ ,\quad L_q = \frac{\Psi_o \sin\alpha}{i_q} \qquad (4)$$

For the prototype IPMSM, the d-axis and q-axis inductances considered with cross magnetic saturation are shown in Fig. 3. The d-q axis inductances are scatteringly calculated by using FEA, the d-q axis inductances over the entire operation spaces are computed from the spline interpolation.

III. Proposed Analysis Method

The IPMSM has a saliency and the reluctance torque is available, each current vector is controlled in order to produce the MTPA control in the constant torque regions and the flux weakening control in the constant power resigns. Basically, the condition of the MTPA control can be derived by differentiating the torque equation with respect to β and equating the derivatives to zero, and the condition of the flux weakening control is accomplished by the satisfaction of a voltage limitation. However, these mathematical formulations are complicate or insufficient for considering cross magnetic saturations in d-q equivalent circuit model.

Therefore, the evaluation of the d-q equivalent circuit model is accomplished by using the fundamental voltage equation and constrains of the control resigns in this paper. The proposed computation method is based on the iteration algorithm shown in Fig. 4.

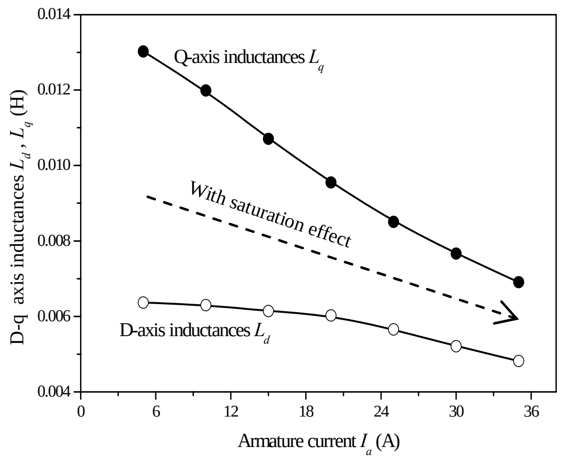
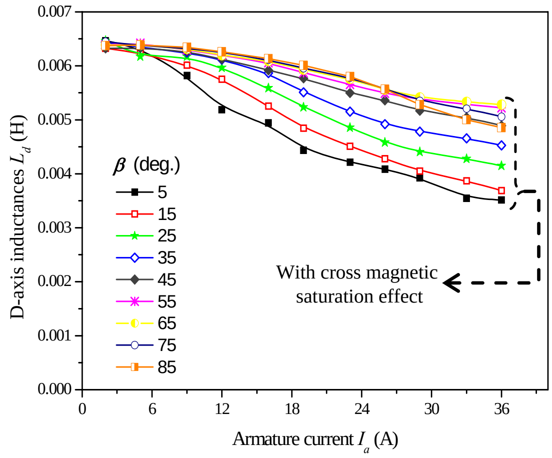
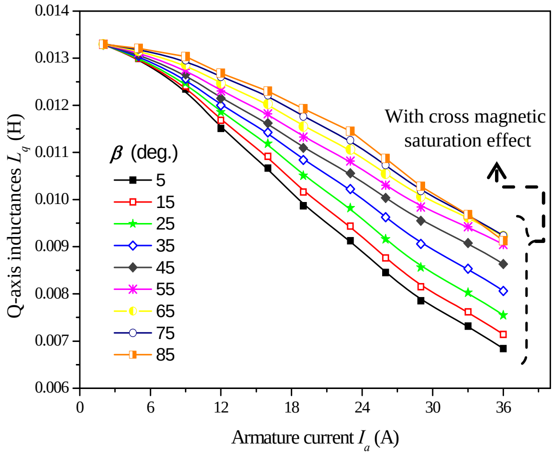


Fig. 2. Inductance profiles with including the magnetic saturation effect



(a) d-axis inductance, L_d



(d) q-axis inductance, L_q

Fig. 3. Inductance profiles with including the cross magnetic saturation effect

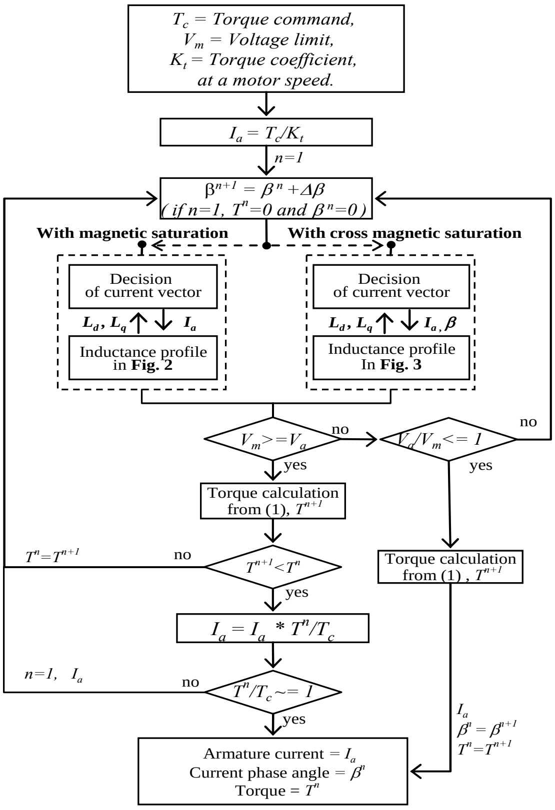


Fig. 4. Flow-chart of the proposed Analysis method

In order to choose a proper current vector at the operating point, the proposed analysis method uses the inductance profile of Fig.2 and Fig. 3 respectively. In each iteration step, the inductances, which correspond to the current vector, are replaced to the voltage and torque equation.

IV. Results and Discussion

Fig. 5 shows the prototype IPMSM employed for the performance comparison between magnetic saturation and cross magnetic saturation effects. The parameters of the prototype IPMSM are listed in Table I. Fig. 6 shows the set of the bench test for the proto type IPMSM.

Fig. 7 shows the analysis results of a MTPA curve in motoring mode. In an anticlockwise direction, the MTPA curve considered with cross magnetic saturation is shifted more than that with magnetic saturation. Another characteristics of the MTPA curve are that lower armature currents are required to generate torques when the performance comparison between magnetic saturation and cross magnetic saturation effects. These characteristics occur prominently as torque is higher. As shown in Fig 8, these results are caused by a difference of saliency ratio between cross magnetic saturation and magnetic saturation effects. About the points mentioned above, the results of the experiment are shown in Fig. 9.

When the prototype IPMSM is operated as the rated torque, the comparison of analysis results shown in Fig. 10 and Fig. 11. In this case, the analysis results with cross magnetic saturation is that the d-axis current i_d is higher and the q-axis current i_q is lower than the analysis results with magnetic saturation in overall operating points. Moreover, the efficiency characteristics with cross magnetic saturation is higher than that of the analysis results with including the magnetic saturation effects. The experiment verifications of these characteristics are illustrated in Fig. 12 and Fig. 13 respectively.

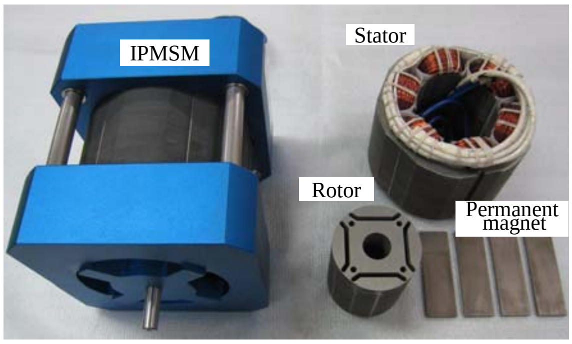


Fig. 5. Bench testing set for the IPMSM

TABLE I SPECIFICATION OF THE PROTOTYPE IPMSM

Parameters	Values	Unit
Phase / pole / slot	3 / 4 / 6	Phase/pole/slot
DC linkage voltage	310	V
Back-emf	0.021	V
Resistance Rs	0.34	Ω
Rate speed	3800	rpm
Rate torque	8	Nm

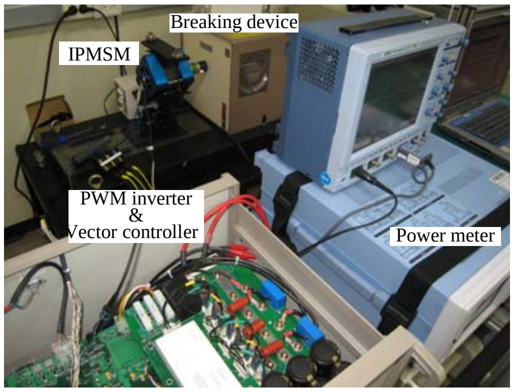


Fig. 6. Set of the bench test for the proto type IPMSM

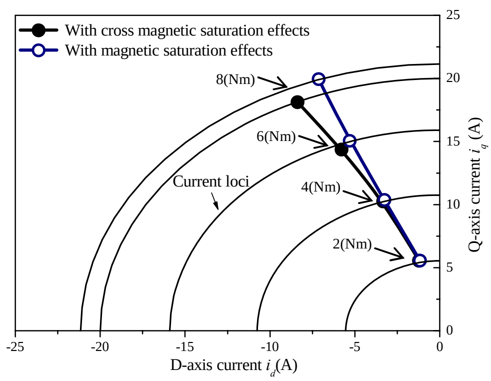


Fig. 7. Analysis results of the MTPA curve

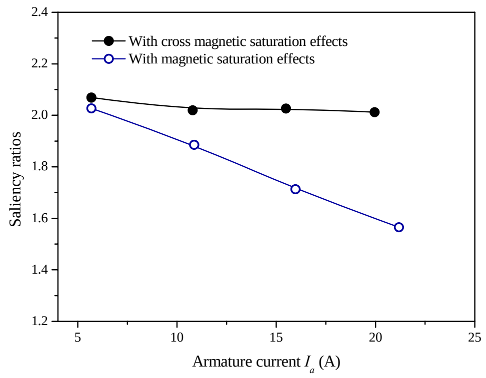


Fig. 8. Saliency ratios at the MTPA operation

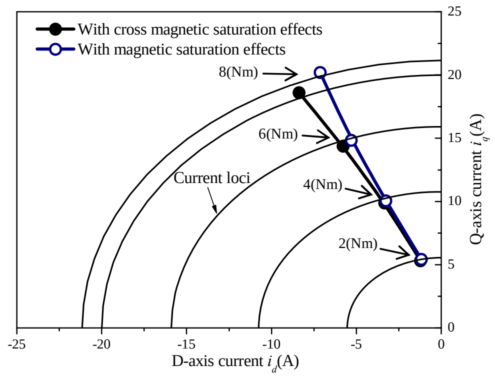


Fig. 9. Experimental results of the MTPA curve

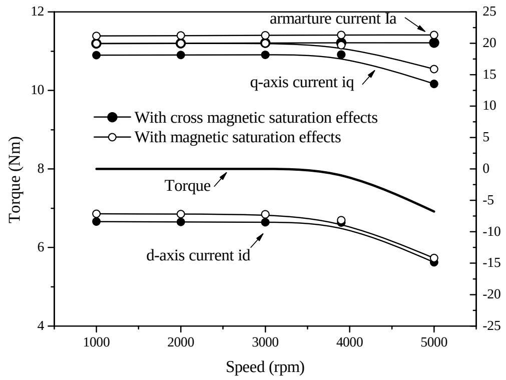


Fig. 10. Analysis results of torque characteristics

V. Conclusion

This paper investigated the effect of both the magnetic saturation and cross magnetic saturation in the motor performance point of view. It was confirmed that the impact of the cross magnetic saturation was more remarkable as the power density of the IPMSM was high. When the IPMSM is designed, the motor designer is frequently faced with the constraint of the motor volume and the unavoidable magnetic saturation. Therefore, in order to achieve the performance improvement of the IPMSM with the high power density, it is necessary to consider the cross magnetic saturation effects.

References

[1] S. Morimoto, Y. Tong and Y. Takeda, "Loss Minimization Control of Permanent Magnet Synchronous Motor Drives," *IEEE Trans. on Industry Electronics*, IE-41, 5, pp. 511-517, 1999.

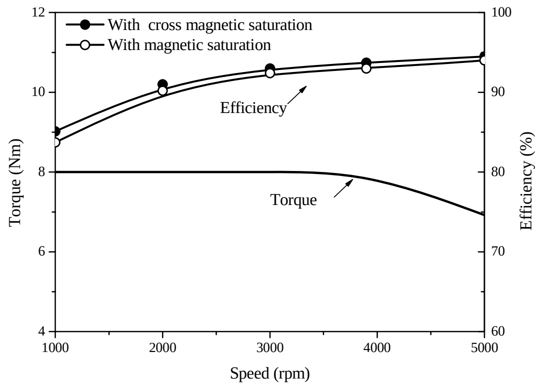


Fig. 11. Analysis results of efficiency characteristics

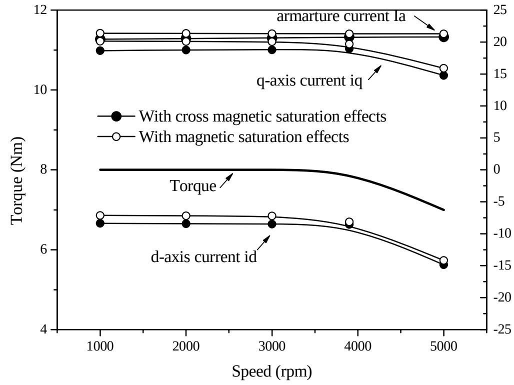


Fig. 12. Experimental results of torque characteristics

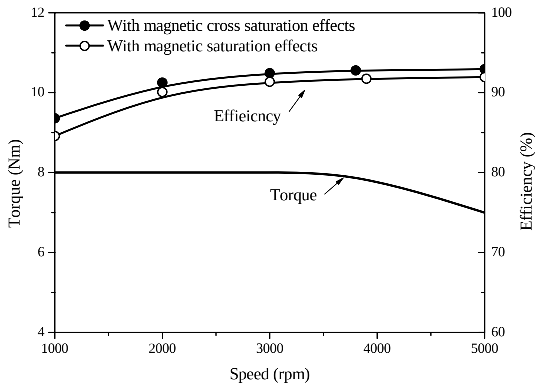


Fig. 13. Experimental results of efficiency characteristics

[2] Nicola Bianchi and Thomas M. Jahns, *DESIGN, ANALYSIS, AND CONTROL OF INTERIOR PM SYNCHRONOUS MACHINES*, CLEUP, 2004.

[3] Chedot, L. and Friedrich, G, "A cross saturation model for interior permanent magnet synchronous machine. Application to a starter-generator, " *Proc. of Industry Applications Conf.*, Vol. 1, pp. 64–70, April, 2004.

[4] B. Stumberger, B. Kreca, and B. Hribernik, "Determination of parameters of synchronous motor with permanent magnets from measurement of load conditions, " *IEEE Trans. Energy Conv.,* Vol. 14, pp. 1413-1416, Dec. 1999.

[5] S.I. Kim, J.H. Bhan, J.P. Hong, and K.C. Lim, "Optimization Technique for Improving Torque Performance of Concentrated Winding Interior PM Synchronous Motor with Wide Speed Range," *in Proc. IEEE IAS Annual Meeting*, vol. 4, pp. 1933 - 1940, Oct. 2006.

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