COMPUMAG 2007 – 12. ELECTRIC MACHINES AND DRIVES

Analysis Strategy Considering Magnetic Saturation of Interior Permanent Magnet Synchronous Motors

[1]Young-Kyoun Kim, [2]Jung-Pyo Hong
[1]Artificial Intelligence & Mechatronics Research Center, [2]Mechanical engineering, Hanyang University
[1]Korea Electronics Technology Institute (KETI), Puchon 420-140, Korea
[2]#17, Hendang-dong, Seoul, 133-791, South Korea
ensigma@hitel.net, hongjp@hanyang.ac.kr

Abstract — This paper presents a method to calculate the motor performance of interior permanent magnet synchronous motors. Traditionally, the motor analysis is accomplished by using equivalent circuit, which consists of motor parameters including constant inductances. However, inductances are affected critically magnetic saturation according to both the load current and the current angle. This paper proposes the analysis method with considering fluctuations of these inductances.

I. INTRODUCTION

Interior permanent magnet synchronous motors (IPMSM) are widely used in industrial applications, which require high power density. In the applications such as electric vehicles and compressor drives, the efficiency is one of the most important performances. The operating efficiency depends on the control strategies. Several control methods have been proposed in order to reduce the loss of IPMSM and improve their performance. One of the control strategies is the maximum torque-per-ampere current control. The possibility of operating methods depends on parameters of IPMSM. Therefore, the effects of magnetic saturation due to both the armature current and the current angle are dominant. Specially, the d- and q-axis inductances vary depending on the d- and q-axis current respectively, and as a result the control performances are affected by the magnetic saturation. This paper presents a simulation method to decide correct the current vector of IPMSM.

II. SIMULATION OF IPMSM

An equivalent circuit analysis for IPMSM are based on a rotate synchronous d-q reference frame, and frequently used to simulate their performances. The mathematical model of the equivalent circuit is given as follow the voltage equations [1]-[2].

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_s + pL_d & -\omega L_q \\ \omega L_d & R_s + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \Psi_a \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (1)$$

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

Where i_d and i_q are d- and q-axis components of armature current, v_d and v_q are d- and q-axis components of terminal voltage, L_d and L_q are d- and q-axis components of armature self-inductances, R_s is armature resistance per phase, Ψ_a is $\sqrt{3/2}\ \Psi_f$, Ψ_f is maximum flux-linkage due to permanent magnet per phase, p is differential operator, P_n is number of pole pairs. β is current angle.

IPMSM has a saliency and the reluctance torque is available, the current vector is controlled in order to produce the maximum torque per current in the constant torque region. The condition of the maximum torque-per-ampere current control can be derived by differentiating equation (2) with respect to β and equating the derivatives to zero. As a result, the condition is given by [1]-[2]

$$\beta = \sin^{-1}\left\{ \frac{-\Psi_a + \sqrt{\Psi_a^2 + 8(L_q - L_d)^2 I_a^2}}{4(L_q - L_d) I_a} \right\} \quad (3)$$

The above equation is derived as if the magnetic saturation is ignored and L_d and L_q are assumed to be constant parameter. It seems that the operating performances become worse and the control system may become unstable.

Therefore, in order to improve the operating performances, the decision method of the current vector should be considering the effects of magnetic saturation. In this paper, the proposed computation method is based on the iteration algorithm shown in Fig. 1. Also, the iteration method can be solved by using a numerical optimization algorithm. In the proposed Method, L_d and L_q are calculated by FEA according to the d- and q-axis current [3] and used in the torque calculation. Fig. 2 and Fig 3 show the L_d and L_q of the prototype IPMSM. The L_d and L_q vary depending on the d- and q-axis current respectively.

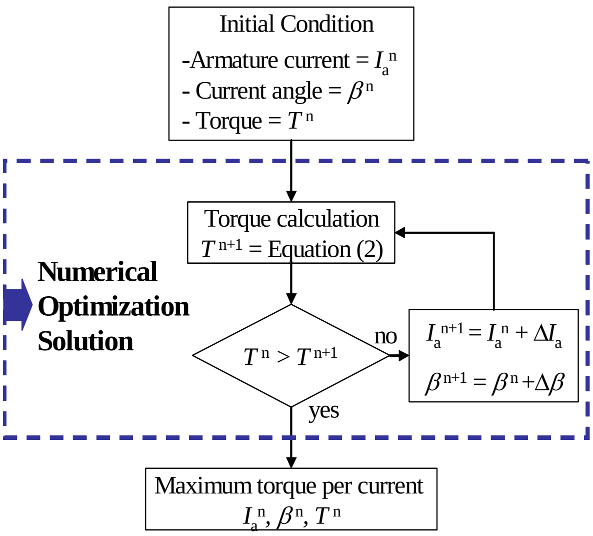


Fig. 1. Flow-chart of the proposed simulation method

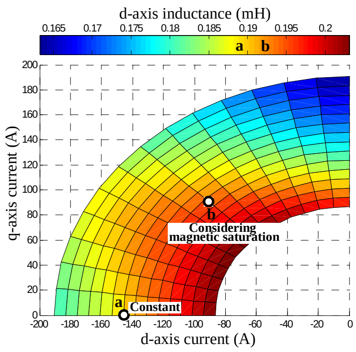


Fig. 2. L_d profile according to the d- and q-axis current

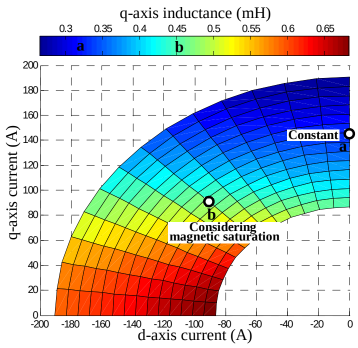


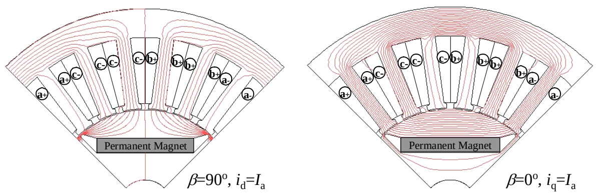
Fig. 3. L_q profile according to the d- and q-axis current

III. SIMULATION RESULTS

The parameters of the prototype IPMSM are listed in Table I, When d-axis is placed in the direction of resistance as shown in Fig. 4.a, L_d is a value at i_d=145A, i_q=0A, and when q-axis is placed in the direction of least resistance as shown in Fig. 4.b, L_q is a value at i_q =145A, i_d=0A. The simulation results of the torque and the terminal voltage controlled by the maximum torque-per-current control are shown in Fig. 5. The solid-circle curves represent the calculated characteristics without consideration of the magnetic saturation, in which the constant value of inductances (listed Table 1.) and equation (3) are used. The open-circle curves represent the calculated characteristics with consideration of magnetic saturation, in which the value of inductances is based on both Fig 2 and Fig3 according to the d- and q-axis current. Fig. 5. shows the calculated results of the armature current and current angle, and Fig. 6. shows the computed results of the power and efficiency.

TABLE I
SPECIFICATION OF PROTOTYPE IPMSM

Parameters	Value	Unit
Number of Phase	3	phase
Number of Pole	4	pole
DC linkage Voltage	42	V
Rated Speed	3500	rpm
Rated Torque	9.8	N-m
Back-emf coefficient	3.49	mV/rpm
Resistance per a phase	12.5	mΩ
Ld	0.188	mH
Lq	0.324	mH
Maximum current	145	A



(a) d axis (b) q axis

Fig. 4. Cross section of IPMSM

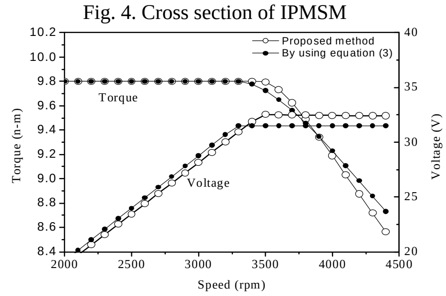


Fig. 5. Torque and voltage characteristics of prototype IPMSM

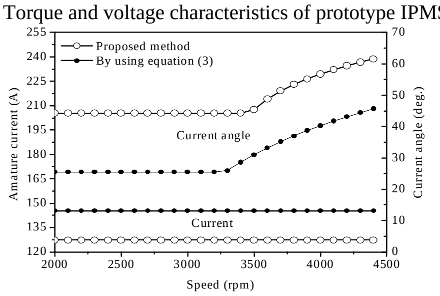


Fig. 6. Armature current and angle characteristics of prototype IPMSM

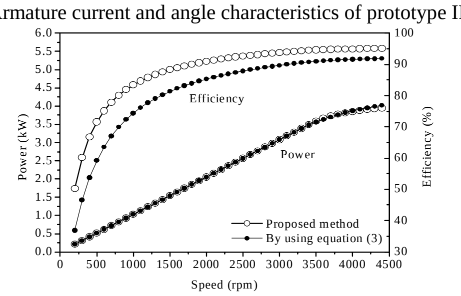


Fig. 7. Efficiency and power characteristics of prototype IPMSM

IV. CONCLUSION

The consideration of magnetic saturation was proposed for the analysis method of the IPMSM performance in this paper. The L_d and L_q of IPMSM vary depending on the d- and q-axis current because of the magnetic saturation. The L_d and L_q are simply used as the proposed analysis method. It can be considered that the ability of the proposed method is useful for the analysis of operating performances of the IPMSM.

V. REFERENCES

[1] Murakami, H., Honda, Y., Kiriyama, H., Morimoto, S., Takeda, Y., F. Henrotte and K. Hameyer, "The performance comparison of SPMSM, IPMSM and SynRM in use as air-conditioning compressor ", Ind. Appl. Conference, 32(1):840-845, Oct. 1999.

[2] T. Sebastian, G.R. Slemon, and M.A. Rahman, "Modelling of Permanent Magnet Synchronous Motors," *IEEE Trans. on Magn.*, vol. 22, No. 5, pp. 1069-1071, Sept. 1986.

[3] Sheppard J. Salon, *Finite Element Analysis of Electrical Machines*, Kluwer Academic Publishers.

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