Determination of Parameters Considering Magnetic Nonlinearity in Interior Permanent Magnet Synchronous Motors

Ji-Young Lee, Sang-Ho Lee, Geun-Ho Lee, and Jung-Pyo Hong
ECAD Lab., Dept. of Electrical Engineering, Changwon National University
Sarimdong #9, Changwon, GyeongNam, 641-773, Korea
jyecad@korea.com, jphong@sarim.changwon.ac.kr

Abstract— **This paper presents a method to calculate motor parameters considering magnetic nonlinearity in Interior Permanent Magnet Synchronous Motors (IPMSM). The motor characteristics are estimated by using equivalent circuits, and inductance and resistance of iron loss affected critically magnetic saturation are obtained by using finite element analysis method. The accuracy of the method is examined by the comparison of calculated and measured results of an example IPMSM.**

I. Introduction

These days, interior permanent magnet synchronous motors (IPMSM) are very attractive for application to the systems required high power density such as hybrid vehicles and compressors. As those systems become more compact, the electric motors are getting highly saturated. It is, therefore, naturally required to consider the magnetic nonlinearity when the machines are designed or analyzed.

Although there are several papers for the parameter determination in equivalent circuits considering iron loss [1, 2], the parameters are obtained from measurement, experimental equations, or electric linear equations. These methods, however, can not be used in design process or can not estimate the parameters accurately in saturated condition.

Therefore, this paper presents a method to calculate motor parameters considering magnetic nonlinearity in IPMSM. The motor characteristics are estimated by using equivalent circuits, and some parameters, consisting the circuit and affected magnetic saturation, are obtained by using finite element analysis method (FEM). Permanent magnet flux, resistance of stator iron loss, and d- and q-axis inductances are the examples for the parameters. The other parameters can be calculated by common equations [1].

Since the method about calculation of permanent magnet flux is very fundamental in FEM [3], only the computation methods about inductance and resistance of iron loss are presented in this paper. It is evident that each method is not very new. However, it is new challenge that the critical parameters of equivalent circuit are calculated by FEM, and the characteristics are estimated from the circuit. The accuracy of the method is examined by the comparison of calculated and measured results of an example IPMSM.

II. Equivalent Circuit

Equivalent circuits for IPMSM based on a synchronous d-q reference frame including iron losses [2, 4] are presented in Fig. 1. The mathematical model of the equivalent circuit is given as follow equations. When iron loss is considered by equivalent resistance R_c , the d- and q-axis voltage, and effective torque equations are given by (1), (2), and (3) respectively. Fig. 2 shows a cross section of a typical IPMSM along with d- and q-axis and experimental devices.

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

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_a \end{bmatrix} \quad (2)$$

$$T = P_n \left\{ \psi_a i_{od} + \left(L_d - L_q\right) i_{od} i_{oq} \right\} \quad (3)$$

where, i_d and i_q are d- and q-axis component of armature current, i_{cd} and i_{cq} are d-and q-axis component of iron-loss current, v_d and v_q are d-and q-axis component of terminal voltage, R_a is armature winding resistance per phase, R_c is iron-loss resistance, Ψ_a is flux linkage of permanent magnet per phase (rms), L_d and L_q are d- and q-axis armature self inductance, and P_n is pole pair.

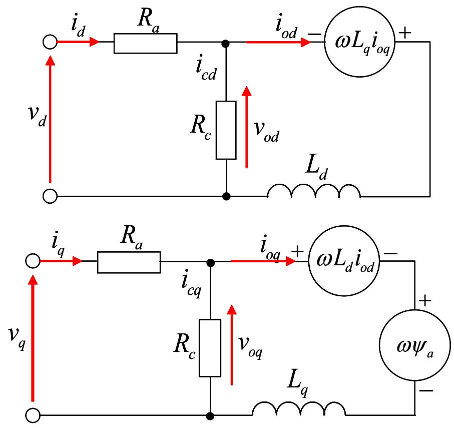

Fig. 1. D-(upper) and q-axis (lower) equivalent circuits of IPMSM

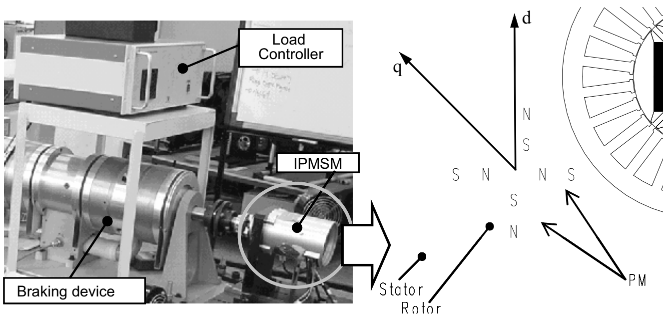

Fig. 2. A configuration of IPMSM with experimental devices

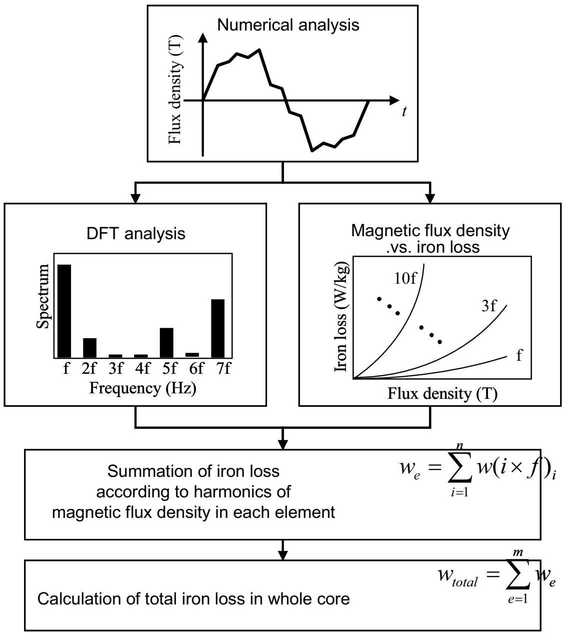

Fig. 3. Flowchart for iron loss calculation

II. Motor Parameter Calculation

There are four parameters to be calculated in order to use the circuit model of Fig. 1, which are as follows [1]:

1) flux linkage of permanent magnet per phase, Ψ_a
2) armature winding resistance per phase, R_a
3) iron-loss resistance, R_c
4) d- and q-axis armature self inductances, L_d and L_q

This paper, however, only deals with the two parameters, iron-loss resistance and inductances which are affected critically by nonlinearity of magnetic material.

A. Equivalent Iron-Loss Resistance, R_c

Fig. 3 shows the flowchart for the iron loss calculation. [5] gives the detail explanation about the flowchart. After calculating power of iron loss, P_{loss}, the iron-loss resistance can be calculated by (4).

$$P_{loss} = v_0^2 / R_c \qquad (4)$$

where, v_o is terminal voltage at no load and base speed.

B. Inductances, L_d and L_q

Fig. 4 shows the flowchart for the inductance calculation. [6] gives the brief explanation about this flowchart, and [6] and "in press" [7] show the validity of this method.

III. Conclusions

Fig. 5 shows the accuracy of the method by comparison of calculated and measured currents according to the variation of load and current angle for the IPMSM shown in Fig. 2, which has 3.6kW output power for a compressor. A more detailed explanation of the calculated parameters and this comparison will be given in the full paper

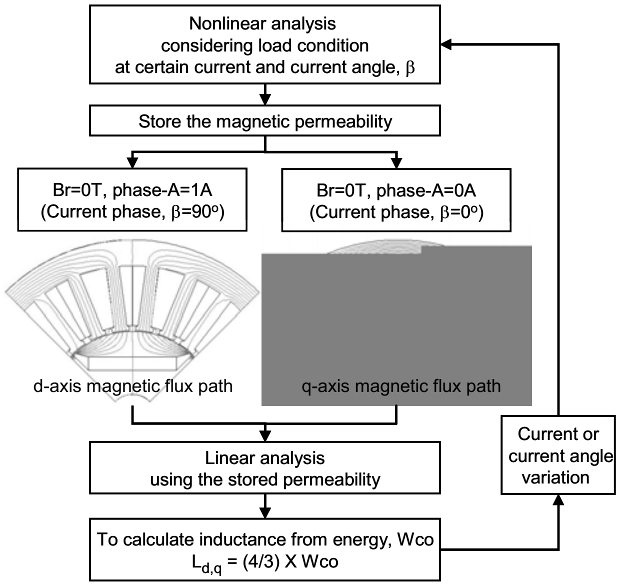

Fig. 4. Flowchart for d- and q-axis inductance calculation

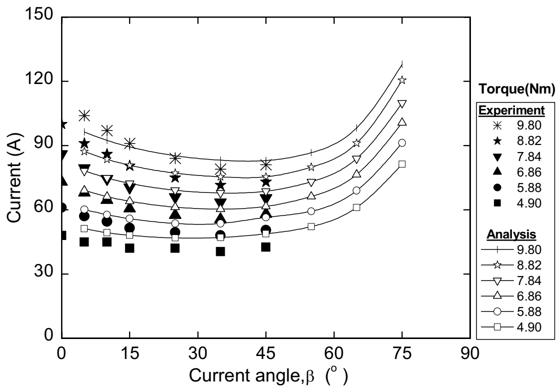

Fig. 5 Comparison of current for load and current-angle, β, variation

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