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Session EL

PERMANENT MAGNET MACHINES III (POSTER SESSION)

Jiabin Wang, Chair

EL-01. Determining parameters of a line-start interior permanent magnet synchronous motor model by the differential evolution. *T. Mar či č*[1], G. Štumberger[2,1], B. Štumberger[2,1], M. Hadziselimovi č[2,1] and P. Virti č[1] *1. TECES, Research and Development Centre for Electrical Machines, Maribor, Slovenia; 2. University of Maribor, Faculty of Electrical Engineering and Computer Science, Maribor, Slovenia*

EL-02. Design and performance measurement of high speed permanent magnet synchronous motor with full-ring magnet for axial-flow turbo fan. S. Jang[1], *J. Park*[1], K. Ko[1] and J. Hwang[2] *1. Electrical Engineering, Chungnam National University, Daejeon, South Korea; 2. MAGPLUS, Daejeon, South Korea*

EL-03. Finite element analysis of stator winding faults in permanent magnet brushless AC motors. *J.A. Farooq*[1], T. Raminosoa[1], A. Djerdir[1] and A. Miraoui[1] *1. Electrical Engineering and Control Systems, University of Technology Belfort Montbeliard, Belfort, France*

EL-04. Analysis method for considering the effect of magnetic cross saturation of IPMSM. *Y. Kim*[1], I. Jung[1], J. Hur[1] and J. Hong[2] *1. KETI, Bucheon, South Korea; 2. Hanyang University, Seoul, South Korea*

EL-05. Design and finite-element analysis of interior permanent magnet synchronous motor with flux barriers. *B. Stumberger*[1], G. Stumberger[1], M. Hadziselimovic[1], T. Marcic[2], P. Virtic[2], V. Gorican[1] and M. Trlep[1] *1. University of Maribor, Faculty of EE&CS, Maribor, Slovenia; 2. TECES, Development centre for Electrical Machines, Maribor, Slovenia*

EL-06. Performance of IPMSM for Electro-Hydraulic Power Steering with Electric Driven Pump Unit. *Y. Kim*[1], S. Rhyu[1], J. Hur[1] and J. Hong[2] *1. KETI, Bucheon, South Korea; 2. Hanyang University, Seoul, South Korea*

Analysis Method for Considering the Effect of Magnetic Cross Saturation of IPMSM

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This paper presents the evaluation method of the performance in interior permanent magnet synchronous motor (IPMSM) over the entire operation condition. The conventional mathematical model of the IPMSM is accomplished by using d-q axis equivalent circuit model, which consists of motor parameters such as the permanent magnet flux, the copper resistance, the iron loss resistance, and the d-q axis inductance. In IPMSM, it is well known that the phenomenon of the magnetic cross saturation occurs depending on the operating condition, however, for convenience, the influence of magnetic cross saturation is usually neglected in the d-q axis machine model. This paper proposes the analysis method with considering the magnetic cross saturation based on d-q axis equivalent model, and the proposed method is verified by the comparison between computed results and experimental results.

***Index Terms*—IPMSM, d-q axis equivalent model, Magnetic saturation, Cross saturation, Core loss resistance**

I. Introduction

THESE days, 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]. Appropriate control of the current vector is necessary for high-performance control, several control methods have been proposed in order to reduce the power loss of IPMSM and improve their performance. 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). 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 non-linearity when the machine is designed and analyzed, because that the motor parameters vary nonlinearly depending on operating condition, which is able to change the level of saturation and magnetic field distribution in the motor [3].

Especially, the d- and q-axis inductances vary depending on the d- and q-axis current respectively. Moreover, IPMSM has the magnetic cross saturation phenomenon according to the current vector control. In order to analyze the performance of IPMSM, previously, an equivalent magnetic circuit model of IPMSM have been developed without directly including magnetic saturation and cross saturation effects [3],[4]. This paper is based on recent work that presents the analysis method to decide correct the current vector with considering the cross saturation effect and core loss in the d-q axis model of the IPMSM.

II. Modified D-Q Equivalent Circuit Model

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 [1],[5].

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

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

where, i_d, i_q = d- and q-axis component of armature current;
I_e = phase armature current (rms);, $I_a = \sqrt{3}\, I_e$;
v_d, v_q = d- and q-axis component of terminal voltage;
R_s = armature winding resistance per phase;
Ψ_f = flux linkage peak of permanent magnet;
$\Psi_a = \sqrt{3}\, \Psi_f$;
L_d, L_q = d- and q-axis armature self inductance;
P_n = pole pair; , p = differential operator (=d/dt);
ω_s = rotor speed in angular frequency;
β = current angle;

When core losses are considered, the voltage equations of the IPMSM are given by [11];

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_s \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1 + \frac{R_s}{R_c}\right) \begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} + p \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega_s L_q \\ \omega_s L_d & 0 \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_s \psi_a \end{bmatrix} \quad (4)$$

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

The mathematical model with considering the core losses is induced by core loss resistance, Rc.

where, i_{cd}, i_{cq} = d- and q-axis component of iron loss current;
i_{od}, i_{oq} = d- and q-axis component of load current;
R_c = iron loss resistance;

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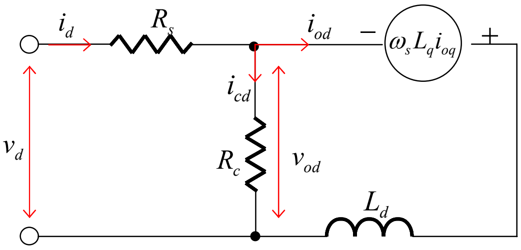
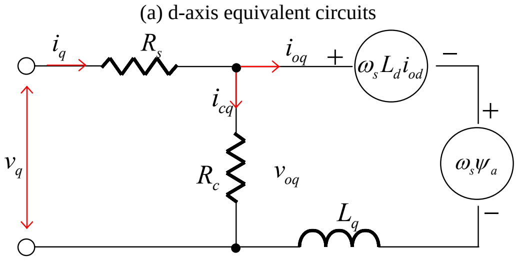


(a) d-axis equivalent circuits



(b) q-axis equivalent circuits

Fig. 1 Equivalent circuits of IPMSM

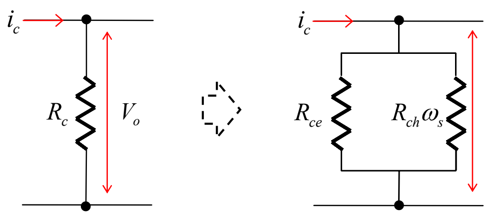


Fig. 2 Modified segment of core loss resistance from d-q equivalent circuit

Fig. 2 shows the d-q equivalent circuit frequently used for the representing of the mathematical model with considering the core losses [1],[5].

The equivalent core loss resistance (R_c) in this d-q equivalent circuit is proportional to product of squared magnitude and squared frequency of flux. However, the core losses consist of the eddy current and hysteresis losses.

Therefore, in order to consider hysteresis loss to product of squared magnitude and absolute frequency of flux, the equivalent core loss resistance (R_c) can be divided by two resistances, which are both eddy current resistance (R_{ce}) and hysteresis loss resistance (R_{ch}), in parallel form as follows;

$$\frac{1}{R_c} = \frac{1}{R_{ce}} + \frac{1}{R_{ch} \times \omega_s} \tag{6}$$

After calculating total iron loss, W_c, the iron loss resistance R_c can be calculated by (7).

$$P_{ce} \times \omega_s + P_{ch} = \frac{W_c \times \omega_s}{V_0^2}, \quad where \ \ P_{cx} = 1/R_{cx} \tag{7}$$

The core loss calculation of an electric motor is given the detail description by other authors in [6]

The parameters of the prototype IPMSM are listed in Table I, the motor is in the employment of the compressor of the air conditioner.

TABLE I SPECIFICATION OF PROTOTYPE IPMSM

Parameters	Value	Unit	Parameters	Value	Unit
Phase	3	phase	Back-emf	0.0214	V/rpm
Pole	4	pole	Rs	0.25	Ω
Vdc	300	V	Rce, Rch	865, 1.5	Ω

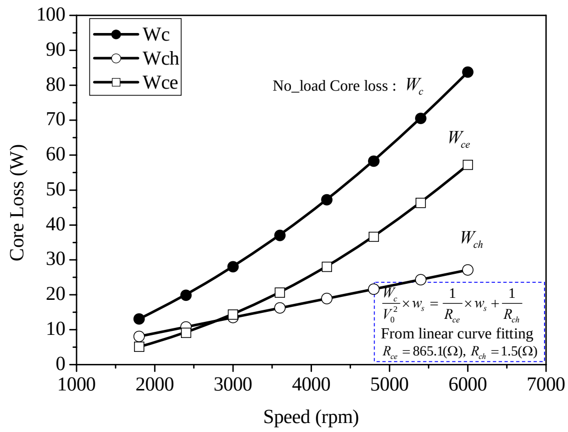


Fig. 3. No load core loss and equivalent core loss resistance

Fig. 3 shows the estimated results of the core loss, eddy current resistance (R_{ce}) and hysteresis loss resistance (R_{ch}) for the proto type IPMSM. The amount of two core loss resistances at each operating frequency can be found by using FEA about the core loss. From the analysis result, it can be estimated that the resistance R_{ce} and R_{ch} by using the linear curve fitting method, and the estimated core loss resistance R_c can be calculated from (6) and (7).

III. Introduction Evaluation for Magnetic Cross Saturation

Actually, L_d and L_q is function of the d- and q-axis current, if the magnetic cross saturation effects are ignored and, the 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 analyze accurate operating performances of IPMSM, cross saturation effects of the inductances should be considered.

In this paper, the L_d and L_q are obtained directly by using armature linkage flux and magnet linkage flux, which are obtained from the FEA. So, L_d and L_q according to the armature current vector can solved by using (7) and from Fig. 4 [2].

$$L_d = \frac{\psi_o \cos\alpha - \psi_a}{i_d}, \quad L_q = \frac{\psi_o \sin\alpha}{i_q} \tag{8}$$

where ψ_o = linkage flux of the armature current reaction,
α = phase difference between ψ_a and ψ_o.

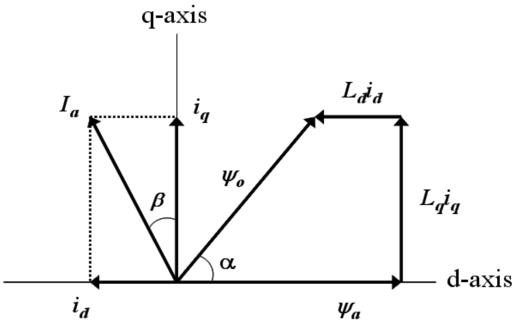
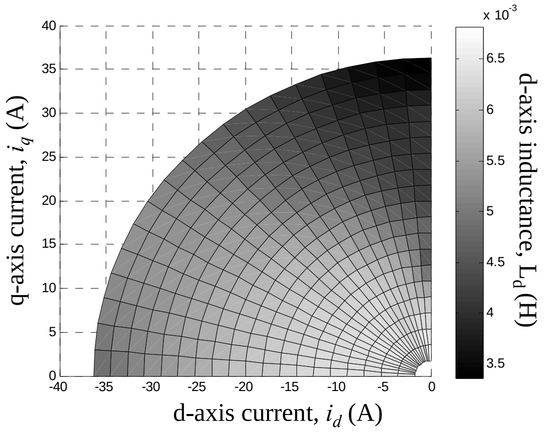
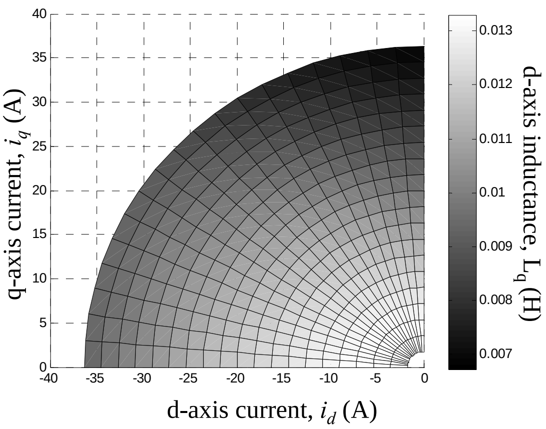


Fig. 4. Phasor diagram of IPMSM.



(a) d-axis inductance, L_d



(d) q-axis inductance, L_q

Fig. 5. L_d and L_q profile according to the cross saturation effect

Although it is evident that above method is not very novel, it is new challenge that the evaluation of the d-q equivalent circuit is characterized with both the magnetic cross saturation and two components of core loss resistances, which are variable at rotating speed .

Fig. 5 shows the inductances that consider magnetic cross saturation. The d-q axis inductances are scatteringly calculated by using FEM, the d-q axis inductances over the entire operation spaces can be derived from the spline interpolation. These inductances are used in the analysis considering the effect of the magnetic cross saturation.

IV. Description of Proposed Analysis Method

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 both magnetic cross saturations and core losses 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. 6. Also, the iteration method can be solved by using a numerical optimization algorithm. In order to choose a proper current vector that satisfies the constrains of the operating resigns, the proposed analysis method uses the inductance profile of magnetic cross saturations and core loss resistances, In each iteration step, the inductances, which correspond to the current vector, are replaced to the voltage and torque equation.

V. Analysis Results and Discussion

Fig. 7 shows the configuration of performance measurement of the IPMSM for driving the compressor of air conditioner. This motor is adopted for the verification of the proposed analysis method.

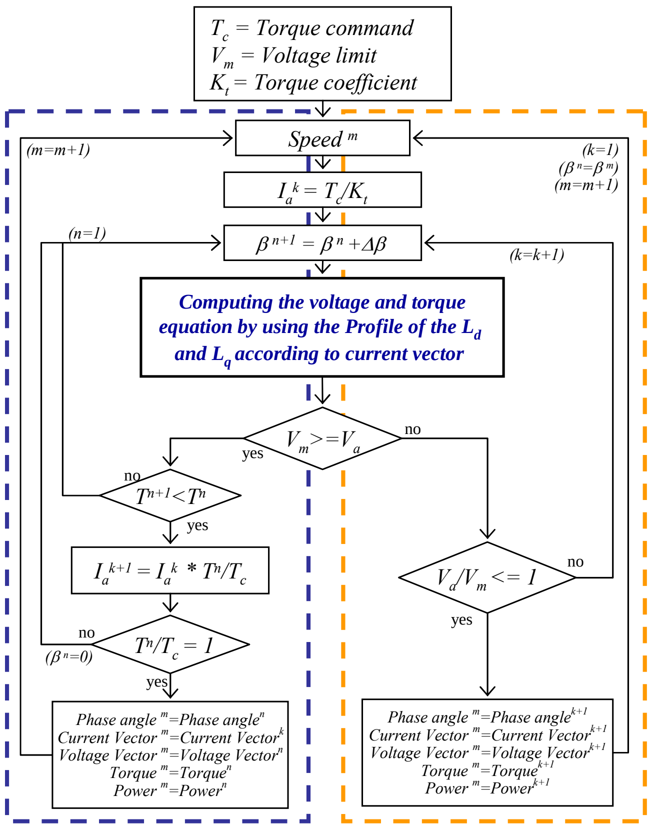


Fig. 6. Flow-chart of the proposed evaluation of the d-q equivalent circuit

Fig. 8 and Fig. 9 display the comparison of the computed results and the measured results, where the each operating condition over the overall speed is constant torque as 2 N-m and 4 N-m respectively. In fig. 8, the analysis results agree well with the measured results except in the high speed resign, which needs more time for tuning the proper control gain of the high speed. From the analysis results of Fig. 9, it can be known that, when the operating point is moving to ‘A ‘, the current is slightly increasing reason for raising the core loss current according to the motor speed, and when the operating point is moving to high speed as ‘B ‘, the current is surging up because of keeping the constant torque in the flux weakening area.

Fig. 10 and Fig 11 show the loss and efficiency distribution in overall operating points respectively. These results are accomplished by the proposed analysis method, and it can easy estimate the overall performance of the motor.

VI. Conclusion

In this paper, the analysis method of IPMSM, in which the d-q axis equivalent magnetic circuit is solved by using the iteration algorithm, is proposed.

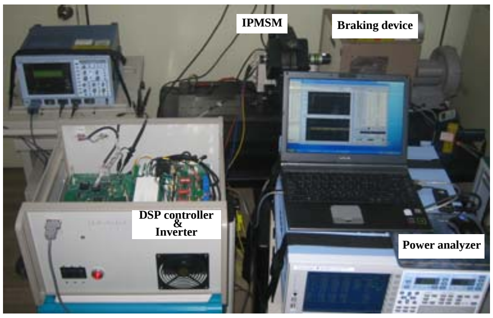


Fig. 7. Bench testing set for the IPMSM

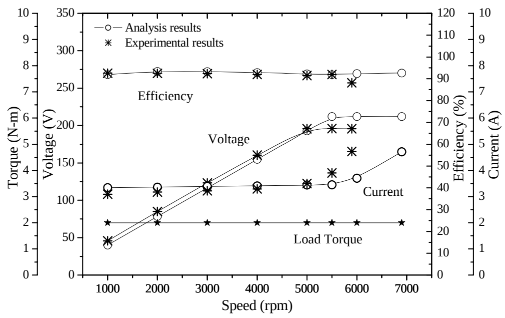


Fig. 8. Characteristics of the IPMSM at constant torque, 2 N-m

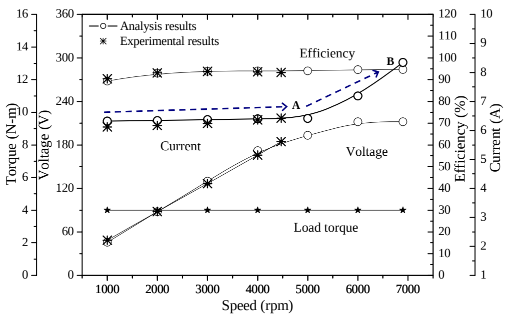


Fig. 9. Characteristics of the IPMSM at constant torque, 4 N-m

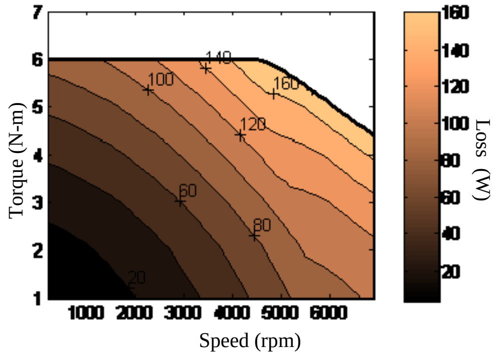


Fig. 10. Loss distribution for overall operation point

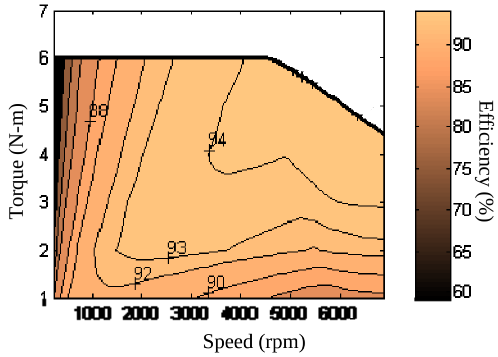


Fig. 11. Efficiency Loss distribution for overall operation point

The influence of the magnetic cross saturation is considered by using the d-q axis inductance due to operating condition. Additionally, the core loss is reloaded at each load condition by using two components of the core loss resistance.

The proposed analysis procedure can easy evaluate the overall performance of the IPMSM, has been successfully demonstrated. Therefore, it can be considered that the proposed method is useful for the analysis and design of the IPMSM.

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