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Comparisons of Inductance Evaluation Methods in Interior Permanent Magnet Synchronous Motors

Tao Sun, Soon-O Kwon, Jeung-Jong Lee, and Jung-Pyo Hong, *Senior Member, IEEE*

School of Mechanical Engineering, Hanyang University, Seoul, CO 133791, Korea

The purpose of this paper is to investigate and compare the inductance evaluation methods of interior permanent magnet synchronous motors (IPMSM). Three major finite element methods are discussed. Their detail calculation processes will be presented as well as their fundamental principles. Not only the results, but also their solving method, computation time and complexity also will be compared. Finally, the calculated results will be verified with a laboratory test. The investigation of the calculation methods and the comparison of the evaluated results will be helpful to choose the appropriate inductance calculation method for IPMSM.

***Index Terms*—Finite Element Analysis, Flux Linkage, Inductance, Interior Permanent Magnet Synchronous Motor,**

I. Introduction

THE SUPERIORITIES of Interior permanent magnet synchronous motors (IPMSM), such as high power density, wide speed range, and high efficiency have been demonstrated by many literatures. The dominant influences in the correct prediction of the steady-state characteristics and precise vector control for the IPMSM are the d- and q-axis armature inductances and flux linkage of permanent magnet (PM) [1]. The flux linkage of permanent magnet can be easily and accurately calculated or tested under no-load condition. And [3]-[8] also have given several considerable choices for inductance measurement. Due to the nonlinear electromagnetic characteristics including the saturation and cross-coupling effect in the rotor of IPMSM [5], [6], however, the d- and q-axis armature inductances of IPMSM become much difficult to be evaluated accurately.

In spite of the fact that the corresponding evaluation methods have been discussed for last two decades, there is still no standard for the inductances calculation processes of IPMSM. Although some papers [7], [8] claimed that the accurate results were calculated by analytical methods, the much linearization leads that the available structure is constrained. The finite element analysis (FEA) still is the most trustable method as well known. Among the proposed FEA methods, three kinds can be classified. They are frozen permeabilities method [1], [2], vector control method [3], [4], and differential flux linkage method [5], [6], respectively. First, the principle and calculation process of each method will be investigated so that the solving method of FEA, computation time and complexity can be compared. After considering the end winding leakage inductance, the calculated results of all three methods then will be compared and analyzed.

In addition, the practical test methods also will be briefly discussed according to the analysis conclusions. The vector control method in experiment will be applied to verify the simulation results and reveal the accuracy of each calculation method. The final conclusions of this paper will be helpful to guide motor design and drive researchers to choose proper method to evaluate d- and q-axis inductances of IPMSM as particular situation.

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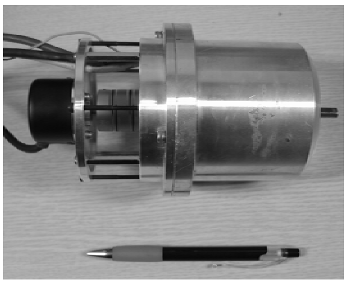
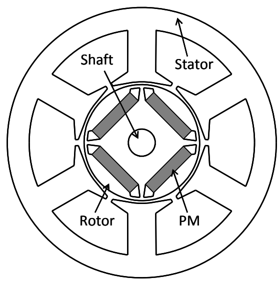
II. Analysis Model

A spindle-type IPMSM is analyzed in this paper. Its photo and cross-section are shown in Fig. 1 (a) and (b), respectively. The structure of 6-slot/4-pole and the concentrated winding pattern are because that the extremely high speed (40000rpm) needs to be reached. The detail dimensions and specification of this motor is shown in Table I.



(a)



(b)

Fig. 1 Photo and cross-section of analysis motor: (a) photo of analysis motor, (b) cross-section of analysis motor

TABLE I
DIMENSIONS AND SPECIFICATION OF ANALYSIS MOTOR

Parameter	Value	Unit
Stator Outer Radiu	79	mm
Rotor Outer Radiu	34.5	mm
Airgap length	0.8	mm
Stack length	35	mm
Volume of PM	16×3.5×34	mm^3
Remanent flux density of PM (@ 20°C)	1.2	T
No. of turn in series connected	60	
No. of parallel circuit	2	
Rated output power	2	kW
DC link Voltage	300	V
Rated current (R.M.S.)	9	A

III. Investigation of Evaluation Methods

The general definition of inductance is the number of flux linkages in web turns per ampere of current flowing in the coil. [9] In the IPMSMs, however, the existing flux linkages of PM are superimposed in the flux linkages due to the excited armature currents, which means that it is impossible to calculate the inductance by the definition without any extra handling.

A. Frozen Permeabilities Method

As known, the operating point of permanent magnet (PM) varies with the load. It means the flux density and permeability of PM will be different for the different excited current. In addition, the PM permeability influences the distribution and saturation of flux linkage which generated by excited armature windings, while the distribution and saturation of flux linkage also affect the operating point of PM. Therefore, the PM cannot be canceled before the inductance analysis.

Making use of the flexibility of FEA, [1] and [2] proposed a method to calculate the pure flux linkages due to the exciting current by removing the magneto-motive force of PM. The procedure of this method is shown in Fig. 2. First, the nonlinear calculation is processed for each load condition, i.e. certain current and current vector angle. And store the permeability of each element including stator, rotor and PM. Next, by using the stored permeabilities, the stored field energy of motor is calculated by a linear calculation with different current and current vector angle. Finally, the d- and q-axis inductances are calculated by (1).

$$L_{d/q} = \frac{2}{3}\left(\frac{2W_s}{i^2}\right) \qquad (1)$$

where W_s is the stored filed energy, i is d- and q-axis currents.

It can be seen that excited current is the initial condition of FEA. Thus, the 2D magneto-static filed analysis can be used in this method. Its governing equation is expressed in (2). It can be seen that this is a typical Poisson equation.

$$\nabla \times \left[\frac{1}{\mu}(\nabla \times \boldsymbol{A})\right] = J \qquad (2)$$

where $\boldsymbol{A}$ is the magnetic vector potential, μ is the isotropic permeability, and J is the excited current density of the stator winding. When the model is meshed into about 6500 elements, the computation time this method spent is less than twenty minutes in a computer with Intel Core Due CPU.

B. Vector Control Method

Depending on the Park's Transformation, the IPMSM usually can be expressed in (3).

$$v_d = R_a i_d + L_d \frac{di_d}{dt} - \omega L_q i_q$$

$$v_q = R_a i_q + L_q \frac{di_q}{dt} + \omega L_d i_d + \omega \psi_a \qquad (3)$$

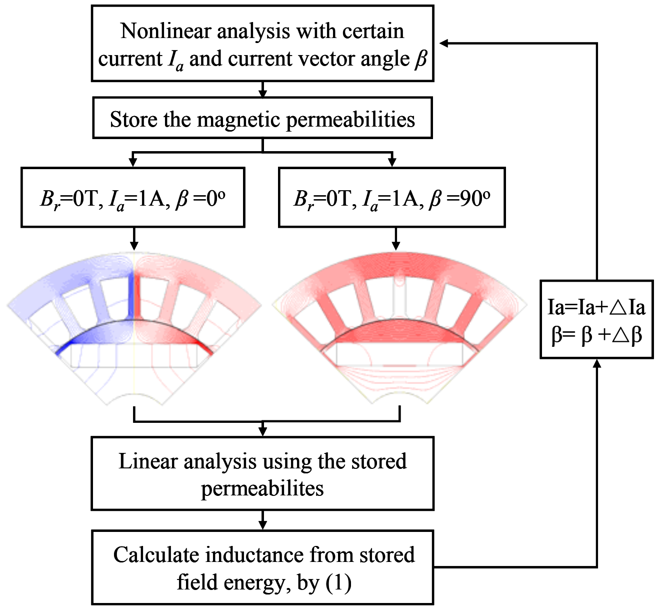


Fig. 2 Procedure of frozen permeabilities method

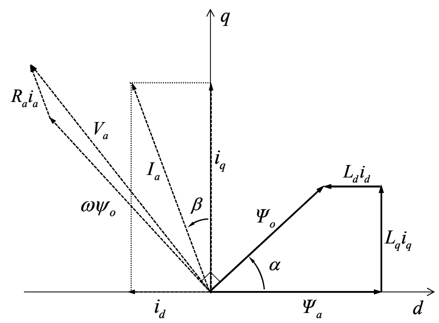


Fig. 3 Vector diagram of IPMSM

And its vector diagram can be described in Fig. 3. In the solid-line part, it can be seen that there are following relationships as described in (4)

$$L_d = \frac{\psi_0 \cos\alpha - \psi_a}{i_d}$$

$$L_q = \frac{\psi_0 \sin\alpha}{i_q}$$

(4)

where ψ_a is the flux linkage generated by permanent magnet in no-load condition, ψ_0 is the flux linkage generated by permanent magnet and excited armature current, L_d is d-axis inductance, and L_q is the q-axis inductance, respectively.

Although the principle is simple, the implement should be paid much attention. First, it is impossible to give d- and q-axis currents directly. The Park's Transformation must be processed for every load condition. Additionally, these relationships are available without considering the harmonics. Hence, the flux linkages obtained in load condition should be filtered by Fourier transform. The detail calculation procedure of this method can be found in Fig. 4. It is obvious that this method also uses the magneto-static field FEA. But in practice, the computation time needs about several-ten minutes with same

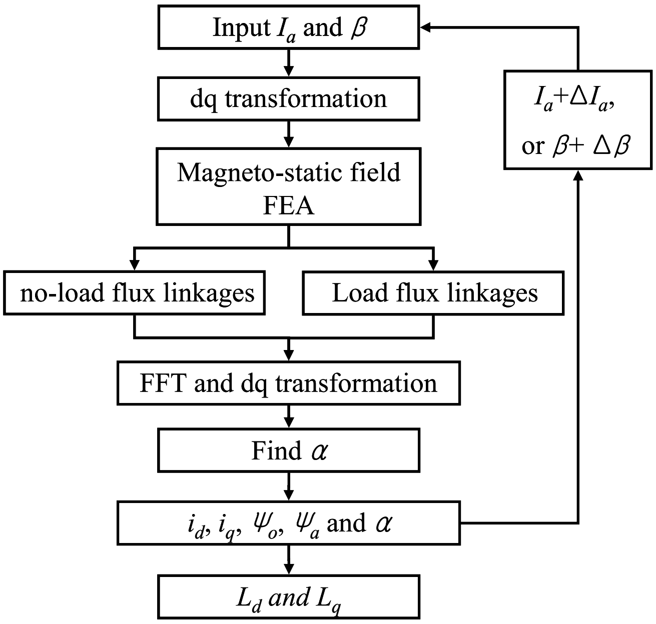


Fig. 4 Procedure of vector control method

computer before, because of the twice nonlinear analysis, FFT, and α angle searching. This method has been proposed in [3], [4]. The corresponding experiments also have been implemented to verify its validity.

C. Differential Flux Linkage Method

As mentioned before, the difficulty for calculating the inductance of IPMSM is because of the existing PM. Furthermore, the operating point of PM also varies with the load condition. [5], [6] proposed a method to eliminate the PM effect without removing the magneto-motive force like frozen permeabilities method. This method regards the operating points of PM under two near load conditions as the approximately same. Thus, the difference of the flux linkages from two near load condition is totally effect of inductance. Additionally, in order to eliminate the q-axis flux linkage when the d-axis inductance is calculating, the q-axis armature current should be constant, vice versa. Then, the d- and q-axis inductance calculation equations can be calculated by dividing the difference of two near load currents as expressed in (5). The detail procedure of this method has been shown in Fig. 5.

$$L_d = \left(\frac{\psi_{d1} - \psi_{d2}}{i_{d1} - i_{d2}} \right)_{i_q = \text{constant}}$$

$$L_q = \left(\frac{\psi_{q1} - \psi_{q2}}{i_{q1} - i_{q2}} \right)_{i_d = \text{constant}} \quad (5)$$

Because the desired variable is the flux linkage, this method can be processed in both magneto-static field FEA and coupled field-circuit FEA, and also can be realized in laboratory experiment. The computation time of this method in magneto-static field FEA is more than that of vector control method because more nonlinear calculation steps.

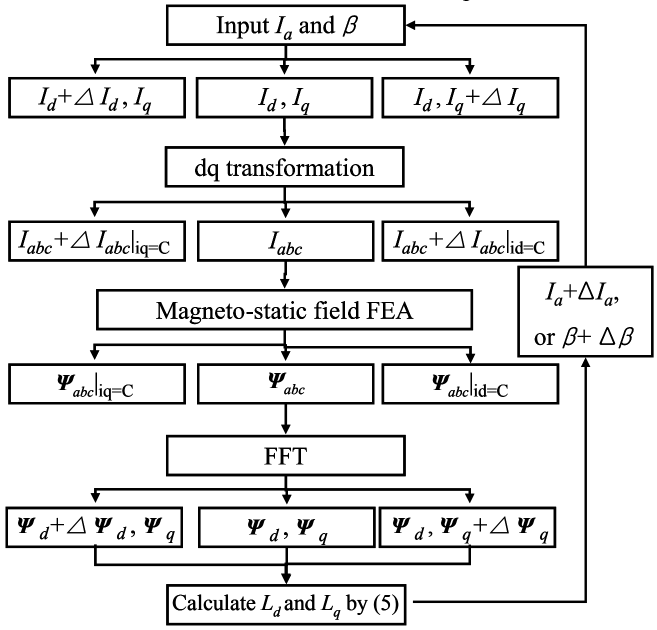


Fig. 5 Procedure of differential flux linkage method

D. Experimental Method

1) Vector control method in experiment

It is impossible to obtain the flux linkage in both no-load and load condition directly. However, the flux linkage can be calculated by Back-EMF with known speed. The flux linkage in the no-load condition is measured in zero d-axis current control, and calculated by (6)

$$\omega\psi_a = v_{q0} - R_a i_{q0} \quad (6)$$

where v_{q0} is the q-axis voltage generated by PI controller in steady state, i_{q0} is the measured q-axis current. And the d- and q-axis inductances are calculated by (7)

$$L_d = \frac{v_q - R_a i_q - \omega\psi_a}{\omega i_d}$$

$$L_d = \frac{(v_d - v_{d0}) - R_a i_d}{-\omega(i_q - i_{q0})} \quad (7)$$

where v_{d0} is the d-axis voltage in no-load condition. The v_{q0}, v_{d0} supply the energy losing in the mechanical losses under no-load condition. That is why they do not exist in theory equations.

2) Differential flux linkage method in experiment

In vector control method, the flux linkage under no-load condition is obtained by voltage and current. However, it is impossible to obtain the flux linkage under load condition in the same method, due to the Back-EMF. This problem has been solved by a locked-rotor method proposed in [5]. The brief procedure of this method for measuring L_q is:

1. lock the rotor.at 0 position;
2. apply a stepwise voltage v_q and control i_d to constant;
3. measure the i_q and record the t;
4. According to (8), the $\Psi_q(t)$can be calculated.

$$\psi_q(t)=\int_0^t (v_q(\tau)-R_a i_q(\tau))d\tau \quad (8)$$

5. According to (5), the q-axis inductance is calculated.

The d-axis inductance can be measured and calculated in the same way.

3) AC standstill method

Except the vector control method and differential flux linkage method, there is another experiment method named AC standstill method for measuring the inductance of IPMSM. [10] Unlike the previous two method, this method measures the phase self and mutual inductance. Also, the tested motor should have a neutral line. After obtain the self- and mutual-inductance in each frequency, the least square method and FFT have to be used to find the fundamental value and calculate the d- and q-axis inductances. It is evident that there is not current vector variation in the AC standstill method, i.e. this method can not present the cross-saturation effect. The measured results can not be used to the accurate vector control.

Due to the limitation of hardware, this paper adopts the vector control experiment method to verify the calculation inductance results.

IV. Results Comparison and Discussion

As known, the operating point of permanent magnet (PM) varies with the load. It means the flux density and permeability of PM will be different for the different excited current. In addition, the PM permeability influences the distribution and saturation of flux linkage which generated by excited armature windings, while the distribution and saturation of flux linkage also affect the operating point of PM. Therefore, the PM cannot be canceled before the inductance analysis.

V. Conclusion

Most authors will be able to prepare images in one of the allowed formats listed above. This section provides additional information on preparing PS, EPS, and TIFF files. No matter how you convert your images, it is a good idea to print the files to make sure nothing was lost in the process.

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Manuscript received May 5, 2008. Corresponding author: Jung-Pyo Hong (e-mail: hongjp@hanyang.ac.kr; fax: 82-2-2220-4465).