Improved Parameter Modeling of Interior Permanent Magnet Synchronous Motor Based on Finite Element Analysis

Gyu-Hong Kang, Jung-Pyo Hong, *Member, IEEE*, Gyu-Tak Kim, and Jung-Woo Park

***Abstract*—This paper presents an investigation of the parameter modeling on the basis of an improved Finite Element (FE) analysis in which the variable frequency characteristic in field weakening is considered in Interior Permanent Magnet Synchronous Motors (IPMSM). The parameters of IPMSM have a nonlinear characteristics under variable load conditions and due to the current phase angle in a system fed inverter. From the analysis of FE, a new vector control algorithm is proposed by neural network using a variable inductance estimator. The performances of variable frequency are simulated by using the proposed algorithm, and the validity of the proposed FE analysis is compared with experimental results.**

***Index Terms*—Parameter modeling, IPMSM, FE.**

I. Introduction

THE conventional analysis method of Interior Permanent Magnet Synchronous Motor (IPMSM) is usually modeled and analyzed by two-axis theory [1], [2]. The method is often used for performance simulation and control system design because of their fast and flexible computation. However, the parameters of IPMSM, such as direct and quadrate axis inductance, vary nonlinearly due to the structural specialty of the rotor, the load condition and current phase angle [3]. This is specially so since the operating condition of IPMSM vary considerably with load and velocity. Accordingly the IPMSM has a characteristic in which the d and q axis inductances, L_d and L_q, vary greatly.

For this reason, in order to improve the accuracy in the computation of the motor parameters and performance, the FE analysis method is used to consider the saturation effect [4]–[6]. In a FE analysis, the d-q axis inductances of IPMSM can be calculated from the stored magnetic energy or flux linkage. However, this fails to estimate the saturation effect of rotor including the PM, which in turn modifies the current phase angle. If the change of these parameters is not considered in an inverter control system, the characteristic of the current controller can worsen and the velocity estimation can fail at certain operating velocities [1].

To overcome the drawbacks, an improved method is presented for the computation of the d-q axis inductances. This method allows the d-q axis inductances to be calculated with the changes of current phase angle and load condition in which the magnetic saturation in field weakening region is considered [7].

Therefore, the new vector control algorithm, based on the FE analysis, is proposed for IPMSM. It refers to the control method in which the property of the variable parameters is considered by using a variable inductance estimator of a neural network. The performance of variable frequency is simulated with the use of the proposed algorithm. This paper presents the analysis method for accurate parameter modeling by FE analysis and is verified by comparison with experimental results.

II. Computation of Parameters by FE Analysis

A. Method of Parameter Modeling

In a linear condition which includes a constant torque region and a constant current phase angle, the flux linkage due to PM and the d-q axis inductances are constant quantities. In this case, L_d and L_q are varied by only the current magnitude [2]–[3], [5]. The parameters of IPMSM in a system fed inverter for field weakening, resulting from the saturation effect, have nonlinear characteristics relating to the current magnitude and the current phase angle [6], [7]. Therefore, in order to improve the accuracy of the computation of the parameters, an adaptive FE analysis is proposed in which saturation effects due to the load condition and current phase angle are allowed for.

The derived governing equation in improved FE analysis from Maxwell's electromagnetic equation is as follow [4].

$$-\frac{1}{\mu_0}\nabla^2\vec{A} = \vec{J} + \nabla\times\vec{M} \tag{1}$$

where $\vec{A}$ is vector potential, $\vec{J}$ is exciting current density and $\vec{M}$ is the magnetization.

The flux linkage λ can then be calculated from the average vector potential over each winding cross section [4].

$$\lambda = \left[\iint_{S_1} A_1\, dS/S_1 - \iint_{S_2} A_2\, dS/S_2\right] l \tag{2}$$

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G.-H. Kang is with the Department of Electrical Engineering at Changwon National University, Changwon, Kyungnam, 641-773, Korea (e-mail: kgh1004@cosmos.changwon.ac.kr).

J.-P. Hong and G.-T. Kim are with the Department of Electrical Engineering at Changwon National University, Changwon, Kyungnam, 641-773, Korea (e-mail: {jphong; gtkim}@sarim.changwon.ac.kr).

J.-W. Park is with Korea Electrotechnology Research Institude, Changwon, 641-120, Kyungnam, Korea (e-mail: jwpark@keri.re.kr).

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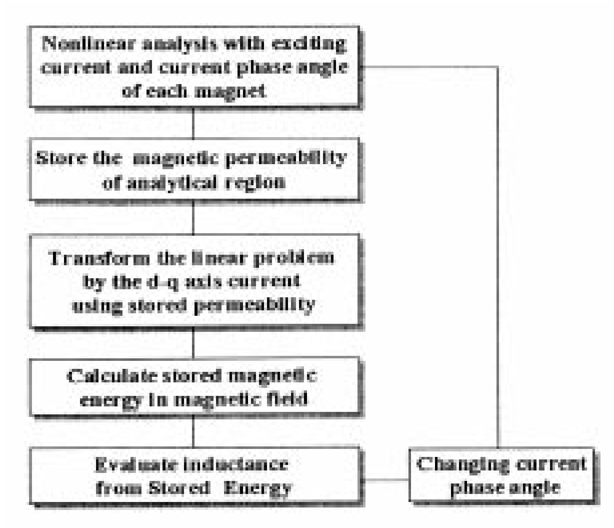

Fig. 1. Inductance computation process by energy dual method considering current phase angle.

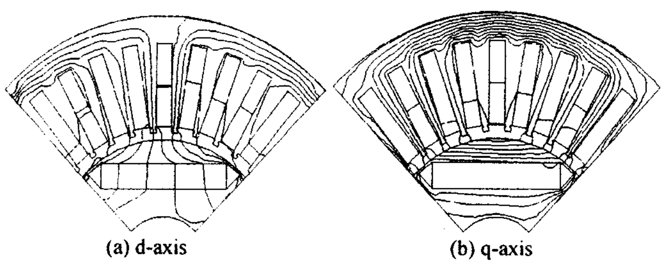

Fig. 2. D-q axis equi-potential distribution. (a) d-axis. (b) q-axis.

where l is the stack length and S_1 and S_2 represent the total areas of an N-turn winding carrying the positive current and negative current, respectively.

As shown in Fig. 1, the computation process of inductances is presented by the energy dual method, which consider both the load condition and current phase angle.

The main point of this method is that it can transform nonlinear problems into linear ones by storing the permeabilities from the nonlinear analysis. This method is a very useful for the parameter modeling in a system fed inverter, and makes it possible to calculate the variation of inductance with the change in current phase angle.

B. Result of FE Analysis

The equi-potential distribution of the d-q axis is shown in Fig. 2. The d-axis flux distribution has a linear characteristic but the q-axis flux varies considerably with the load condition and the current phage angle because of the degree of saturation in the magnetic flux barrier [2], [3], [8].

If the current phase angle is not considered, inductance will become a function only of the current magnitude. In the case of IPMSM, L_q, changes greatly with current magnitude but the L_d, hardly varies. The result of analysis is shown in Fig. 3. If the current phase angle changes with field weakening under constant voltage, the conditions of inductance will vary, which is the same phenomenon as occurs when the magnetic flux barrier saturate [6], [8]. Fig. 4 shows the variation of airgap and leakage

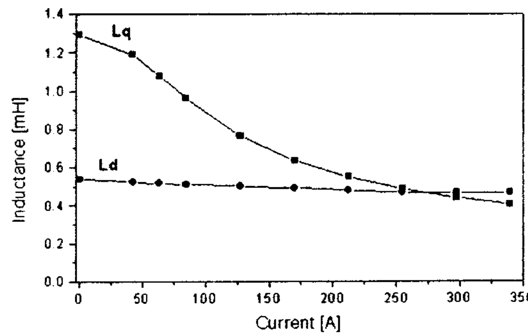

Fig. 3. Variation of L_d and L_q with current magnetite.

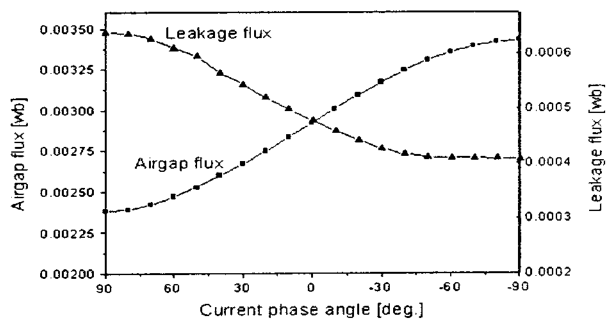

Fig. 4. Variation of fluxes according to current phase angle in rate load.

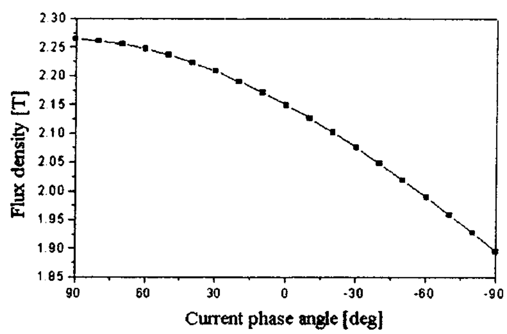

Fig. 5. Flux density in the magnetic barrier according to current phase angle.

flux with changing current phase angle. The airgap flux is decreased when current phase angle is controlled over 0°, while the leakage flux is increased. Moreover, that characteristic of flux contributes to the degree of saturation in the magnetic barriers and accordingly the inductance changes with current phase angle as shown in Fig. 5. Fig. 6 shows how L_d and L_q change in accordance with changing current phase angle and load condition in the FE analysis. It should be noticed that the L_d is slightly influenced by current phase angle and load condition and characterized by its linearity whereas L_q is severely affected by both factors. This is mainly due to saturation.

III. Comparison of FE Analysis to Experimental Results

The accuracy of the described FE analysis is examined in comparison to experimental results. Fig. 7 shows the rotor structure of IPMSM and a dynamo-system for torque and inductance evaluation.

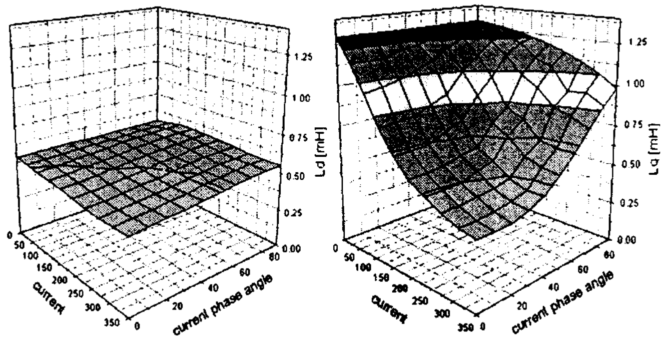

Fig. 6. Variation of L_d and L_q by current magnetite and current phase angle.

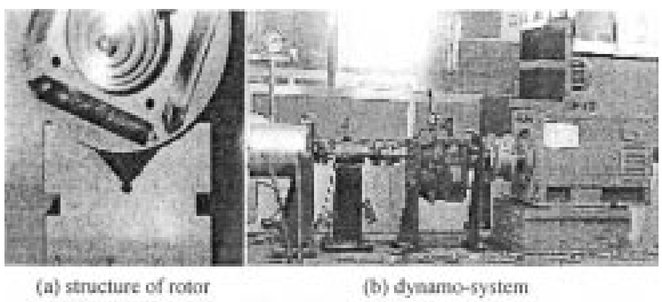

Fig. 7. Experimental equipment. (a) Structure of rotor. (b) Dynamo-system.

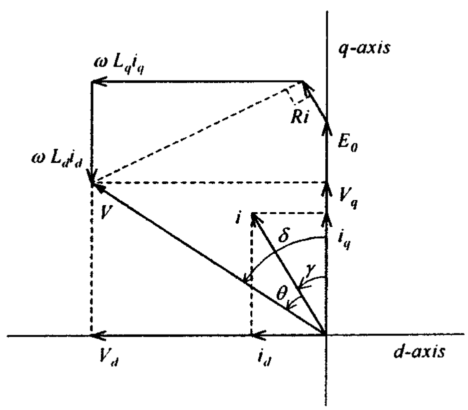

Fig. 8. Vector diagram of the IPMSM.

Fig. 8 shows the vector diagram of the IPMSM in the d-q coordinates. It is difficult to measure the inductance in load condition, thus an indirect method by way of the vector diagram is applied. This method is used in an inverter system enabling the control of i_d and i_q to control current phase angle γ. On the other hand, it is possible to measure the other components. The computation of L_d and L_q by an indirect method under the rated load condition is as follows [8].

$$L_d(\gamma) = \frac{E_0 + Ri_q - V_q}{\omega i_d} \tag{3}$$

$$L_q(\gamma) = \frac{V_d - Ri_d}{\omega i_q} \tag{4}$$

where E_0 is the no load electromotive force, R represents the phase resistance and ω is electrical angular velocity.

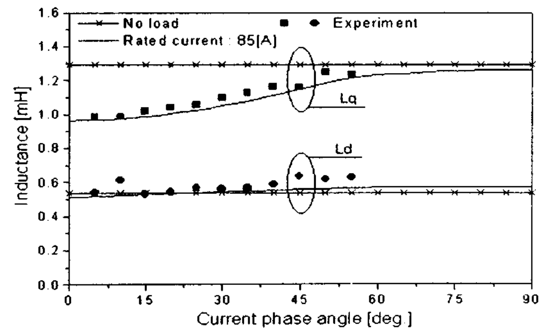

Fig. 9. D-q axis inductance with current phase angle.

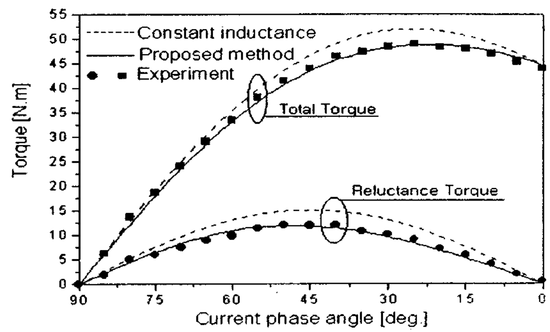

Fig. 10. Torque characteristics with current phase angle equipment.

Fig. 9 shows L_q has a nonlinear characteristic with changing current phase angle. Fig. 10 shows the comparison of the torque characteristic between the analysis and experimental results. In the case of using constant inductance without considering saturation effects by current phase angle, reluctance torque becomes larger than that by experimental results. However, when considering saturation effects, the torque characteristics agree with the experimental results. Thus, the proposed analysis method is verified as an improved parameter modeling.

IV. Investigation on Vector Control Based on Saturation Effect

From the improved FE analysis, it is known that L_d and L_q become a function of current magnitude and current phase angle. To analyze the dynamic characteristic with a system fed inverter, a parameter estimator is used to predict the characteristics of L_d and L_q in accordance with variable load and frequency [8]. This paper proposes a combination of neural network and vector control algorithm, which estimates the changing L_d and L_q. The variable characteristics of L_d and L_q have a great influence on the current controller for vector control when it is operated in a high velocity region [7], [8]. These inductance variations are verified by dynamic characteristic simulation.

Fig. 11 shows the process of vector control algorithm with a neural network estimator, which can estimate L_d and L_q when current magnitude and current phase angle become its inputs. In this study, updates of L_d and L_q values used to calculate the d-axis current in the current controller which is the executed by

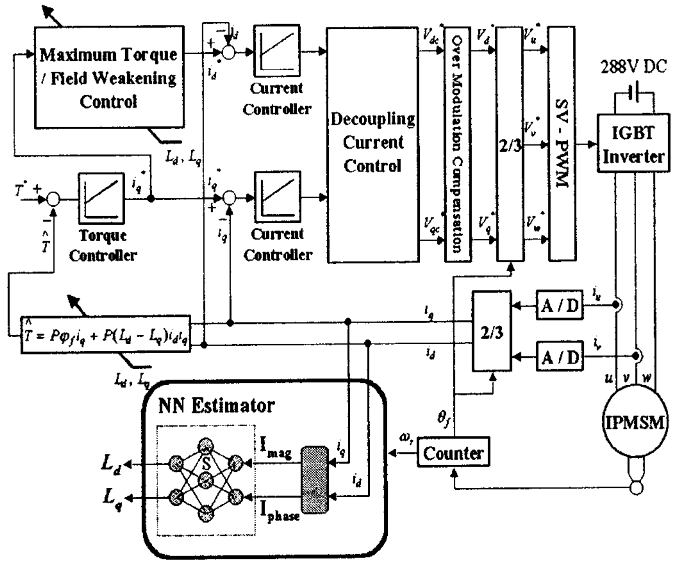

Fig. 11. Vector control block diagram with L_d and L_q estimator for IPMSM. (a) Without estimator. (b) Estimator using neural network.

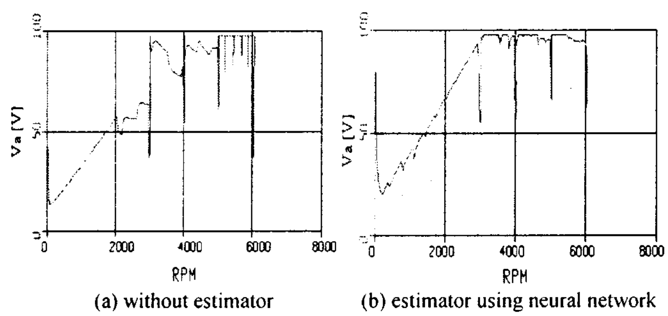

Fig. 12. Voltage characteristic of current controller. (a) Without estimator. (b) Estimator using neural network.

the estimator while the results of the FE analysis are used as input values.

Fig. 12 shows the difference in the voltage characteristic of the current controller with and without a parameter estimator. When using a parameter estimator, the improved performances of the current controller are shown in Fig. 12(b). On the other hand, Fig. 12(a) shows the phase voltage is heavily distorted in every region due to the failure of parameter estimation. Fig. 13(a) shows the constant L_d and L_q with changing current phase angle, and Fig. 13(b) presents the estimated values of L_d and L_q by the neural network estimator.

From these results, it is shown that the characteristics of variable velocity in the field weakening control region and the performance of the current controller can be improved by an accurate analysis of parameters. Furthermore, the process is characterized by an accurate voltage control. It is concluded that parameters of IPMSM, L_d and L_q, vary nonlinearly depending on its current magnitude and phase angle.

V. Conclusion

Due to saturation, the parameters in IPMSM vary nonlinearly. Especially for an optimal driving condition, field weakening control and maximum torque per current, it is necessary to vary the current phase angle in a system fed inverter. This paper presents an improved FE analysis using energy dual method in which the characteristic of the system fed inverter is taken into account. It is observed that the d-axis inductance is slightly influenced by current phase angle and load condition, while L_q is severely affected by both current phase angle and the load condition. This analysis method is verified by comparison with experimental results.

Since the nonlinear variation of the parameters has an effect on the control characteristic of the system fed inverter, the parameters variation should be evaluated as a function of driving characteristic in an inverter. Therefore, the analysis of both dynamic and static characteristics of IPMSM requires a precise parameter computation with consideration given to the driving characteristic of the inverter system.

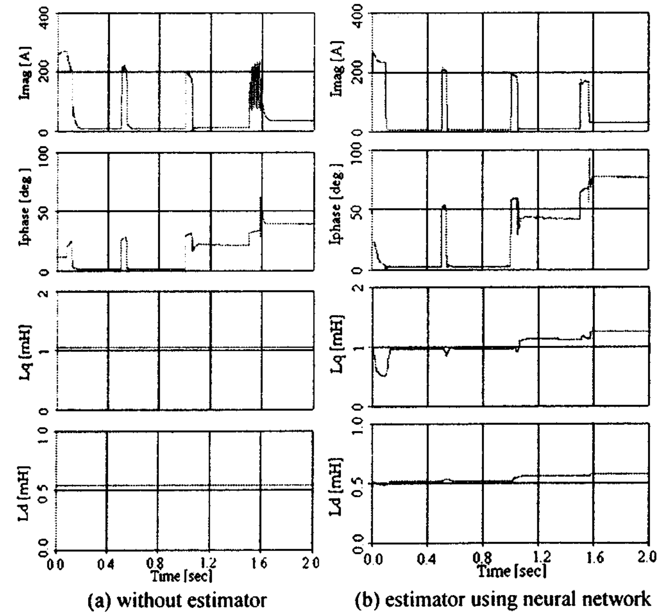

Fig. 13. Current and inductance characteristics in dynamic simulation.

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