Nonlinear characteristic analysis of Interior type Permanent Magnet Synchronous Motor

Gyu-Hong Kang, Jung-Pyo Hong, Gyu-Tak Kim
Dept. of Electrical Engineering, Chang-won National University, Chang-won 641-773, KOREA

Abstract - **The characteristics of permanent magnet synchronous motor defined by airgap flux and circuit parameters. Interior Permanent Magnet Synchronous Motor(IPMSM) has a nonlinear characteristics due to structural specialty of rotor, so it is difficult to analyze circuit parameters and characteristics. This paper presents the calculation of circuit parameters by using Finite Element Method(FEM) considering of nonlinear characteristics. Using the circuit parameters by FEM, IPMSM is analyzed and is compare with the experimental values.**

Index term – **IPMSM, FEM, Nonlinear characteristics.**

_. Introduction

Interior type Permanent Magnet Synchronous Motor(IPMSM) which is generated the reluctance torque because of its saliency by structural characteristic of rotor, so its torque and speed versus power characteristics should analyze to precise.[1][2] Especially, In inverter feeding, field-weakening driving is required for expansion of speed versus output region, so circuit parameters should analyze to precise because of speed versus power characteristics depend only on circuit parameters of machine.[3][4] Direct and quadrate axis reactances of IPMSM according to magnetic pole position are change to nonlinear by structural characteristics of rotor. So numerical method is required to parameters calculation because of nonlinear characteristics according to rotor position is difficult to analyze by analytical method.[1][2]
In this paper, d-q axis inductances are precisely calculated with rotor position by using Finite Element Method(FEM) which has been widely used to accurately predict the electromagnetic response.[2][3] In the case of rotary machines, in order to analyze to nonlinearity of inductances by rotor position, the moving method to rotor position is mainly applied but it has problems to remesh of element and to increase calculating time according to rotor moving. Therefore, changing method to current phase angle apply for d-q axis inductance in defined analysis model.[2][3] The field-weakening characteristics of IPMSM by using circuit parameters which is estimated by FEM is analyzed and compare with EMC and experimental value.

_. Characteristic analysis

A. EMC analysis

To estimate parameters of IPMSM by using Equivalent Magnetic Circuit(EMC), simple form of magnetic circuit and distribution of flux density should precisely calculate magnetic flux from the relationship of magnetic motive force(MMF) with permeance.[1][3] Cross section and specification of analysis model are shown Fig.1 and Table 1.

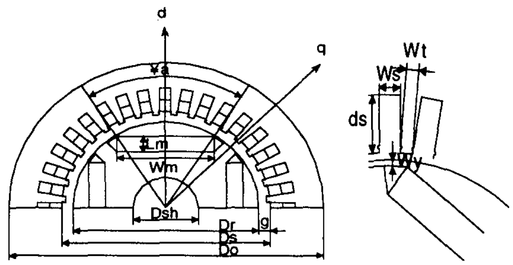

Fig .1 Cross section of analysis model

Table. 1 The specification of analysis model

Output / pole	15[kW]-4P	**Stator**	
number	98[V]	Do	171 [mm]
Phase voltage	85[A]	Ds	91 [mm]
Rated current	3000[rpm]	Stack length	87 [mm]
Base speed	36	Ws	5.8 [mm]
Number of slot	8/9	Wt	2.1405[mm]
Chording	2.2[mm]	Ds	30[mm]
Airgap length	1.12[T]	**Rotor**	
Residual flux	21[Koe]	Dr	87[mm]
density	0.75	Dsh	40[mm]
Coercive force	47[mm]	Wy(link	1[mm]
Polr arc coefficient	91[mm]	width)	9[mm]
Magnet width		Lm	
Magnet length			

D-q axis reactances, X_d and X_q, calculated from the MMF of d-q axis current and the equivalent effective airgap are as follows.[1][4]

$$X_d = \frac{6\mu_0 D L_{stk} f}{p^2 g_d''}(k_{w1}N_{ph})^2 + X_\sigma \qquad (2.1)$$

$$X_q = \frac{6\mu_0 D L_{stk} f}{p^2 g_q''}(k_{w1}N_{ph})^2 + X_\sigma \qquad (2.2)$$

where μ_0 is magnetic permeability of vacuum, D is the rotor diameter, L_{stk} is the stack lengh, k_{w1} *is* the winding coefficient, N_{ph} *is* the coil turns per phase, X_σ is the leakage reactance. g_d" is equivalent d-axis effective airgap and g_q" is q-axis.
The results of analysis by EMC, inductances, airgap flux and electro motive force(E_0)and due to magnet, are shown Table 2. Saliency of analysis model is 1:2.94.

Table. 2 Calculating parameters by using EMC

X_d	0.3585[mH]	ψ	0.0027294[wb]
X_q	1.0555[mH]	E_0	55.02[V]

Torque - current angle characteristics of IPMSM at base speed as estimated from an EMC is shown Fig. 2. Magnetic torque is 44[N.m] at zero degree and reluctance torque is generating 15[N.m] at 45 degree to current angle. Reluctance torque is generating about 1/3 of magnetic torque, so total torque which is generating 52[N.m] at 24 degree to current angle is enhanced 18.2[%] relate to

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magnetic torque. This is due mainly to the saturation effect of rotor. Inductance analysis considering a nonlinear characteristic, saturation effect, leakage effect, is difficult by EMC because nonlinear analysis is could not. A more accurate inductance calculation method is therefore necessary to improve the accuracy of analysis, especially for inductance evaluation.

Fig .2 Torque characteristics according to current angle

B. FEM Analysis

To estimate nonlinear reactance of IPMSM, each of magnetic flux path and equivalent magnetic resistor should calculate according to rotor position. In EMC, however, precise calculation to reactance is limited to each of rotor position by generating error which are in selection of magnetic flux path and nonlinear flux density in link and calculation of magnetic resistor in order to fringing. Rotor position, therefore, is defining d-q axis and reactance is calculating, d-q axis, each of axis. Field-weakening characteristics, speed versus power characteristic by changing current angle, using the parameters which is calculate a method of this sort accompany by large error. [2][3][4]

In this paper, reactances considering nonlinear characteristics of IPMSM are` calculated precisely with rotor position by using FEM. By using the parameters by FEM, a field-weakening characteristic is to analysis and compare with EMC.

Assuming a two dimensional analysis, the derived governing equation from Maxwell's electromagnetic equation is as follow.[2]

$$-\frac{1}{\mu_0}\,{}^{2}\vec{A} = \vec{J} + \leftrightarrow\vec{M} \qquad (3.1)$$

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

The inductance that has a nonlinear characteristic calculated by using energy dual method.[2][3] Energy dual method is calculating inductances from increase in current versus storage energy. Inductance calculation process by energy method showed Fig. 3.

Fig .3 Inductance calculation process

The equation of inductance calculation, increase in energy due to increase in current, is as follows.

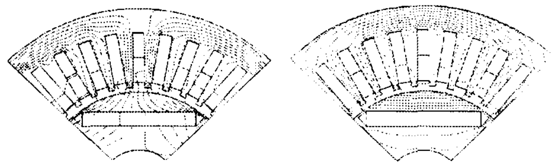
IPMSM has a large dispersion effect of flux because permanent magnet inset into the rotor. Although magnetic pole arc of the analytic model is 135° of electric angle, airgap flux density by permanent magnet distributed from one pole to almost area. Fig.4 shows flux density in airgap and the link in case of only excited permanent magnet. The link fully saturated to prevent short between magnets.

(a) Airgap flux density (b) Flux density in link

Fig .4 Characteristics of Flux density by permanent magnet

Fig. 5 shows flux distribution of the d-q axis. D-axis flux varies linearity respect to phase angle but q-axis flux largely varies according to phage angle because of nonlinear region by saturation in the link.

Fig.6 and 7 shows variation of inductance and saliency ratio according to current phase angle.



(a) d-axis (b) q-axis

Fig .5 d-axis, q-axis Equi-potential distribution.

Fig .6 Current angle versus Inductances

Fig .7 Current angle versus X_q / X_d

_. Analysis results

EMC has a large dif ference at speed-power characteristics compare to FEM because inductance and salient ratio(X_q / X_d) of the IPM change according to current phase. Fig.8 and Fig.9 shows speed-power characteristics on field weakening using calculated d-q inductance by FEM. The result of field weakening analysis by using FEM parameter which is d-q axis inductance considering nonlinear characteristics by FEM, q-axis inductance and salient ratio at base speed is decreased compare to EMC, so generated torque decrease. However, the current phase that generated maximum torque per ampere is increased, so based speed is increased from 4,000[rpm] to 4,500[rpm]. In field weakening driving, d-axis and q-axis inductance according to current phase increased, maximum speed increased from 8,000 to 11,000 compare to EMC. As increment of saliency to current phase, torque increase at over based -speed region.

The operating limits deeply depended on the parameters, especially in the case of IPMSM. Therefore, it is important to analyze parameters precisely in order to analysis speed characteristic satisfied power of IPMSM.

Fig .8 Voltage versus current characteristics according to velocity

Fig .9 Speed versus output characteristics by Field-weakening

_. Conclusion

This paper is analyzed d-q axis inductance of IPMSM as FEM and EMC then compared each of speed-power characteristics. In the EMC, it cannot consider inductance according to rotor position, in FEM it is able to analyze variation of inductance according to current phase. As a result of FEM analysis, q-axis inductance varies non-linear respect to current phase so speed-power region have much difference compare to EMC.

Variable speed motor that speed-power region determined system performance have to analyze nonlinear characteristic of parameters precisely. Especially, speed-power region of IPMSM is largely changed by nonlinear characteristics of system. Throughout this paper, we will verify result of analysis by the experiment and compare of them.

REFERENCE

[1] T.J.E. Miller, Design of Brushless Permanent Magnet Motor, Clarendon Press, Oxford, 1994.

[2] Liuchen Chang, "In Improved FE Inductance Calculation for Electrical Machine", IEEE Trans. on Magn, Vol. 32. No. 4, pp. 3237~3245, july.1996

[3] Masayuki Sanada, Shigeo Morimoto and Yoji ta keda, "Interior Permanent Magnet Linear Synchronous Motor for High-Performance Drives", IEEE Trans. on Ind, VOL. 33, NO. 4, pp. 966~972, JULY/AUGUST 1997

[4] Shigeo Morimoto, Yoji Takeda, "Generalized Analysis of Operating Limits of PM Motor and Suitable Machine Parameters for Constant Power Operation", T.IEE, vol. 177-D, No. 6, pp. 751~757, 1997