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유전자 알고리즘을 이용한 매입형 영구자석 전동기의 최적 설계

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EFFICIENCY OPTIMIZATION OF INTERIOR PERMANENT MAGNET SYNCHRONOUS MOTORS USING GENETIC ALGORITHM

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Abstract

Since Interior Permanent Magnet syncronous Motor has a structure whose magnet is inserted in the rotor, d, q inductance is differ and the motor products hybrid torque combined allignment term and reluctance term. Air gap flux density and d, q axis inductances of the Interior Permanent Magnet Synchronous Motor obtained by analytical method are compensated using Finite Element Method. For optimal design, the efficiency of the motor is taken as the objective function, and Genetic Algorithm finds the value of design parameters which maximize the objective function.

1. Introduction

Developement of the optimization technique utilizing the vast capacity and the high speed of computers makes the optimal design of the motor possible. Most of the optimization techniques applied to the motor design are based on the deterministic method.[1-3] But, they cannot guarantee that the solution reaches the global optimum in case the objective function has many local maxima or minima. Recently, to overcome this difficulty, several stochastic methods are used which are proved to find the global optimum of the function.

This paper presents a method suitable for the optimal design of Interior Permanent Magnet Synchronous Motor (IPMSM) of which performance formulas have complex forms. To obtain more accurate formulas, the air gap flux density and *d, q* axis inductances computed from the equivalent magnet circuit analysis are compensated using Finite Element Method(FEM). For the optimization, the efficiency of the motor are taken as the objective function, and the values of design parameters which maximize the objective function are found by using genetic algorithm. Through the comparisons between the prototype and the optimally designed motor, it is verified that more improved results can be obtained by the proposed algorithm.

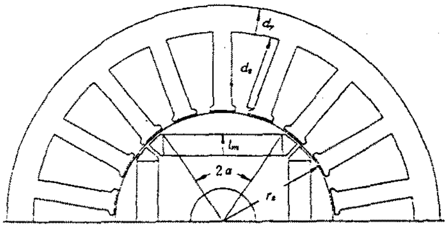

Fig. 1 Cross section of IPMSM

2. Air Gap Flux Density and Inductances

IPMSM has a structure that magnets are inserted in the rotor as shown in Fig.1. The air gap flux density distribution is rectangular under ideal assumption. The equivalent magnetic circuit analysis can give the approximate formula for the air gap flux density B_g.[4]

$$B_g = \frac{B_r w_m l_r - \Phi_l}{\mu_r k_c g w_m l_r / l_m + 2\alpha r_s l_r / p} \qquad (1)$$

where,

B_r : residual flux density of magnet
g : air gap length
k_c : Carter coefficient
l_m : magnet thickness
l_r : stator axial length
p : number of pole pairs
r_s : stator bore radius
w_m : magnet width
2α : pole arc angle
μ_r : relative permeability of the magnet
Φ_l : leakage flux

But Eq. (1) does not give the exact value and waveform of air gap flux density. This is because the value of leakage flux component and the increment of magnet pole arc angle, due to fringing effect and the saturation of rotor link section, cannot be calculated analytically if the shape of the motor is complex.

Their relatively exact values can be obtained by using FEM. The result shows that actual flux density waveform is near trapezoidal as in Fig.2. To apply this result to the analytical method, this waveform is replaced by an equivalent rectangular one with same area and amplitude. Effective magnet pole arc angle is computed from the width of the equivalent waveform. This is approximately equal to the average of the upper and lower width of actual waveform. And the value of leakage flux component is calculated from the amplitude of the waveform.

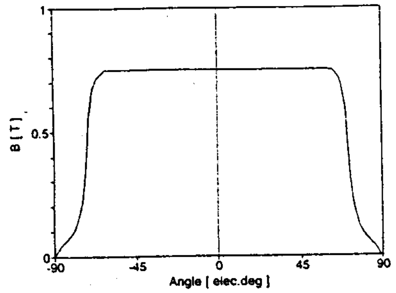

Fig.2 Air gap flux density distribution obtained by Finite Elemenмt Method

And, d, q axis inductances are also compensated similarly. Eqs. (2) and (3) represent the d,q axis inductances, respectively.

$$L_d = \frac{6\mu_0 r_s l_r (k_w N_s)^2}{\pi p^2 g_d} + L_l \qquad (2)$$

where,

$$g_d = \frac{k_c g}{k_{d\alpha} - \dfrac{k_1 k_\alpha}{1 + \mu_r p k_c g w_m / 2\alpha r_s l_m}},$$

$$k_{d\alpha} = (1/\pi)(2\alpha + \sin 2\alpha),$$

$$k_\alpha = \frac{\sin\alpha}{\alpha}, \quad k_1 = \frac{4\sin\alpha}{\pi}$$

$$L_q = \frac{6\mu_0 r_s l_r (k_w N_s)^2}{\pi p^2 g_q} + L_l \qquad (3)$$

where,

$$g_q = \frac{g_e}{k_{q\alpha}}, \qquad k_{q\alpha} = \frac{2\alpha - \sin 2\alpha}{\pi}$$

k_w : winding factor
L_l : leakage
N_s : number of turns per phase
y : width of rotor link section
μ_0 : permeability in the free space

Using the compensated formulas of air gap flux density and d, q axis inductances, more accurate prediction of the motor performance is possible. The computed increment of magnet pole arc angle and leakage flux from the equivalent waveform are used throughout the optimization process in this paper. It is assumed that these values are constant as far as the motor dimensions are varied in the limited region given by the constraints.

3. Optimal Design

Objective Function

The aim of the optimization in this paper is to maximize the efficiency of the motor η. It can be represented as follows.

$$\eta = \frac{\text{output}}{\text{output} + \text{loss}} \times 100\ [\%] \qquad (4)$$

In the salient pole type motor such as IPMSM, power optput consists of the two terms-magnet alignment and reluctance components.

$$P_{out} = 3(E_{ph} I_q + (X_d - X_q) I_d I_q) \qquad (5)$$

where,

$$E_{ph} = \frac{4\sqrt{2}}{\pi p} k_w N_s r_s l_r B_g \sin\alpha\ \omega_s$$

$$I_d = -I_s \sin\gamma, \quad I_q = I_s \cos\gamma$$

I_s : stator current
γ : current angle
ω_s : source frequency

Motor losses are composed of the stator winding loss (P_{sw}), the stator core loss (P_{cl}), and mechanical loss(P_{mech}), and can be represented as a function of design parameters as follows.[5]

$$P_{sw} = \frac{36\rho_c N_s^2 I_s^2}{\pi f_s d_s (r_s + d_s)} \left(l_r + \frac{\pi r_s k_\sigma}{p}\right) \qquad (6)$$

$$P_{cl} = \frac{16 k_{cl}}{\pi p} S r_s l_r d_s B_g^2 \omega_s^2 + \frac{16 k_{cl}}{p}\left(r_s + d_s + \frac{d_y}{2}\right)\frac{r_s^2 k_i l_r \alpha}{d_y} B_g^2 \omega_s^2 \qquad (7)$$

d_s : slot depth
d_y : yoke depth
f_s : slot fill factor
k_{cl} : core loss factor
k_σ : overhang coefficient of the winding
S : number of slots
ρ_c : resistivity of wire

This paper concerns with the design at the rated speed and output power. So, load current and mechanical loss are considered as constant. And other loss components such as stray load loss and rotor loss are neglected because of their little contribution to the overall loss of permanent magnet type motors. magnet residual flux density, number of slots, air gap length, stator outer radius and output power are also given by constant values in accordance with the prototype motor.

In this case, the number of stator turns (N_s), stator bore radius (r_s), stator axial length (l_r), stator yoke depth (d_y), stator slot depth (d_s), magnet pole arc angle (2α), magnet thickness (l_m) are chosen as the design variables. And the constraints are given as follows.

i) constant stator outer radius
ii) constant motor output
iii) limits of magnet width

$$w_m \le 2\left((r_s - g - y)\cos\frac{\alpha}{p} - l_m\right) \qquad (8)$$

iv) limits of stator teeth flux density B_t and yoke flux density B_y

$$B_t \cong 2B_g \le B_{tmax} \qquad (9)$$

$$B_y = (r_s \alpha B_g)/(p\, d_y) \le B_{ymax} \qquad (10)$$

v) limits of specific loading M

$$M_{min} \le M = \frac{2\alpha r_s l_r B_g}{3 k_w N_s I_s} \le M_{max} \qquad (11)$$

vi) limits of stator current density J_c

$$J_c = \frac{6 N_s I_s}{\pi f_s d_s (r_s + d_s)} \leq J_{\max} \qquad (12)$$

vii) capability of the magnet to protect the demagnetization

$$-(U_m - U_s) \leq H_d l_m \qquad (13)$$

where,

U_m : mmf due to the magnet
U_s : armature reaction mmf
H_d : magnet field intensity of the knee point

Genetic Algorithm

Optimization method used in this paper is Genetic Algorithm which imitates the natural selection and genetics. This method consists of three operator-reproduction, crossover, and mutation.

From the two equality constraints, two variables (d_s, l_r) are eliminated so that the number of variables are reduced to five. The population of each variable is 100, and the code length is 10. Every population which is generated randomly in first stage is checked if the constraints are satisfied. After the constraints checking step, the value of the objective function-fitness value-is evaluated. Objective function is scaled by multiplying a suitable constant- 100 in this paper- so that the algorithm works properly.

Then, reproduction is a process by which individual strings are copied according to their fittness. The probability of reproduction is directly proportional to the fitness of each string.

This resembles the natural selection, that is, the survival of the fittest.

Crossover follows the reproduction. Members in the mating pool are mated at random, and along each pair of strings an integer position k is selected uniformly at random on the interval (1, 9). Then, two new strings are created by exchanging all characters between positions k and 10 inclusively.

Using these two operators, Genetic Algorithm finds the more fit strings, but it happens to find the local peak by these operators only. To overcome this difficulty, algorithm offers the mutation operator. This is the random alternation of a string position which is also chosen at random. In a binary code used in this paper, this simply means changing 1 to 0, or vice versa. By chance, if the upper bit is alternated, algorithm can escape from the local maximum and finds the global optimum.

4. Comparison between the Prototype Motor and the Optimized Motor

With the result of optimization and performance formulas, the parameters and performance of optimally designed motor(optimized motor) are calculated. Some of the main results are as follows.

1) Design parameters of the prototype motor and the optimized motor are shown in Table 1. As shown in the table, some parameters (N_s, r_s, l_m) of the optimized motor decreases, and some (l_r, d_y) increases. Consequently, the mass of the magnet and copper reduces. Also, the dimensions of the rotor reduces. From these results, it is concluded that rotor inertia decreases and power rate increases. That is, it means the improvement of servo performance.

2) Efficiency of the optimized motor at rated load becomes 77.83 %, which is greater than that of the prototype(75.9 %). Fig. 3 shows the relationships between the load and the efficiency of the prototype and the optimized motor. The simulation and experimental results of prototype motor are in good agreements, and the efficiency of the optimized motor becomes greater than that of the prototype for every load. This shows that better results can be obtained by using the design optimization method proposed in this paper.

Table 1. Design parameters of the prototype motor and the optimized motor

parameters	unit	protype motor	optimized motor
the number of turns	-	480	444
stator bore radius	mm	20.25	18.20
stator axial length	mm	41.60	49.59
yoke depth	mm	5.82	7.71
slot depth	mm	13.25	13.30
pole arc angle	elec.deg	68.00	72.40
magnet thickness	mm	4.00	3.37

5. Conclusion

An optimal design method for Interior Permanent Magnet Synchronous Motor employing genetic algorithm is presented which maximizes the efficiency of motor. It is found that the optimized motor shows higher efficiency and improved servo perfomance, and requires less amount of material. The proposed method can be applied to the optimal design of other types of motors.

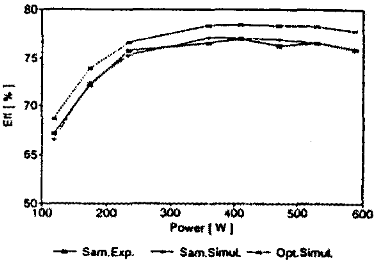

Fig. 3 Load-efficiency curve

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