Experimental Verification and Electromagnetic Analysis for Performance of Interior PM Motor according to Slot/Pole Number Combination

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Abstract— This paper deals with experimental verification and electromagnetic analysis for performance of interior PM (IPM) motor according to slot/pole number combination. First, for a conventional 6-pole IPM rotor, stators with 18, 27 and 36 slots satisfied with same required and restricted conditions are designed. And then, performances and parameters of each IPM motor such as cogging torque, torque ripple, d- and q- axis inductance, total harmonic distortion (THD) of back-emf, etc. are investigated using 2-d finite element analyses (FEA). Finally, test results such as d-/q- axis inductance, back-emf, cogging torque measurements are given to confirm the analyses.

I. Introduction

IPM motor is being studied as a promising candidate for many industrial applications due to its high torque density, higher efficiency, and a wide constant power operating range [1]. In particular, when the IPM motor is applied to electric vehicles or home appliance applications, it should be run quietly and smoothly. Therefore, the reduction of cogging torque and torque ripple that may cause vibration and acoustic noises has become a critical issue. Also, in order to achieve high performance sensorless drive, particular attention is paid to the improvement of control parameters such as THD of back-emf and d- and q-axis inductance characteristics. Many researchers have studied optimal design of the IPM motor in order to reduce ripple components of torque and improve control parameters [2]. However, because of many design parameters, it is difficult to implement the optimal design of IPM motor, especially, rotor shape optimization.

Therefore, since our work is motivated by an effort to find alternatives to improve performances of IPM motor without rotor shape optimization, slot/pole number combination method is selected as a promising alternative. First, for a same rotor, stator structures of which slot number per pole per phase is 1, 1.5 and 2 suitable for distributed windings are arranged. These arranged stator structures are already designed in order to be satisfied with same rated and restricted conditions. And then, using 2-d FEA, this paper compares and analyzes performances and parameters of each IPM motor. In addition, by performing experiments such as back-emf, d- and q- axis inductance, cogging torque measurements, etc., the validation of analysis results is verified extensively. Finally, the results show that IPM motor with 27-slot stator has even more outstanding performances than others. So, we confirm that performances and parameters of IPM motor can be improved by slot/pole number combination method.

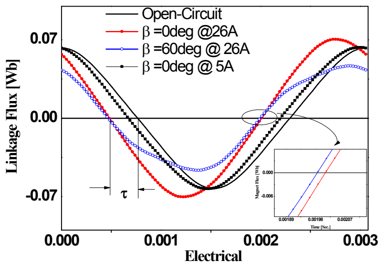


Fig. 1. Flux linking one-phase of the IPM motor obtained under various loads.

II. Equations in IPM Motor

A. Voltage and Current Equation

The voltage and current equations of the IPM motor may be expressed as follows [3]:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_a + PL_d & -\omega L_q \\ \omega L_d & R_a + PL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_f \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -i_a \sin\beta \\ i_a \cos\beta \end{bmatrix} \quad (2)$$

Where v_d, v_q: d- and q-axis armature voltage, i_d, i_q: d- and q-axis armature current, L_d, L_q: d- and q-axis inductance, P: differential operator, ω: rotor angular speed, ψ_f : effective value of magnet flux at no-load, R_a: armature resistance, i_a: effective value of load current and β: current phase angle.

B. D- and Q- axis Inductance Equation

The equations for d- and q- axis inductance of IPM motor can be obtained as

$$L_d = \frac{\psi_o \cos\alpha - \psi_f}{i_d} \quad (3.a) \qquad L_q = \frac{\psi_o \sin\alpha}{i_q} \quad (3.b)$$

where ψ_o is the effective value of linkage flux at on-load. α is the phase difference between fundamental component of linkage flux at no-load and that at on-load, and can be calculated by $\alpha = \omega\tau$ from Fig .1. It can be seen that α is much more affected by current value than current phase angle due to saturation of rotor core.

C. Torque Equation

Torque equation of IPM motor is given by

$$T = p\left\{\psi_f i_q + \left(L_d - L_q\right) i_d i_q\right\} \quad (4)$$

where p is the number of pole-pairs. In (4), first and second term of right-hand side are excitation and reluctance torque, respectively. Due to $(L_d - L_q) < 0$ in the IPM motor, i_d should be negative value in order to utilize reluctance torque. Thus, it should be careful for irreversible demagnetization due to armature reaction flux produced by negative d-axis current.

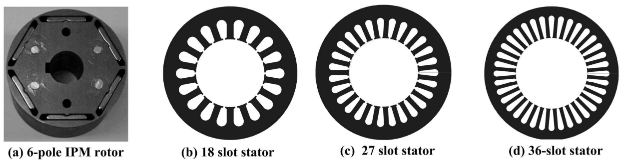
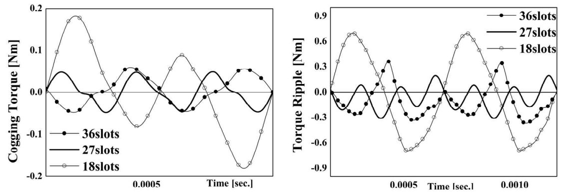
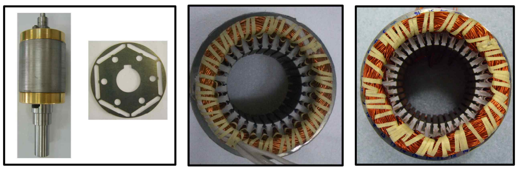


Fig. 2. IPM rotor with 6-pole NdFeB magnets and stator structures with three different slot numbers.



(a) (b)

Fig. 3. (a) Cogging torque and (b) torque ripple obtained under rated torque conditions of the IPM motors with 18, 27 and 36 stator slots.



(a) (b) (c)

Fig. 4. Manufactured IPM Motor: (a) rotor core steel sheet and fabricated rotor with 6-pole NdFeB magnets, stator with (b) 27 slots and (c) 36 slots.

III. Results and Discussion

Figure 2 shows the IPM rotor with 6-pole NdFeB magnets and stator structures with three different slot numbers, employed for comparative study of IPM motor according to slot/pole number combination.

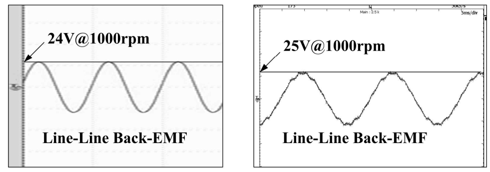
Figure 3 (a) and (b) show the cogging torque and the torque ripple obtained under rated torque conditions of each IPM motor with different slot numbers, respectively. Zhu [4] introduced 'goodness' factor (C_T) of slot and pole number combinations from the point of view of cogging torque as:

$$C_T = 2pQ_s / N_c \tag{5}$$

where N_c is the smallest common multiple between the slot number Q_s and the pole number $2p$. According to ref. 4, the larger the factor C_T, the larger will be the cogging torque. The value of C_T for the 6-pole IPM motor with 18, 27 and 36 stator slots are 6, 3 and 6, respectively. Therefore, as shown in Fig. 3(a), cogging torque of the IPM motor with 27-slot stator is lower than that of other two types. In a PM synchronous motor, main source of torque ripple occurs when either the back-EMF or current shape contains harmonic terms. If there are no harmonics in current, the torque ripple can be expressed as [5]

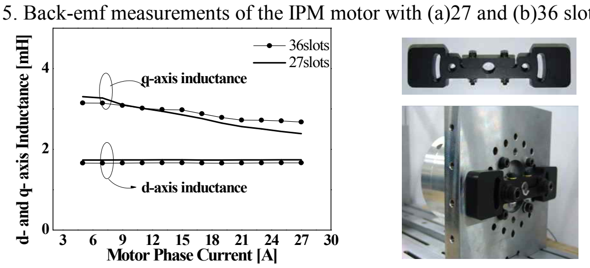
$$T_r(\theta) = \frac{1}{2}\sum_{n=3,..odd}^{\infty} K_n I_1 \left[1 + 2\cos\left\{(n\pm 1)\frac{2\pi}{3}\right\}\right]\cos\left\{(n\pm 1)\theta\right\} \tag{6}$$

where K_n and I_1 are n-th order harmonic component of back-emf and fundamental component of the current, respectively. It is found that if n is any odd integer other than a multiple of 3, namely, n= 5, 7, 11, 13, etc., torque ripple is produced. Thus, it can be judged from Fig. 3(b) that 5th, 7th and 11th harmonic component amplitude of the back-emf for IPM motor with 27-slot stator is the lower than the others.



(a) (b)

Fig. 5. Back-emf measurements of the IPM motor with (a)27 and (b)36 slots.



(a) (b)

Fig. 6. (a) Experimental results for d- and q-axis inductance of manufactured IPM motors and (b) d-and q-axis inductance measurement device .

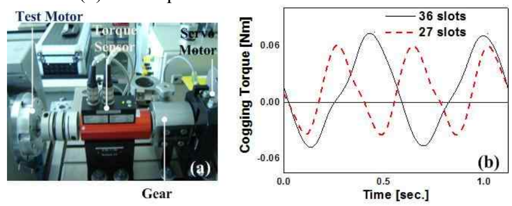


Fig. 7. Cogging torque: (a) experimental setup and (b) measured results.

Figure 4 shows the 6-pole IPM rotor and stators with 27 and 36 slots, manufactured in order to confirm the validity of comparative study. Figure 5 shows the experimental results for the line-line back-emf of manufactured IPM motors. It can be predicted from these results that the THD of IPM motor with 27-slot stator is lower than the others. Figure 6(a) shows the d-/q-axis inductance measurements according to motor phase current. The measured values of d- and q- axis inductance are shown in good agreement with their predicted values, which will be presented in the final paper. Figure 7 shows an experimental setup and measured results of cogging torque. As predicted in Fig. 3(a), it can be observed that cogging torque of the IPM motor with 27-slot stator is lower than that with 36-slot stator.

The more detailed analysis results such as d- and q- axis inductance, back-emf and their FFT analysis results and total torque, discussion and relevant equations will be given in final paper.

IV. References

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