Design Process of Interior PM Synchronous Motor for 42V Electric Air-conditioner System in Hybrid Electric Vehicle

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Abstract — This paper presents the design method taking the efficiency of interior PM synchronous motor (IPMSM) for the compressor of a hybrid electric vehicle operated in 42V battery system into account. The method, named parametric design in this paper, is to estimate the range of inductance and back-EMF satisfying the requirements of IPMSM in the initial design. Thereafter, the optimization is performed to consider magnetic saturation and reduce cogging torque and torque ripple respectively. At this time, simulation results are based on finite element analysis and gotten in consideration of operating temperature. In the end, the validity of the design process proposed in this paper is verified by test.

I. INTRODUCTION

Recently, a great interest is focused on a hybrid electric vehicle (HEV) and idling stop systems as technologies for low fuel consumption vehicle. In order to adapt to the idling stop system, the automobile air-conditioner must continue to work even while the engine is stopped. Because of this reason, the conventional engine-driven compressors are gradually being replaced with electric motor-driven types. Furthermore, the miniaturization, lightweight and high efficiency of the motor for electric air-conditioner system in HEV are required due to the appearance of integrated starter generator system. Accordingly, in order to satisfy these requirements, interior permanent magnet synchronous motor (IPMSM) with concentrated winding is one of the most suitable motors on account of their merits.

However, it is very difficult and complex to design the IPMSM satisfying the demanded efficiency from the initial design stage. So, in this paper, more practical and simpler design method is presented to consider the efficiency.

II. INITIAL DESIGN

A. Parametric design

The parametric design method proposed in this paper is used to consider the efficiency of IPMSM in the initial design. That is, it is to estimate the range of inductance and back-EMF treated as the most critical factors in the design of IPMSM. The region is obtained by changing the value of inductance and back-EMF in (1), (2) and (3) expressed as the voltage and torque equation of IPMSM in the steady-state. At that time, there are four assumptions. First, the iron loss is ignored. Second, the resistance is assumed as 10mΩ at the operating temperature, and that is determined by past experiment data or designer's experience. Third, the ratio between L_d and L_q is 1.5. Finally, mechanical loss is 0.25% of rated output power at 1000 rpm.

In this paper, the requirements of IPMSM for the compressor of a HEV are listed in Table I, and Table II and Fig. 1 shows the results obtained by the parametric design.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_a \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1 + \frac{R_a}{R_c}\right) \begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} \tag{1}$$

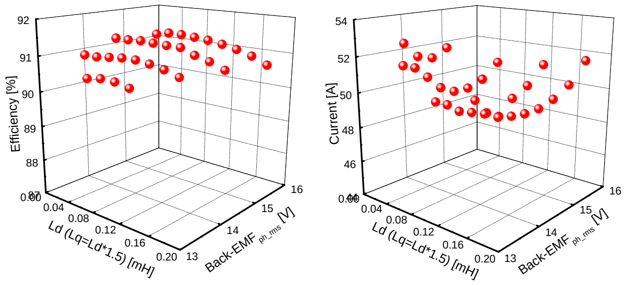
$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix} \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_a \end{bmatrix} \tag{2}$$

$$T = P_n [\psi_a i_{oq} + (L_d - L_q) i_{od} i_{oq}] \tag{3}$$

where i_d, i_q: d- and q-axis components of armature current; i_{cd}, i_{cq}: d- and q-axis components of iron loss current; v_d, v_q: d- and q-axis components of terminal voltage; ψ_a: $\sqrt{3/2}\,\psi_f$; ψ_f: maximum flux linkage of permanent magnet; R_a: armature winding resistance; R_c: iron loss resistance; L_d, L_q: inductance along d- and q-axis; P_n: number of pole pairs.

TABLE I
THE REQUIREMENTS OF IPMSM

Items	Value
Stator outer diameter	Less than 100.4 mm
Stack length	Less than 100 mm
Number of poles	8
Br (@120°C)	1.16 T
Efficiency	More than 90%
DC link voltage	42 V
Maximum current	60 A_{rms}
Current density	Less than 5 A/mm^2
Rated output power	2kW
Rated speed	3500 rpm



(a) Efficiency (b) Current

Fig. 1. A part of the results by parametric design

TABLE II
THE RESULTS BY PARAMETRIC DESIGN

Parameters	Range
d-axis inductance (L_d)	0.01 ~ 0.2 mH
Phase back-EMF @ 3500rpm	13 ~ 16 V_{rms}
Current	47 ~ 53 A_{rms}
Current angle	0 ~ 50°
Power factor	93 ~ 100 %

B. *Sizing*

Fig. 2 displays the procedure to determine the size of IPMSM. Above all, in the process, the thickness and width (or angle) of surface PM determined by analytical model are applied in the PM shape of IPMSM [1]. Next, the current density of the motor is concluded according to cooling method, then coil diameter based on the density and the current obtained by the parametric design is calculated [2]. Lastly, if the shape of stator is approximately decided with fill factor and coil diameter, torque per rotor volume (TRV) according to PM type is estimated within the dimension of the compressor shown in Fig. 3 [2]. In Fig. 2, the dotted line indicates the procedure without the size constraint unlike this paper. In the end, the final result of initial design is given in Fig. 4.

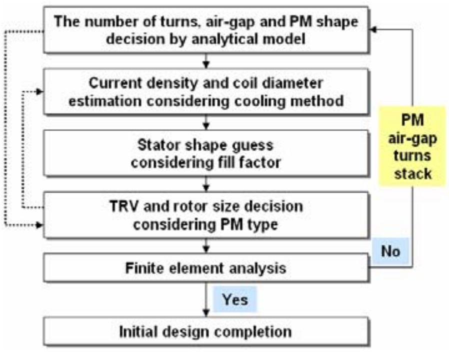
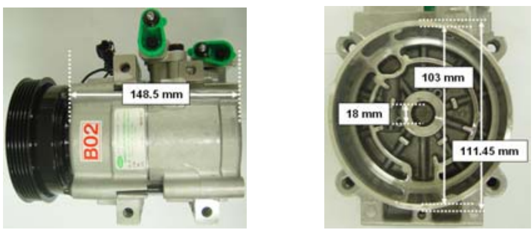
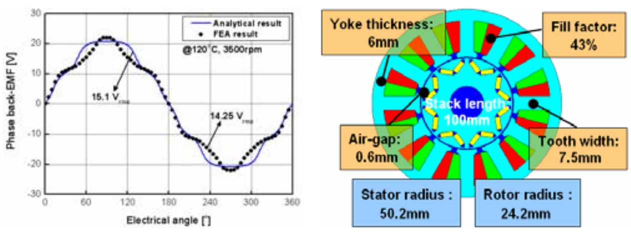


Fig. 2. Procedure to decide the size of IPMSM



(a) Side (b) Front

Fig. 3. Compressor configurations

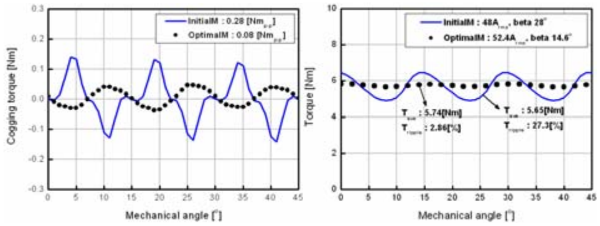


(a) Comparison of back-EMF (b) Dimension of initial model

Fig. 4. Initial design results

TABLE III
OPTIMAL CONDITIONS

Design factors	Initial model	Optimal model
Barrier angle [°]	97.9	87
Chamfer [mm]	0	0.57
Slot opening [mm]	2.5	1.9



(a) Cogging torque (b) Torque ripple

Fig. 5. Performance comparison between initial and optimized model

III. OPTIMIZATION

The detailed explanation as regards the optimization of IPMSM has been given in [3]. Therefore, this paper shows the only results in Table III and Fig. 5.

IV. CHARACTERISTIC ANALYSIS AND TEST RESULTS

The estimation method of inductance and iron loss for the characteristic analysis of optimized IPMSM is presented in [3] and [4]. Fig. 6 shows the characteristics evaluated with them, and the optimized IPMSM is fabricated as shown in Fig. 7. In the end, Fig. 8 indicates back-EMF obtained by FEA and test at 1000rpm.

V. REFERENCES

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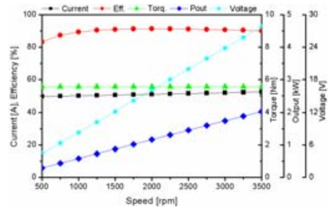
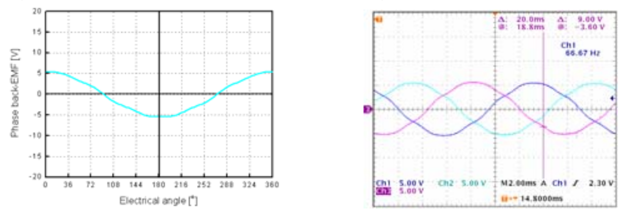


Fig. 6. The characteristics of IPMSM

Fig. 7. The fabricated IPMSM



(a) Simulation result (b) Measured result

Fig. 8. Back-EMF @ 1000rpm

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