Design Optimization of Interior Permanent Magnet Synchronous Motor for Electric Compressors of Air-Conditioning Systems Mounted on EVs and HEVs

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This paper deals with the optimization design process of an interior-type permanent magnet synchronous motor (IPMSM) for electric compressors of air conditioners applied to electric cars and hybrid vehicles. Based on a prototype IPMSM, we identified the current level for efficiency and cogging torque using finite-element analysis (FEA). The IPMSM's main design variables are optimized to primarily satisfy the target of efficiency and cogging torque. A second optimization design is carried out using the response surface method (RSM) for the main design variables obtained from the Taguchi method analysis. As a result, the optimization design is carried out through a two-step optimization design process using the Taguchi method and RSM. The IPMSMs are analyzed using FEA, and their validity is confirmed by comparing the test results against each step-by-step model. We validate an effective optimization design process using a two-stage design process. We conclude that the proposed approach provides an effective design method for engineers.

Index Terms— **Cogging torque, design optimization, electric vehicle/hybrid electric vehicle (EV/HEV), finite-element method (FEM), interior permanent magnet synchronous motor (IPMSM), response surface method (RSM), Taguchi method.**

I. Introduction

RECENTLY, the demand for efficiency improvements in the field of permanent magnet synchronous motors (PMSMs) in electric vehicles and hybrid electric vehicles (EVs and HEVs) has gradually increased, along with the demand for weight reduction and improvement of the performance of NdFeB magnets [1]. Interior PMSMs (IPMSMs) are mainly used in electric compressors for air conditioners of HEV/EVs, which require relatively high-speed operation characteristics.

In IPMSMs, the permanent magnets (PMs) are buried inside the rotor core not only to avoid the separation of the PMs caused by centrifugal force at high speeds but also to employ a hybrid torque generation that includes magnetic torque and reluctance torque. The magnetic torque is produced by the PMs, and the reluctance torque is generated from the unique rotor structure, as shown in Fig. 1 [2].

It is important to improve the motor efficiency of the electric compressor because it has an effect on increasing the mileage of the EV/HEV. Noise reduction is also an important issue as noise generated by the motor can be transmitted to the interior of the vehicle and may be uncomfortable for passengers. It is, especially, important to reduce cogging torque as this is a noise source with significant influence on the noise of the motor [3].

There are many variables to be considered in motor design; each design variable is interrelated and has various effects on the weight, noise, and efficiency of the motor. In IPMSMs, it takes a very long time to analyze the electromagnetic field using the finite-element method (FEM), and it is very difficult to find the proper optimization specifications if various design variables are simultaneously considered in order to satisfy the main performance of the motor.

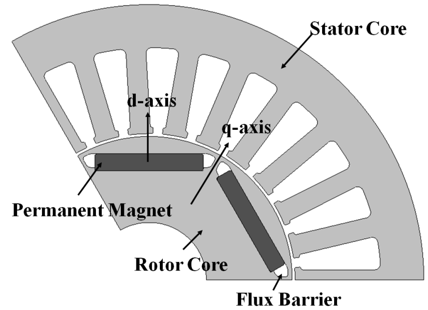

Fig. 1. Configuration of IPMSM model for electric compressor.

In recent years, Taguchi method has been widely used in the optimization design of motors because it can efficiently optimize various variables and has robust characteristic for noise factor [4]–[7]. However, Taguchi method has limitations because it is difficult to optimize the combination of design variables and to decide the exact optimal values of the parameters.

The response surface method (RSM) is a useful optimization method for deriving the optimal values for a small number of design variables. So many studies have been widely conducted to optimal design of motor using the RSM [8]–[10]. However, the RSM is difficult to optimize for many design variables at the same time, and the range of design variables should be close to the optimal value. In order to solve these problems, this paper presents an effective optimization design method as follows.

First, optimization design is carried out using the Taguchi method for the eight motor design variables affecting the motor

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TABLE I
DIMENSIONS AND SPECIFICATIONS OF IPMSM FOR ELECTRIC COMPRESSOR

Items	Value	Unit
Stator Outer Diameter	100	mm
Stack Length	50	mm
Input Voltage	288	Vdc
Pole Number	6	
Slot Number	27	
Rated Speed	6500	rpm
Rated Output Power	4.5	kW

efficiency and cogging torque, and the optimal design variables and results obtained via this procedure are reviewed. Many robust optimization methods have been developed to minimize variances in performance caused by tolerance. Among these, the Taguchi robust design based on orthogonal arrays (OAs) has been widely applied to various fields [11].

Second, three design variables affecting the efficiency and cogging torque are reflected in the next design by considering the design variables reviewed through the Taguchi method, and an optimization design using the RSM is performed to satisfy the main objective function in the next design step. The RSM is a useful optimization method for deriving optimal values of less than three design variables that have a large effect on performance among various other variables.

Finally, the finite-element analysis (FEA) results for efficiency and cogging torque for the IPMSMs obtained from each optimization design were compared. The design process was confirmed by comparing analysis results with the test results after building IPMSM samples for each optimized design. We propose an efficient optimization process using the two-stage design process that takes an advantage of the benefits of each optimization method.

II. MODEL AND SPECIFICATION

Fig. 1 shows the shape of an IPMSM applied to the compressor of an air conditioner mounted on an HEV/EV. The stator assembly has a three-phase distributed winding and the rotor assembly is an inner rotor type, in which the rotor rotates from the inside and has a structure in which PMs are inserted into a single layer. PMs are applied to NdFeB magnets with a high magnetic density to increase motor efficiency and reduce weight. The combination of poles and slots used is six poles and 27 slots. Choi *et al.* [12] analyzed the performance according to various pole/slot combinations for a PMSM for an electric compressor applied to an HEV/EV, and suggested that the combination of six poles and 27 slots is superior in terms of efficiency improvement and cogging torque reduction.

Table I shows the main design dimensions and specifications of the IPMSM. The output power of the IPMSM is 4.5 kW and it is cooled through the refrigerant of the compressor. The rated speed is 6500 r/min and the input voltage is dc 288 V. The design target and requirements of the motor are given and level of the prototype motor is reviewed by magnetic flux density distribution, motor efficiency according to speed, and cogging torque using FEM, as shown in Fig. 2.

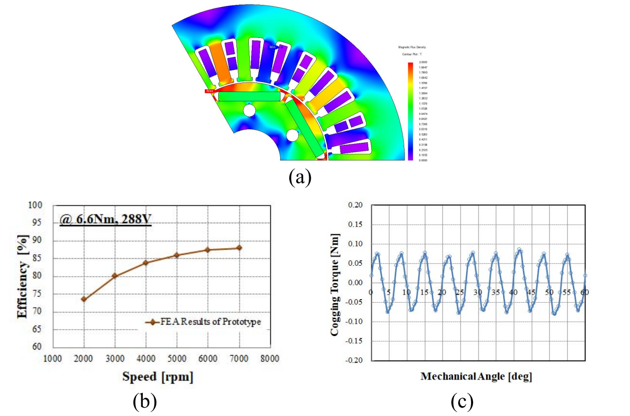


Fig. 2. Analysis results for prototype motor. (a) Flux density distribution. (b) Motor efficiency according to motor speed. (c) Cogging torque.

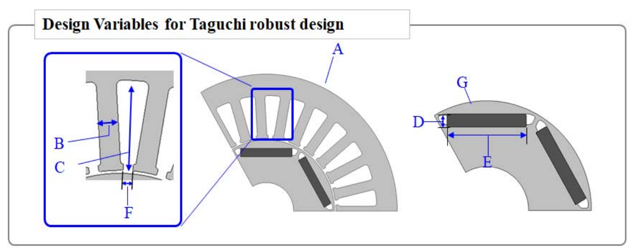


Fig. 3. Design variables (control factor) for Taguchi design of experiment.

III. DESIGN OPTIMIZATION PROCEDURE

A. Taguchi Method

The Taguchi technique is an experimental design method and aims to improve product quality. Robust design is available for noise (environment) factors that cannot be mitigated by controllable factors [11]. We perform a robust design based on the Taguchi method, considering the noise factor according to the environmental conditions in the IPMSM. In the Taguchi method, the intended output is selected as the motor efficiency and the cogging torque and the eight design variables affecting efficiency and cogging torque are selected as control factors, as shown in Fig. 3. Because the PM performance and the motor coil electrical resistance changes due to coolant temperature in the suction port of the compressor and the outdoor temperature, change in temperature is selected as the noise factor. Fig. 3 shows the control factors (design variables) for the Taguchi experimental design model. Table II shows the design variables and the OA of the control factors and noise factors. The L18 OA is applied and the array level is set to three levels for seven control factors and two levels for one control factor. For each model placed in the OA table, the motor efficiency and cogging torque characteristic are analyzed using FEM, and the results are given in Table III. Factor analysis of the results is performed using Minitab V15, and the main effects and signal-to-noise (S/N) ratios of each objective function are reviewed based on the FEA results of Table III. Fig. 4 shows the main effect and the S/N ratio of the motor efficiency and cogging torque. It can be seen that the PM thickness, width, and stack length have a greater influence on the motor

TABLE II

DESIGN VARIABLES AND OA OF CONTROL FACTORS AND A NOISE FACTOR IN TAGUCHI METHOD (L18 MATRIX TWO LEVEL 1EA, THREE LEVEL 7EA)

Index	Control Factors	Array Pattern		
A	Stator Outdiameter	1	2	
B	Teeth width	1	2	3
C	Slot depth	1	2	3
D	Magnet thickness	1	2	3
E	Magnet width	1	2	3
F	Slot opening	1	2	3
G	Rotor Outdiameter	1	2	3
H	Stack Length	1	2	3
	Noise Factors	Array Pattern		
I	Ambient Temperature	25℃	75℃	

TABLE III

FEA RESULTS FOR INNER ARRAY AND OUTER ARRAY IN TAGUCHI METHOD

RUN	Inner Assy [L18, $(2^1\times3^7)$								Outer Assy 1 (Efficiency) [%]				Outer Assy 2 (Cogging Torque) [Nm]			
									Q1 (2000rpm)		Q2 (6500rpm)		Q1 (2000rpm)		Q2 (6500rpm)	
									N1	N2	N1	N2	N1	N2	N1	N2
	A	B	C	D	E	F	G	H	25℃	75℃	25℃	75℃	25℃	75℃	25℃	75℃
L1	1	1	1	1	1	1	1	1	80.94	77.75	89.61	88.40	0.048	0.050	0.048	0.050
L2	1	1	2	2	2	2	2	2	82.84	80.82	90.41	89.46	0.078	0.090	0.078	0.090
L3	1	1	3	3	3	3	3	3	84.97	82.73	90.72	89.95	0.077	0.141	0.077	0.141
L4	1	2	1	1	2	2	3	3	83.23	80.48	90.36	89.37	0.068	0.084	0.068	0.084
L5	1	2	2	2	3	3	1	1	83.42	80.74	90.39	89.45	0.416	0.327	0.416	0.327
L6	1	2	3	3	1	1	2	2	83.37	80.70	90.33	89.38	0.093	0.116	0.093	0.116
L7	1	3	1	2	1	3	2	3	83.52	80.84	90.50	89.61	0.115	0.134	0.115	0.134
L8	1	3	2	3	2	1	3	1	83.56	80.95	90.41	89.49	0.083	0.074	0.083	0.074
L9	1	3	3	1	3	2	1	2	83.12	80.36	90.23	89.25	0.328	0.253	0.328	0.253
L10	2	1	1	2	3	2	2	1	84.21	81.73	90.70	89.84	0.117	0.141	0.117	0.141
L11	2	1	2	1	1	3	3	2	81.59	78.47	89.79	88.62	0.103	0.118	0.103	0.118
L12	2	1	3	2	2	1	1	3	84.11	81.58	90.61	89.73	0.064	0.059	0.064	0.059
L13	2	2	1	2	3	1	3	2	84.40	81.93	90.76	89.90	0.085	0.097	0.085	0.097
L14	2	2	2	3	1	2	1	3	84.16	81.64	90.66	89.78	0.123	0.130	0.123	0.130
L15	2	2	3	1	2	3	2	1	81.47	78.36	89.72	88.56	0.081	0.094	0.081	0.094
L16	2	3	1	3	2	3	1	2	84.28	81.76	90.75	89.87	0.094	0.087	0.094	0.087
L17	2	3	2	1	3	1	2	3	83.95	81.35	90.58	89.67	0.137	0.183	0.137	0.183
L18	2	3	3	2	1	2	3	1	82.03	79.06	89.93	88.83	0.111	0.111	0.111	0.111

efficiency and cogging torque than the other control factors. Based on these reviews, the optimal level for each of the control factors is determined as given in Table IV. As a result of examining characteristics for the optimized IPMSM model, it can be confirmed that the efficiency and cogging torque characteristics and S/N ratio are improved in comparison with the prototype IPMSM as given in Table IV.

B. Response Surface Method

After reviewing the results of the FEA and the test of the sample for the optimization model obtained by the Taguchi method, an additional improvement design is carried out using the RSM to achieve the performance target. The RSM is advantageous in finding the optimal value for less than three design variables and is applied to find the appropriate response to the objective function while considering interaction effects [2]. In order to satisfy the performance target effectively, the two-stage optimization design using the RSM is performed using the main factors obtained from the first optimization procedure without reoptimizing the whole set of motor variables. Table V illustrates the design variables and ranges used in the RSM.

From the variables determined in the Taguchi optimization process, two design variables (tooth width and slot depth) with a major influence on the motor performance are selected.

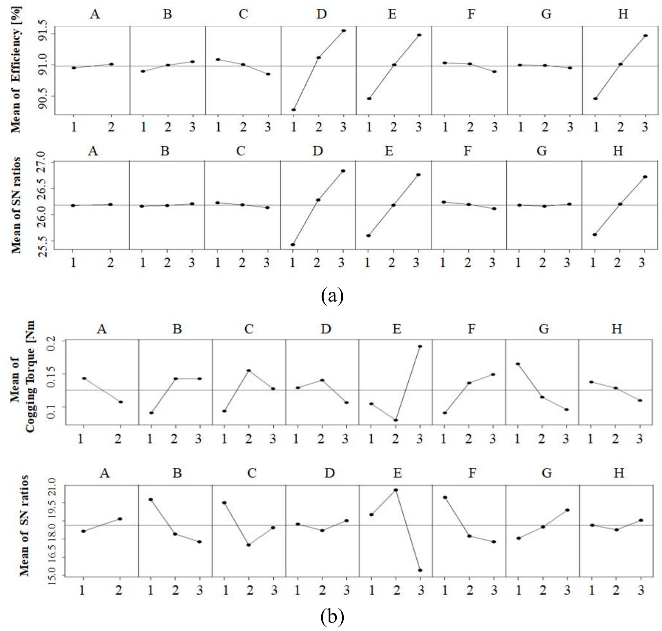


Fig. 4. Main effect analysis and S/N ratios according to the control factors of the IPMSM. (a) Main effect plot and S/N ratios for motor efficiency. (b) Main effect plot and S/N ratios for cogging torque.

TABLE IV

TAGUCHI RESULTS ANALYSIS FOR DESIGN PARAMETERS FOR EFFICIENCY AND COGGING TORQUE AND DETERMINE OF OPTIMAL LEVEL FOR CONTROL FACTOR

Contents		A	B	C	D	E	F	G	H	Values [%, Nm]	S/N Ratio [dB]
Efficiency	Prototype	2	2	2	3	2	2	1	3	87.46	39.28
	Optimized	2	3	1	3	3	1	1	3	90.82	39.34
	Optimized - Prototype									3.36	0.06
Cogging Torque	Prototype	2	2	2	3	2	2	1	3	0.125	18.92
	Optimized	2	1	1	3	2	1	3	1	0.075	30.42
	Optimized - Prototype									-0.050	11.50

TABLE V

RANGES OF DESIGN VARIABLES FOR OPTIMIZATION IN THE RSM

Design variables	Analysis range	Unit
Teeth width	3.3~3.7	mm
Slot depth	13~17	mm
Winding turns	8~10	turns

Another variable (winding turns) is added to review the operating range and motor efficiency; however, variables that increase material cost and weight are excluded. Design variables are set to be three factors and two levels, and the ranges are determined within the reasonable range that the shape of the IPMSM can be configured. When changing the winding turns, the coil diameter is adjusted so that the slot fill factor is set to a production-ready level. The objective function is set up to have a motor efficiency of 92% or more at the rated torque and a cogging torque of 0.08 Nm or less. Increasing the back electromotive force to increase the motor efficiency has the effect of decreasing the maximum operating speed, so the

TABLE VI
DESIGN VARIABLES AND RESPONSES OF RSM SIMULATION

RUN	Teeh Width	Slot Depth [mm]	Winding Turns	Efficiency [%]	Speed [rpm]	Cogging Torque [Nm]
1	3.3	13	8	88.40	6256	0.063
2	3.7	13	8	86.92	6138	0.071
3	3.3	17	8	92.20	6501	0.054
4	3.7	17	8	91.36	6426	0.062
5	3.3	13	10	88.08	4886	0.063
6	3.7	13	10	86.34	4780	0.071
7	3.3	17	10	92.40	5112	0.054
8	3.7	17	10	91.47	5048	0.062
9	3.2	15	9	90.73	5642	0.061
10	3.8	15	9	89.59	5549	0.066
11	3.5	11.6	9	85.02	5299	0.068
12	3.5	18.4	9	91.92	5786	0.053
13	3.5	15	7	90.37	7351	0.066
14	3.5	15	11	90.43	4500	0.066
15	3.5	15	9	90.78	5631	0.065
16	3.5	15	9	90.76	5646	0.067
17	3.5	15	9	90.80	5609	0.064
18	3.5	15	9	90.77	5646	0.068
19	3.5	15	9	90.81	5609	0.064
20	3.5	15	9	90.82	5591	0.065

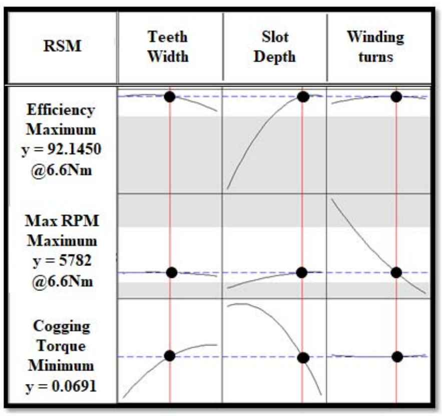


Fig. 5. Response of design objectives based on variables in RSM.

operating speed is also included in the objective function. For all design models determined by the RSM, the efficiency, cogging torque, and maximum operating speed are analyzed by the FEA results are given in Table VI. Fig. 5 shows a graph [response (RS) optimizer] that finds optimal values of the design variables to satisfy the objective functions using Minitab.

The motor efficiency and cogging torque are affected by the slot depth, and the cogging torque of the target level can be achieved at the maximum efficiency point, as shown in Fig. 5. When the winding turns are increased, the maximum operating speed decreases rapidly, but the effect on motor efficiency is not large and the target operating speed is satisfied at the maximum efficiency point. Based on the results and reviewing the RS optimizer, as shown in Fig. 5, we can find the optimal design parameter value satisfying the design target.

IV. RESULTS AND DISCUSSION

The design parameters of the IPMSM are optimized to satisfy the motor efficiency and cogging torque through the proposed design process. Motor efficiency and cogging torque

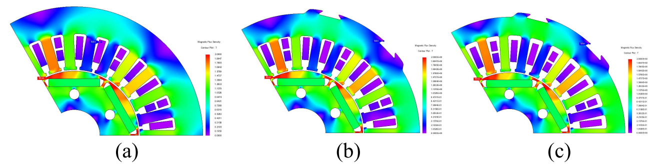


Fig. 6. Flux density distribution for IPMSMs. (a) Prototype. (b) First optimization model by Taguchi method. (c) Second optimization model by RSM.

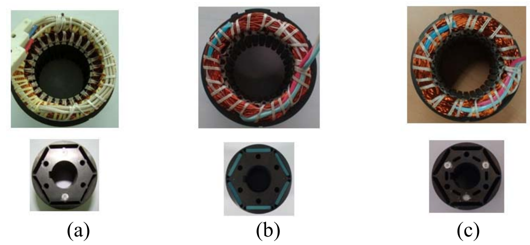


Fig. 7. Configuration for test samples of IPMSM. (a) Prototype motor. (b) First optimization motor by Taguchi method. (c) Second optimization motor by RSM.

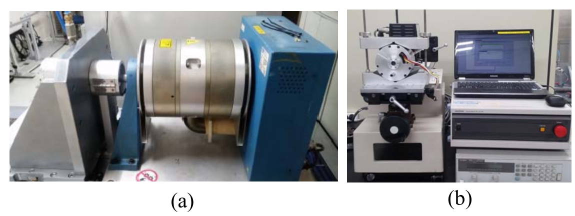


Fig. 8. Measurement equipment. (a) Motor dynamometer for measuring motor efficiency, torque, and power consumption. (b) Cogging torque tester.

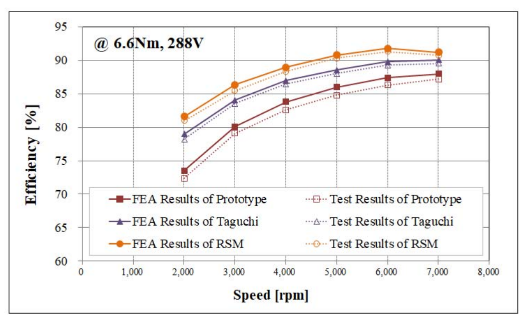
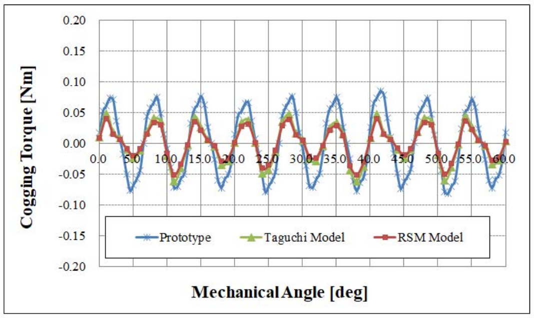
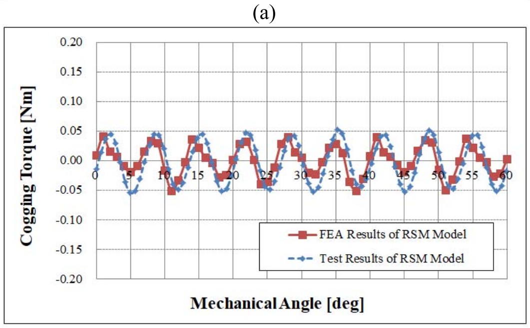


Fig. 9. Comparison of FEA and test results of the motor efficiency according to optimization step.

are analyzed using FEM for the optimization model via the Taguchi method and RSM, and we can see that the results are improved according to each optimization step. Fig. 6 shows the geometry and magnetic field distribution for each IPMSM optimization design model. As shown in Fig. 7, test samples for each IPMSM optimization design model were built, and a test was conducted for those using the motor dynamometer and cogging torque tester in Fig. 8. Fig. 9 shows a comparison between FEA and test results for motor efficiency according to speed for each optimization design model. It can be seen that the motor efficiency improves as optimization progresses, and the FEA and the test results are similar. Fig. 10 shows the FEA



(a)



(b)

Fig. 10. Comparison of the cogging torque FEA and test results. (a) Analysis results comparison according to optimum design process. (b) Analysis and test results for second optimization model by RSM.

results of cogging torque for each optimization design model and a comparison between FEA and test results for the second optimization motor by RSM. As shown in Fig. 10(a), it can be seen that the cogging torque is reduced as the optimization design progresses, and it can be seen that the test results for the cogging torque and the FEA results are similar, as shown in Fig. 10(b). According to the proposed optimization design method, the optimized IPMSM improved the motor efficiency by about 3.9% at the rated torque and speed and the cogging torque is reduced by 54.8% compared to the prototype IPMSM.

V. Conclusion

This paper presented a study on achieving high efficiency and low cogging torque in IPMSMs by adopting two-stage design optimization using the Taguchi method and RSM. There are many design variables that are used in motor design, and these are also correlated with motor performance such as efficiency, cogging torque, and maximum speed. This means that in order to optimize the entire IPMSM at once, a large number of FEA attempts and analysis times are needed. In conclusion, this paper proposes an effective approach to perform the optimization design process to achieve the target IPMSM design.

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