Optimum Design of IPMSM for In-Wheel Direct-Drive by Response Surface Methodology and FEA

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Abstract

In-wheel system is indispensible in eco-friendly vehicles including hybrid and fuel cell vehicles in regard to fuel consumption and degree of freedom. This paper focuses on designing and optimizing an Interior Permanent Magnet Synchronous Motor (IPMSM) for the system with the goals of minimizing torque ripple and Total Harmonic Distortion (THD) of line-to-line Back Electro-Motive Force (BEMF) through response surface methodology and finite element analysis since it is rarely possible to induce the equations which express the relationships between the design parameters and the objective functions. In addition, the IPMSM is comprised of 8 poles and 48 slots considering vibration and noise order, which is strongly connected to the magnitudes of torque ripple and THD of line-to-line BEMF. Particularly, the figures of barriers installed on both sides of magnets in rotor play the main role in satisfying the targets. In conclusion, the results from finite element analysis are compared with those from experiment to prove the validity. Having a lower torque ripple and THD of line-to-line BEMF, the optimum model is anticipated to show a lower degree of vibration and noise while the electromagnetic performances such as average torque and output power are maintained at the same with the prototype.

1 Introduction

Driving and damping devices inside the wheels characterizes In-wheel module. Since individual motor drives a wheel without any helps of a series of power units, there is no loss generated in the courses of transmissions. Combined with other security systems such as electronic stability control or smart parking assist system, it produces a considerable synergy effect. As an example of the advantages, the total weight is diminished and it enables to cut fuel consumption. Antithetically, it is not straightforward to design the motor and determine its constraints [1].

For instance, the magnitudes of vibration and noise are roughly proportional to those of torque ripple and Total Harmonic Distortion (THD) of line-to-line Back Electro-Motive Force (BEMF). The quiver grants displeasure to the drivers and can be a resource of car accidents.

Furthermore, the range of BEMF should be specified because of the limit of input current while the requirements are fulfilled. Thus, this paper aims at designing and optimizing an Interior Permanent Magnet Synchronous Motor (IPMSM) with 8 poles and 48 slots for the system in consideration of the above restrictions through Response Surface Methodology (RSM) and Finite Element Analysis (FEA) [2], [3].
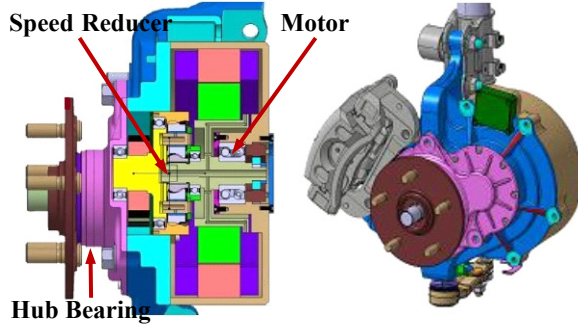
Figure1: In-wheel direct-drive system

2 Response Surface Methodology

The RSM is a representative method for generating meta-models. The original model is evaluated at multiple sample points and the meta-model is constructed usually as a linear or a quadratic function. The coefficients of the meta-model function are determined by minimizing the error. Even though there are a number of types of functions to generate the approximation, a quadratic function approximation is used in this paper and the related equations are illustrated in (1), (2), and (3) [2].

$$\hat{f}_i = d_0 + d_1\zeta_{i1} + \ldots + d_l\zeta_{il} = d_0 + \sum_{j=1}^{l} d_j\zeta_{ij} \ (i = 1 \ to \ k) \quad (1)$$

$$E = \sum_{i=1}^{k} \varepsilon_i^2 = \sum_{i=1}^{k} (f_i - \hat{f}_i)^2 = \sum_{i=1}^{k} [f_i - (d_0 + \sum_{j=1}^{l} d_j\zeta_{ij})]^2 \quad (2)$$

$$\begin{bmatrix} k & \sum_{i=1}^{k}\zeta_{i1} & \sum_{i=1}^{k}\zeta_{i2} & \cdots & \sum_{i=1}^{k}\zeta_{il} \\ \sum_{i=1}^{k}\zeta_{i1} & \sum_{i=1}^{k}\zeta_{i1}^2 & \sum_{i=1}^{k}\zeta_{i1}\zeta_{i2} & \cdots & \sum_{i=1}^{k}\zeta_{i1}\zeta_{il} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \sum_{i=1}^{k}\zeta_{il} & \sum_{i=1}^{k}\zeta_{il}\zeta_{i1} & \sum_{i=1}^{k}\zeta_{il}\zeta_{i2} & \cdots & \sum_{i=1}^{k}\zeta_{il}^2 \end{bmatrix} \begin{bmatrix} d_0 \\ d_1 \\ d_2 \\ \vdots \\ d_l \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{k}f_i \\ \sum_{i=1}^{k}\zeta_{i1}f_i \\ \vdots \\ \sum_{i=1}^{k}\zeta_{il}f_i \end{bmatrix} \quad (3)$$

Where, $\hat{f}_i$ is the approximated function and ζ_{ij} represents the value of the design variable ζ_j at the ith sample point, $\vec{d} = (d_0, d_1, d_2, \ldots, d_l)$ is a regression coefficient vector and obtained by solving (3), and E is an error function. This process is exactly the same as the least squares method.

3 Initial Design Process

Above all, it is needed to identify the design specification in Table1 and determine the ratio of stator to rotor sizes in terms of torque per rotor volume. Thereafter, a poles and slots combination that minimizes the vibration/noise described in (4) and an IPMSM with 8 poles and 48 slots is proposed in this paper.
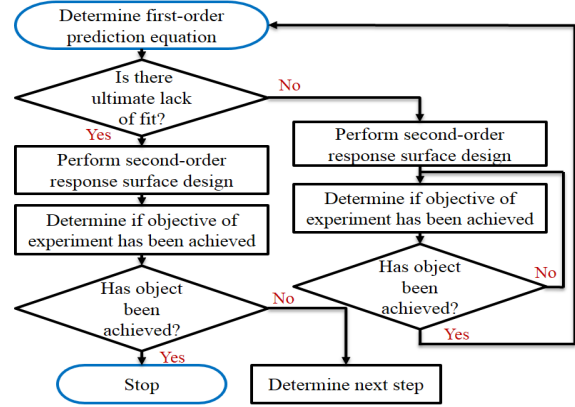

Figure2: Flow chart of response surface methodology

$$\frac{f_\lambda}{2f} = \frac{|(\mu p \pm k s_1 \mp s_1)|}{p} = 1, 2, 3, \ldots \quad (4)$$

Where, μ is rotor MMF harmonic, p is pole pair, s_1 is the number of slots, f is input frequency, and r_λ is vibration and noise order [4]. In addition, torque and BEMF are of the most crucial properties, which would be reflected in parametric design. The prototypes with V and U types of magnets in Fig. 2 are made as a consequence of electromagnetic and structural analyses.

Table1: Design specification for IPMSM prototype

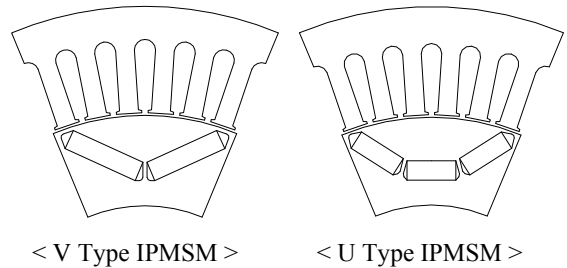| Division		Target Value	Dimension
Wheel size		17	inch
Housing	Outer diameter	222	mm
	Length	84	mm
Motor	Outer diameter	210	mm
	Length	72	mm
	Inner diameter	120	mm
Output Power		35	kW
Maximum torque		75	Nm
Maximum / Base speed		11,000 / 4,400	rpm
DC link voltage		240	V
Cooling type		Oil-cooled	-

< V Type IPMSM >   < U Type IPMSM >

Figure3: V and U types of IPMSM prototype

4   Optimization Procedure

4.1   Strategy

First of all, we need to confirm whether the initial model fulfills the design requirements. As seen in the view of THD of line-to-line BEMF and torque ripple, the prototype has higher values of them and would be optimized in the direction of minimizing the objective functions through RSM, which is useful of expressing two or three dimensional surfaces [5], [6].
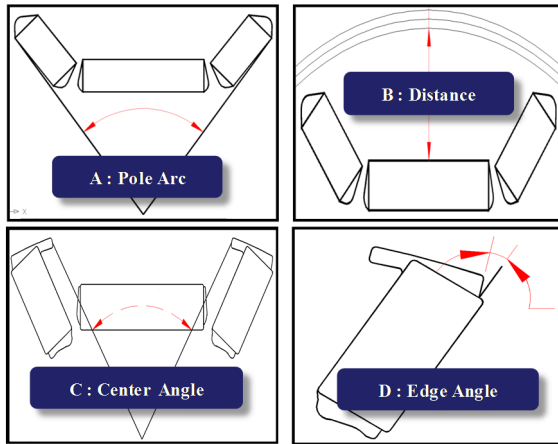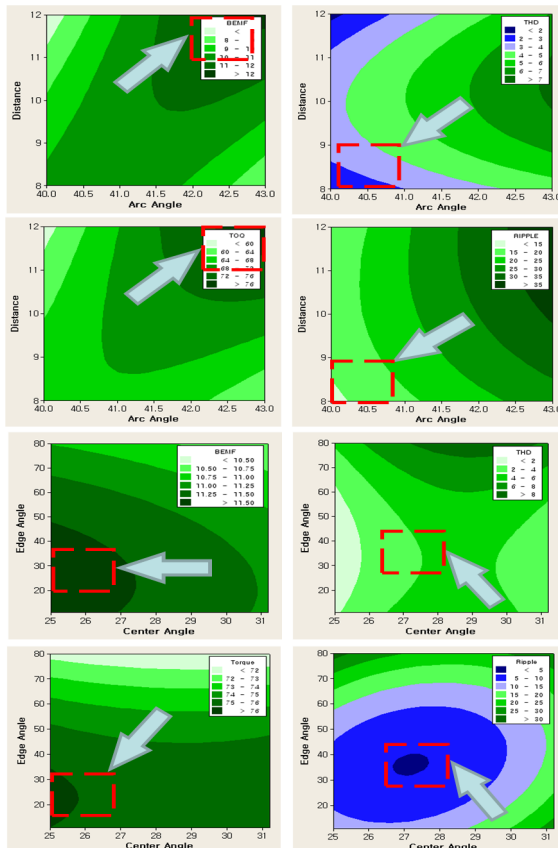

Figure4: Design variables contemplated in RSM

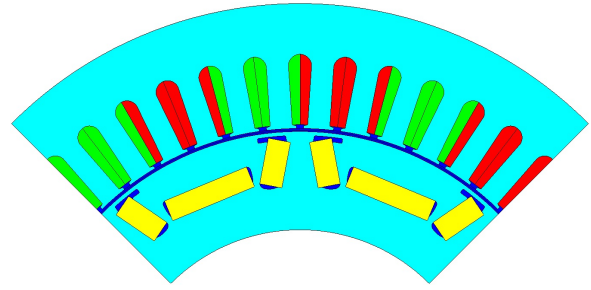Figure5: Response surfaces considering 4 variables

Figure6: Configuration of optimum model, IPMSM

Furthermore, it is crucial that the values of the electromagnetic characteristics, phase BEMF and average torque, should be maintained at more than 11V and 75Nm. Fig. 4 describes four design variables, pole arc, distance, center angle, and edge angle, opted for the optimization procedure. They are actually the most influential factors in downsizing the objective functions compared with those in stator.

Fig. 5 illustrates the response surfaces obtained in a course of the process, which make it possible for us to find out an optimal point in the feasible boundaries of design variables under a series of constraints. Once the point is decided, a final or an optimal model is being set up with the specific dimensions in the rotating machine.

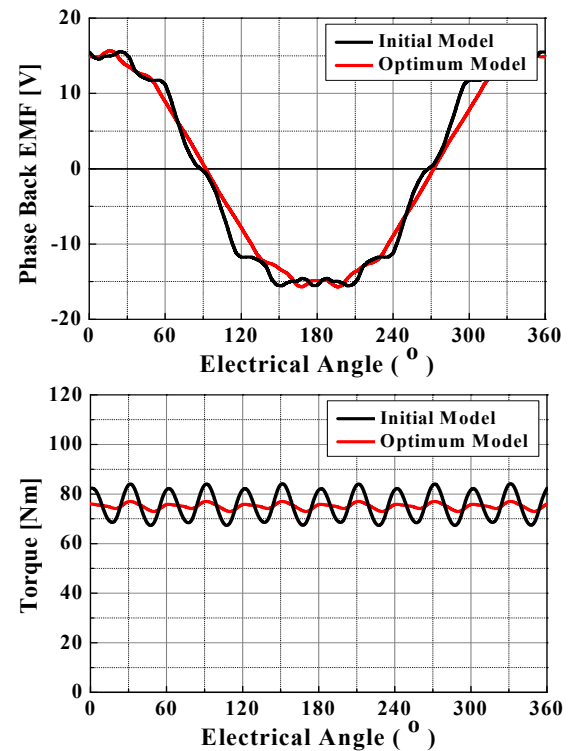## 4.2   Specification and Analysis of Optimum Model

Figure7: Electromagnetic characteristics of initial and optimum models

Based on the results above, an optimum model that has definite dimensions and satisfies all the requirements and constraints would be suggested. Accordingly, an analysis for the characteristics such as output power, average torque, input current, current phase, phase BEMF, and THD of line-to-line BEMF could be performed by Finite Element Analysis (FEA). The scheme of the optimal model with U type of magnets is shown in Fig. 6 and the graphs for phase EMF and average torque in Fig. 7. For the prototype and the optimal model, two values are 11.17V and 75.08Nm whereas THD of line-to-line BEMF changes from 4.6% to 2.9% and torque ripple from 24.0% to 5.8%. Consequently, the data proves that the optimization procedure is accomplished ordinarily to satisfy the targets.

4.3 Experiment

The measurements are carried out under the load and the no-load conditions through a series of experimental setup shown in Fig. 8. The data from FEA are being compared with those from the experiment to verify a validation. Also, Table 2 describes the comparison results for BEMF constant, THD of line-to-line BEMF, output power, average torque, and efficiency at base speed, 4400 rpm. The maximum error is less than 1.4%.
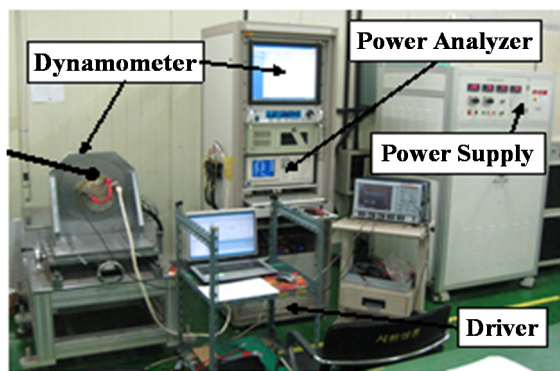

Figure8: Measuring devices for characteristics

Table2: Comparison between analysis and experiment under maximum load condition

Division	Analysis	Experiment	Error
BEMF Constant	0.0373	0.0370	0.9%
THD	4.87%	4.94%	1.4%
Output Power @ base speed	34.6kW	34.9kW	0.9%
Average Torque @ base speed	75.0Nm	75.9Nm	1.2%
Efficiency	92.4%	92.9%	0.5%

4.4 Miscellaneous Properties

Except for the electromagnetic characteristics as before, a rotating machine should satisfy the restrictions for structural and demagnetization analyses, which are being covered below.

4.4.1 Structural Analysis

Material properties for analysis are shown in Fig. 9 and boundary conditions in Table2. Here, stator is not considered because of the structure of teeth and slots. Assuming the worst circumstance, it makes use of a method that bonds the upper edge of each permanent magnet to the core and supports the inner diameter with only the friction force and results in 221.22MPa of maximum stress and 1.72 of safety factor, which are affordable for designing a motor.

Table2: Material properties for structural analysis

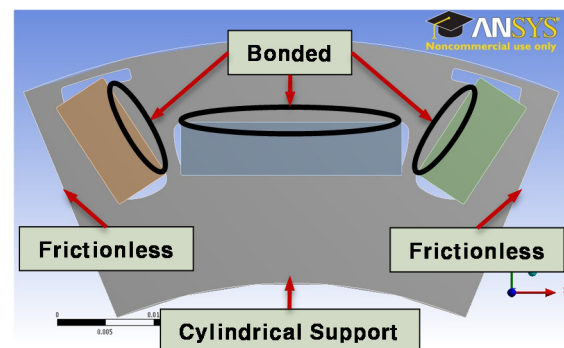| Division	Core	Permanent Magnet
Material	35A230	VACODYM 872TP
Density	7600 kg/m^3	7700kg/m^3
Young`s modulus	175GPa	120GPa
Poisson`s ratio	0.3	0.3
Yield point	380MPa	-

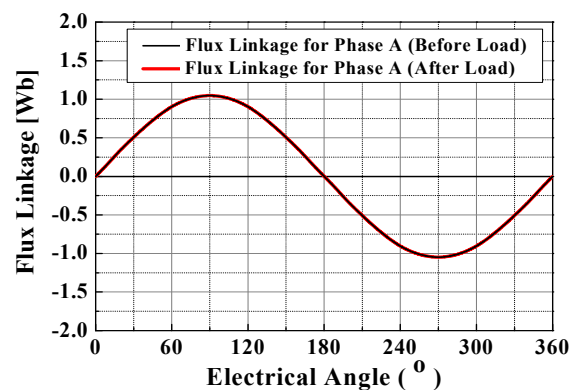Figure9: Boundary conditions for structural analysis

Figure10: Flux linkage for phase A for demagnetization

4.4.2 Demagnetization Analysis

This analysis is needed when the possibility of demagnetization of permanent magnets exists. The order is as follows ; no-load analysis, load analysis with 90 degrees of current angle and 2 times of maximum current, and no-load analysis. Thereafter, we compare and contrast how many errors the results from two no-load analyses have. In this case, the error is less than 0.14%, whereas affordable maximum one is 1%.

5 Conclusion

This paper focuses on the optimization of IPMSM for in-wheel direct-drive by RSM and FEA considering 4 design parameters in rotor. The optimum model is based on an initial model with 8 poles and 48 slots. Having a lower torque ripple and THD of line-to-line BEMF, it is anticipated to show a lower degree of vibration and noise while the performances are at the same.

Acknowledgments

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