

Reduction Design of IPMSM Torque Ripple using Design of Experimental

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Abstract: In the internal permanent magnet synchronous motor (IPMSM), torque pulsation occurs under no load. This is called cogging torque, and this causes noise and vibration during startup. Use factorial design, one of the experimental designs (DoE), to find the level of the factor with the lowest cogging torque and harmonic distortion (THD). The level of the found factor is applied to the analysis model. The main factors in factorial design are the skew step and skew angle. Based on the optimal factor level found through factor design, we compared the waveforms of torque ripple and line voltage at the maximum speed and the base speed of the analysis model and the model to which the skew was applied through finite element analysis (FEM). As the skew was applied, the harmonics were reduced, thereby reducing the torque ripple, and the line voltage waveform was also applied to the skew, resulting in a smoother waveform.

Keywords: Design of Experiment, Total Harmonic Distortion, IPMSM, Skew, Torque Ripple.

1. Introduction

Electric motors using permanent magnets are largely classified into two types. Surface mounted permanent magnet motors (SPMSM) that attach permanent magnets to the rotor surface are divided into interior permanent magnet synchronous motors (IPMSM) that bury permanent magnets into the rotor, and IPMSM are frequently used. However, in the case of IPMSM, a torque pulsation phenomenon called cogging torque occurs. [1-4]. Cogging torque affects vibration at starting and at low speeds and affects torque ripple. In addition, vibration and noise are generated and efficiency may be reduced. As a method of reducing the cogging torque there are many methods, such as increasing the length of the air gap, applying skew to the stator or rotor, increasing the number of slots or poles, using magnet with little magnetic flux density. [5-8]. There is this. The method of increasing the length of the poles has a poor magnetic flux density, which adversely affects the output. From a design point of view it's impossible to completely weak cogging torque by the number of poles or slots. In general, rotor skew is applied to reduce cogging torque. [9-10].

In this paper, we use the general full factorial design, an experimental design method implemented in all combinations according to the level of the experimental factors. Based on the data obtained from the FEM, factors were selected using the skew angle of the rotor and the skew stage of the rotor, which affect the total harmonic distortion (THD) and cogging torque, which are the main causes of torque ripple, using the factorial design. The factorial design finds the level of the factor with the lowest harmonic distortion and cogging torque. It was found that the level of the coefficient was applied to the analysis model and torque ripple was reduced through FEM.

2. Analysis Model

The 15KW IPMSM for driving the ultra-compact electric vehicle studied in this paper was selected as the analysis model. The maximum torque is generated up to 65 Nm. In Figure 1, the 2D model is shown through FEM analysis of the analysis model. This analysis model has a structure of 4 poles and 36 slots, and the winding method is concentric

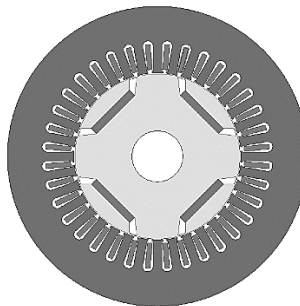


Figure 1. 15KW IPMSM FEM Model

Table 1 is the basic specifications of the analysis model for FEM. The maximum power of the motor

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is 15KW and the battery voltage limit is $120V_{dc}$. The maximum torque is 65kN. The maximum torque is maintained at 2,200 rpm at the rated operating point, and then gradually decreases by controlling the weak magnetic flux while entering the constant power range up to the maximum speed of 5,600 rpm. Figure 2 shows the operational area of the analytical model. The solid line means instantaneous rating, and the dotted line means continuous rating.

Table 1: Specification of motor IPMSM for driving electric vehicles

Parameter	Quantity	Unit
Max. Power	15	KW
Max. Torque	65	Nm
Battery limit voltage	120	V_{dc}
Num. poles	4	
Num. slots	48	
Stator Outer Dia.	175	Φ
Rotor Outer Dia.	92.8	Φ
Stack Length	129	mm
Speed(base/max)	2,200/6,600	rpm

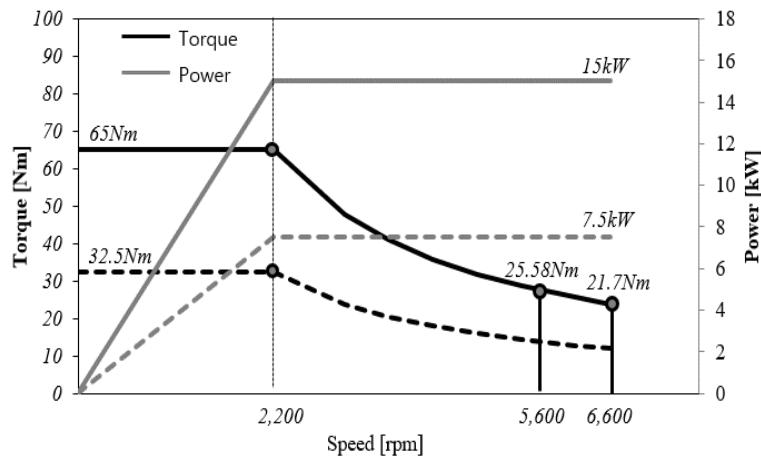


Figure 2. Operation region of model

3. Optimization through factorial Design

Generally, the K^n factorial experimental method is an experimental design method in which the number of arguments is n , and k is the number of levels of each factor. Experiments are performed with level combinations between all arguments. Therefore, even if the experiment is repeated, K^n times of the experiment are performed. In the factorial experiment, the effect of the interaction with the main effect of the argument can be estimated. Table 2 is defined by the level from 1 degree to 10 degree consideration of the slot pitch with the skew angle level at no load (1,000 rpm), and the FEM is used by setting the skew step to 2 steps and 3 steps. The data of cogging torque and THD are shown.

Table 2: Characteristic value using FEM (a) 2nd skew (b) 3rd skew
(a)

Skew angle(deg)	Cogging torque (Nm)	harmonic distortion (%)
1	1.26	12.2
2	0.8728	10.93
3	0.721	8.78
4	0.7639	6.59

5	0.76115	5.25
6	0.72625	5.86
7	0.7541	7.81
8	0.85975	9.95
9	1.30445	11.61
10	1.4817	12.27

(b)

Skew angle(deg)	Cogging torque (Nm)	harmonic distortion (%)
1	1.4099	12.9
2	1.0535	11.89
3	0.7587	10.33
4	0.5728	8.45
5	0.5364	6.55
6	0.4084	5.12
7	0.3026	4.57
8	0.5471	4.83
9	0.8947	5.27
10	0.9964	5.34

Figure 3 shows the THD and the main effect of cogging torque, which affects torque ripple. When looking at the main effect diagram of the THD, the distortion rate is the lowest when the skew is 3 steps and the skew angle is 6 degrees. Looking at the main effect of the cogging torque, the skew is the lowest when the skew is 3 steps and the skew angle is 7 degrees.

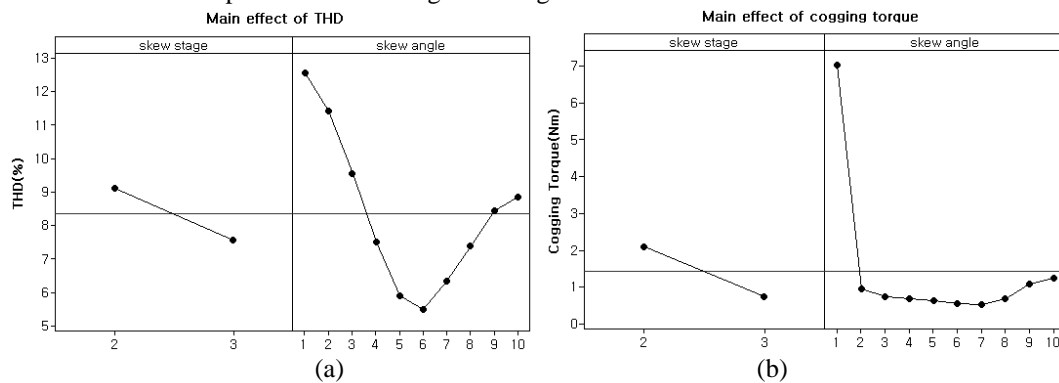


Figure 3. Main effect diagram using Design of experiments (a) THD (b) Cogging Torque

The factorial method was used to investigate the levels of the factors with the lowest THD and the lowest cogging torque. Figure 4 used the reaction optimization tool to find a more accurate optimal solution. In order to find the level of the factor with the THD and cogging torque, the smaller the characteristic value, the better the Manno characteristic is used. D means the overall satisfaction of the experiment and y means the predicted response value. Hi 2 is divided into 3 stages of skew and Lo is divided into 2 stages of skew. Cur represents the level of the factors at the lowest cogging torque and THD. Therefore, when the skew group has three stages and the skew angle is 7 degrees, the lowest characteristic value is shown. Figure 5 shows a model with skew applied to the magnet of the rotor.

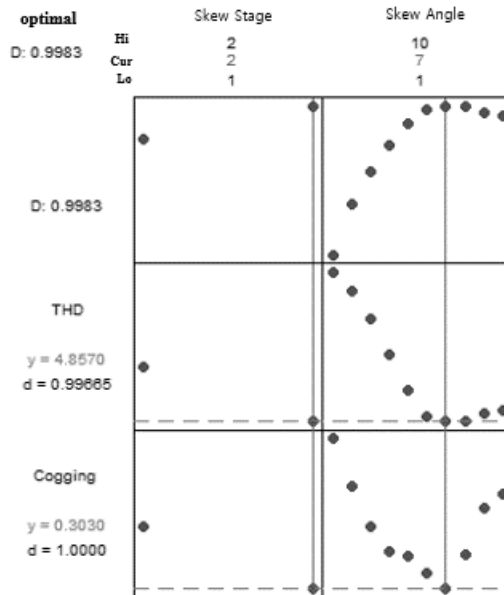


Figure 4. Derivation of the optimal solution for an analysis model using an optimization tool

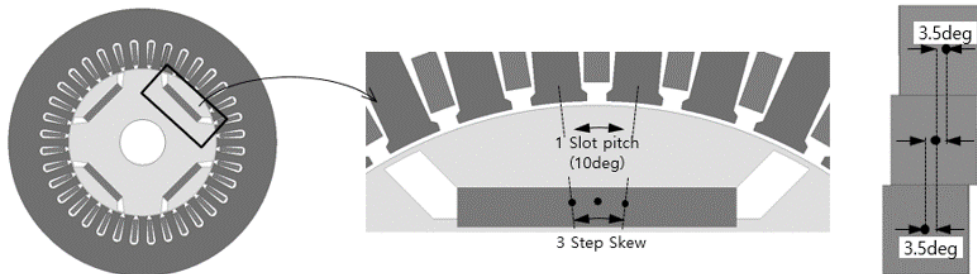


Figure 5. Model with skew applied to the magnet of the rotor

4. Comparison of an analysis model and skew applied model characteristics.

Figure 6 shows the torque waveform and the line voltage waveform of the base speed of the analysis model. Figure 7 shows the torque and line voltage waveforms of the skewed analysis model. If you compare the waveforms of the two models, you can see that the skewed model has a slight increase in torque and a reduction in torque ripple. In addition to the torque waveform, when the skew is applied, the voltage waveform also reduces harmonics, so that the voltage waveform shows a slightly smoother waveform [11].

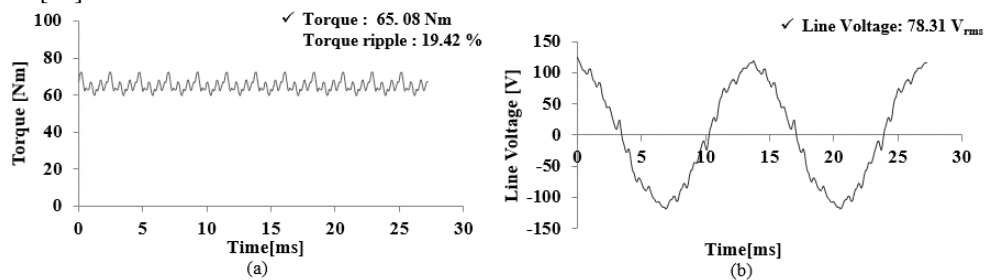


Figure 6. Wave of base model (2,200rpm) (a) Torque (b) Line Voltage

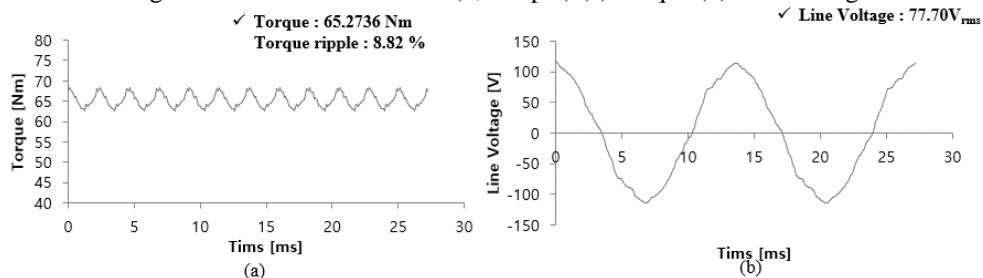


Figure 7. Waveform of skewed model (2,200rpm) (a) Torque (b) Line Voltage

Figure 8 shows the torque waveform and the line voltage waveform at 6,600rpm of the analytical model. Figure 9 shows the torque and line voltage waveforms for a model with skew applied at 6,600 rpm. Comparing the waveforms of the two models, the torque ripple is lowered due to the reduction of the harmonic even at 6,600 rpm, and the line voltage waveform also shows a smooth waveform.

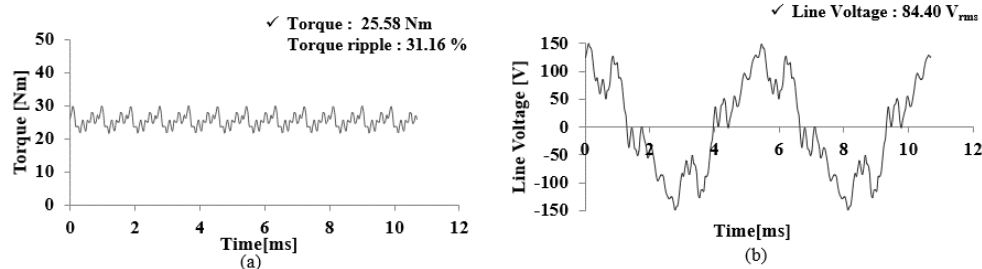


Figure 8. Wave of base model (6,600rpm) (a) Torque (b) Line Voltage

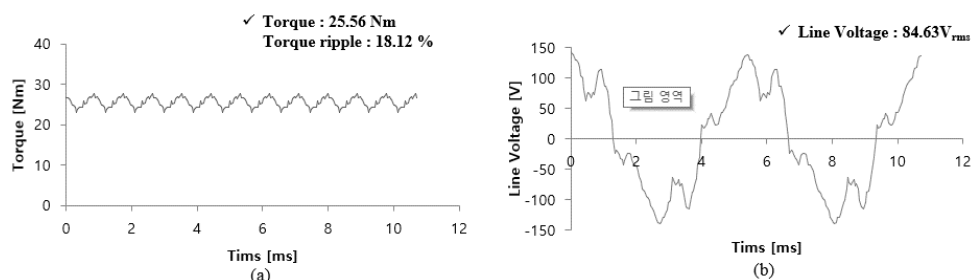


Figure 9. Waveform of skewed model (6,600rpm) (a) Torque (b) Line Voltage

5. Conclusion

In this paper, a study was conducted on the reduction of torque ripple by skew angle and skew stage. Based on the software data, the optimal coefficient level with the lowest cogging torque and THD through the coefficient placement method is a skew angle of 7 degrees and a 3-step skew. Based on this, when applied to the analysis model, the torque ripple and line voltage at the base speed and maximum speed were confirmed. It was confirmed that torque ripple was reduced by reducing harmonics, and it was also confirmed that line voltage waveform showed a smoother waveform.

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