Optimum Design of the Electric Vehicle Traction Motor using the Hairpin Winding

Dae-Sung Jung
Electric Drive Engineering Team
Hyundai Mobis Co., Ltd
17-2, 240 Beon-Gil, Mabuk-Ro, Giheung-Gu, Yongin-Si
Jungds61@mobis.co.kr

Yong-Ho Kim
Electric Drive Engineering Team
Hyundai Mobis Co., Ltd
17-2, 240 Beon-Gil, Mabuk-Ro, Giheung-Gu, Yongin-Si
s1717s@mobis.co.kr

Un-Ho Lee
Electric Drive Engineering Team
Hyundai Mobis Co., Ltd
17-2, 240 Beon-Gil, Mabuk-Ro, Giheung-Gu, Yongin-Si
unho@mobis.co.kr

Hyeoun-Dong Lee
Electric Drive Engineering Team
Hyundai Mobis Co., Ltd
17-2, 240 Beon-Gil, Mabuk-Ro, Giheung-Gu, Yongin-Si
dong@mobis.co.kr

Abstract— **Recently, according to Eco-technology accelerating, new types of traction motor with the high efficiency and power are demanded. This paper presents that the Hairpin winding is applied to a design of the electric vehicle traction motor for the high efficiency and power density. Generally, the winding method using the toroidal coil has the restriction which is the unnecessary spaces between coils. However the Hairpin winding method can reduce the gap between coils, therefore the space factor is higher than that of winding methods. However, because of using the full pitch winding and wave winding, this method has the disadvantages of increasing the THD of back electromotive force and torque ripple. Thus, to minimize the THD and torque ripple, the full factorial method, Response surface method and the step skew to the rotor are applied. The paper presents the motor design using the Hairpin winding for the high space factor, and the analysis result by using RSM, the step skew and full factorial method shows the reduced space harmonics.**

Keywords-component; IPMSM, Hairpin winding, Design

I. INTRODUCTION (HEADING 1)

The global automobile companies pay attention to reducing the air pollution and the greenhouse effects. Many countries have been developing vehicles to reduce carbon emission and Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) are spotlighted as the greener transportation. The HEV is required for relatively lower costs than EV and FCEV because it can need the new infrastructure. Thus, it has been developing from mid of 1990's. However, The EV and FCEV are difficult to commercialize because the motor and battery are more expensive and bigger than that of HEV and they has short driving distance per charging. Also, many infrastructures to charge battery or hydrogen fuel cells are needed. For solving these problems, the cost of battery and the size of traction motor should be reduced and the efficiency of traction motor should be increased to extend the driving distance. Thus, the key of EV motor design is the increasing of the efficiency and power density.

This paper explains the major design factors for the motor with hairpin coil and optimizes the motor. Generally, HEV motor is not sensitive to the noise because the gasoline engine noise is higher than the motor noise but the driving noise of EV traction motor is very critical because the motor is only one driving source. Therefore, the parameters such as the total harmonic distortion (THD) and torque ripple ratio that affect the vibration and noise should be minimized. In this paper, the full factorial method and respond surface method (RSM) are applied to motor design for low noise and vibration.

II. IMPROVING DESIGN OF IPMSM USED FOR EV

A. *Equivalent circuit and governing equation*

The equivalent circuits for IPMSM based on a synchronous d-q reference frame including iron losses are presented in Fig. 1. The mathematical model of the equivalent circuit is given in the following equations. The iron loss is considered by equivalent resistance. The d and q axis voltages and currents are given by (1), (2) and torque, energy loss, and motor efficiency are given by (3), (4), and (5), respectively.[1][2]

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \psi_a \end{bmatrix} \tag{1}$$

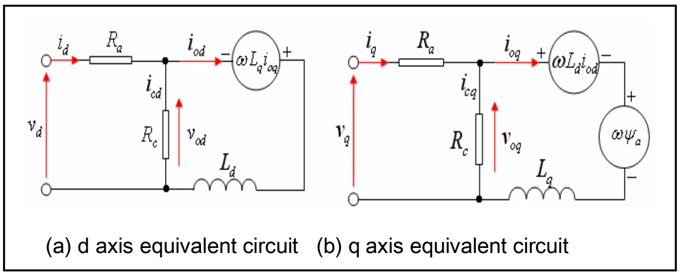


Figure 1. d-q axis reference frame

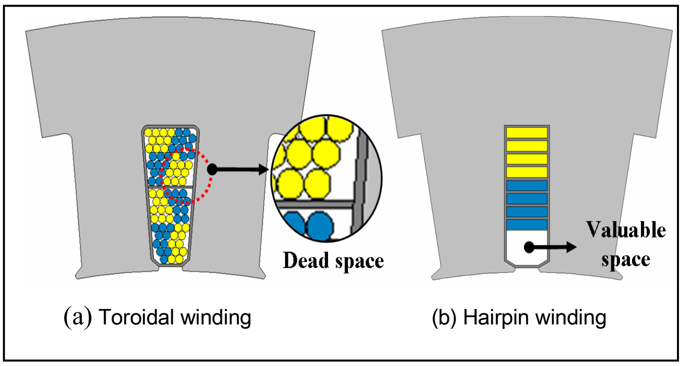


Figure 2. Toroidal winding and Hairpin winding

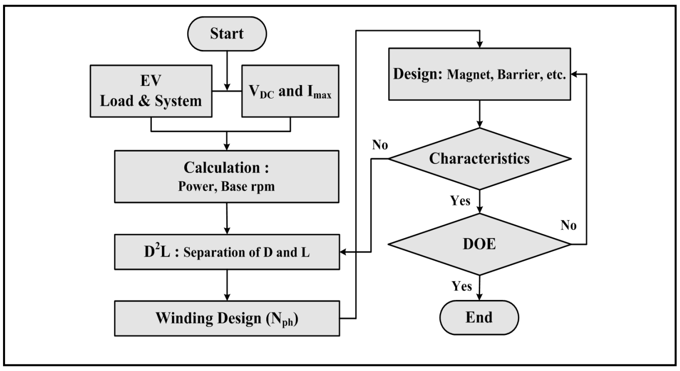


Figure 3. Flowchart for design of EV motor

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R_a & 0 \\ 0 & R_a \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} + p \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{2}$$

$$W_{loss} = W_{iron} + W_{copper} = \frac{(V_{od}{}^2 + V_{oq}{}^2)}{R_c} + (i_d{}^2 + i_q{}^2) R_a \tag{3}$$

$$T = P_n \{\psi_a I_q + (L_d - L_q) I_d I_q\} \tag{4}$$

$$\eta = \frac{P_{out}}{P_{out} + W_{loss}} \times 100\% \tag{5}$$

$$L_d = \frac{\psi_0 \cos\alpha - \psi_a}{i_d} \qquad L_q = \frac{\psi_0 \sin\alpha}{i_q} \tag{6}$$

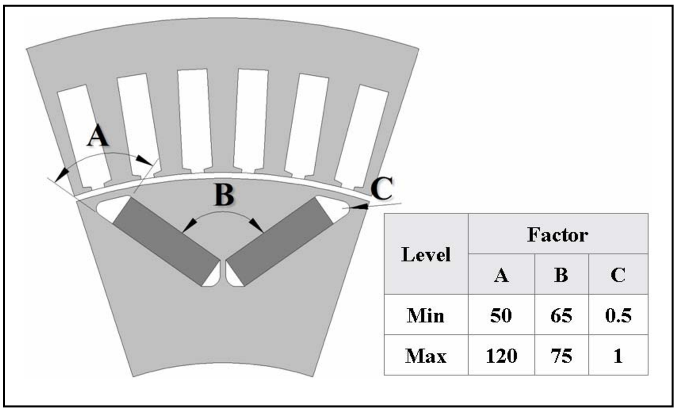
To estimate torque ripple, input armature current and current angle (β) are required at the base and maximum speed and Ld and Lq should be computed according to the change of armature current and angle (β).

B. Hairpin winding design

The hairpin winding is defined as inserting square coils of the hairpin shape to stator slots and welding the end turns. The general winding method is shown by fig. 2(a). There are gaps between the toroidal coil and the teeth and they cause low space factor which is rate of coil area to slot area. If the high space factor can be achieved, the power density of motor can be increased. The hairpin winding is one of the methods to increase the space factor of motor. The hairpin winding methods have largely two advantages for design.

First, due to minimizing the gap between the coil and the teeth, the stator current density can be reduced. It reduces heat generated by coils and improves the efficiency of motor by reducing the copper loss. Also, the teeth width of stator can be increased according to high space factor and it affects on reduction of the iron loss and the vibration & noise.

Next, under the same condition on the area of hairpin windings and toroidal windings, the series turns per phase of hairpin winding can be increased. It is possible to reduce the size of motor or improve the power density. Also, in case of



Level	Factor		
	A	B	C
Min	50	65	0.5
Max	120	75	1

Figure 4. Design factor and level

existing coils in the ATF oil, the cooling performance of the coil is improved and it can maximize the efficiency and power density of the motor. However, due to the welding coil method, the winding method is limited and the wave winding and the full pitch winding should be used. Also, owing to being difficult to make up the number of strands and the design the parallel circuit, the hairpin winding is considerably complicated and can not be applied the motor which has the big outside diameter or is needed by high current. In this paper, the hairpin winding is applied to the design of the 30kW-class permanent magnet motor.

C. Hairpin Design process of permanent magnet motor

In this paper, The IPMSM was designed using the D^2L design approach based on the required power and base speed which were selected by the load characteristics, battery voltage, inverter voltage rating and the current characteristics. The design flow of IPMSM is shown in figure 3.

D. Optimal design using DOE

In the motor design, using both FEA (Finite Element Analysis) and DOE (Design Of Experiments) is the design trend recently. The general design method takes much time to meet the requested target through the trial and error and the designer wonders whether the factors of the designed motor are the best or not. So, the optimal design method should be

Identify applicable sponsor/s here. If no sponsors, delete this text box. (sponsors)

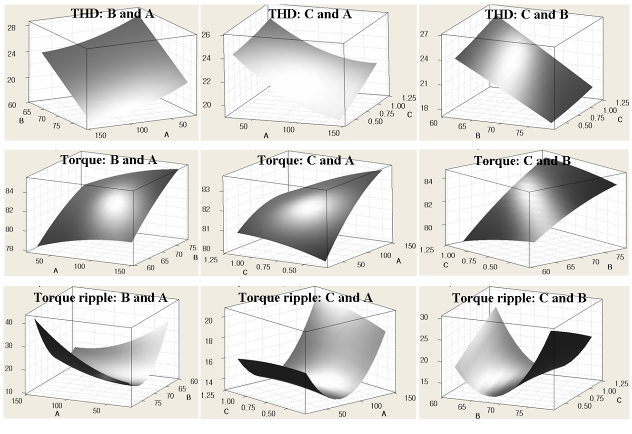
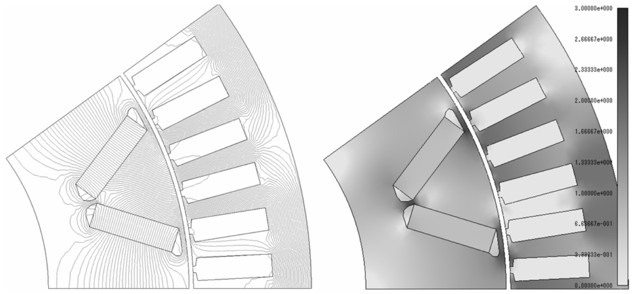


Figure 5. Analysis results of surface between factors



(a) No load Flux line (b) Load Flux density

Figure 6. Flux density distribution

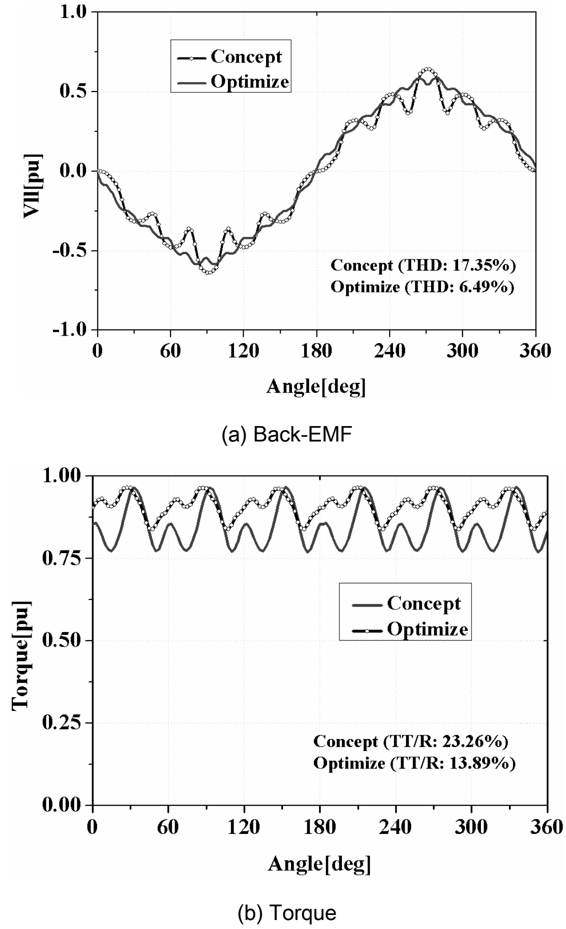


Figure 7. FEA of the optimal design model

carried out to meet the requested specification quickly. In this section, the main effect analysis is conducted with the full factorial method and the design factor. The level is selected according to the analysis result. Figure 4 shows the design factor and level. The object functions for the design are THD (total harmonic distortion) of back EMF (electromotive force), the average torque and the torque ripple.

RSM (Response Surface Method) is the useful method to search the optimal factor in various parameters because it analyzes the surface of response according to an assembly of experiment variables. For performing RSM, the number of trials occurred in 20 considering the Star point and the repeated experiment and the analysis of 40^{th} is conducted according to the no-load and load.

The Figure 5 shows the surface analysis results (THD of back EMF, the average torque and the torque ripple) obtained from the RSM. Through the analysis of the surfaces among design factors, the features of each factor are identified. Using the Y=F(x) function equation, the optimal result routine is derived. It can reduce the time and effort for obtaining the optimal design.

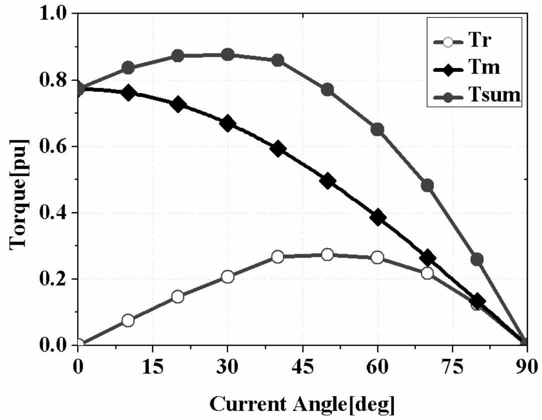
E. Analysis result and study

In this section, the model with the optimal design is analyzed by the FEA. The no load flux line and the load flux density of the optimal model are shown in fig. 6.

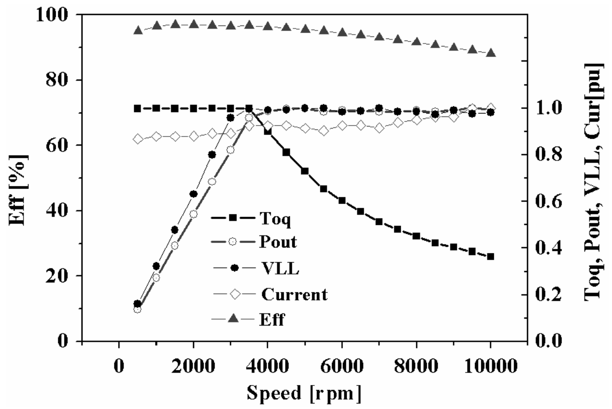
Generally, the model with the hairpin winding is needed to effort design considering the saturation flux density because hairpin winding has the small width in the bottom of the teeth. In this paper, flux density of model is designed at 1.9T level.

The torque ripple reduction is core design factors for decreasing the electromagnetic noise of the motor. The main causes of torque ripple are space harmonics, time harmonics and the cogging torque. The cogging torque is very small and the time harmonics can be reduced by the inverter. Thus, in the motor design, the space harmonics is only factor to decrease the noise. The THD means the rate of harmonics per the fundamental component in back EMF. So, the low THD reduces space harmonics and it can decrease the electric noise of the motor.

In this paper, the THD of back EMF is improved as 67% from initial design model and the torque ripple ratio are decreased as 40% and over. The back EMF and the torque wave of the optimal design model are shown in fig. 7.



(a) Torque division



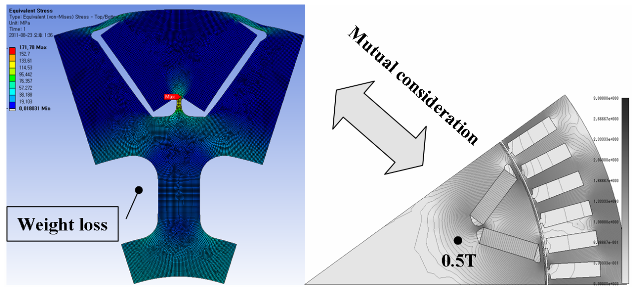
(b) Characteristics analysis

Figure 8. Analysis result of the optimal design model

In the equation 3, the total torque of IPMSM (interior permanent magnet synchronous motor) is presented by the sum of the magnetic torque and reluctance torque. The reluctance torque increases the efficiency at the high speed range. However, the reluctance torque is caused by the vibration and noise. Therefore, In the IPMSM design, it is very important to control magnetic torque and reluctance torque. In the fig 8(a) shows magnetic torque and the reluctance torque of the optimized design model and the characteristic analysis result presents in fig 8(b).

F. Structural Analysis and Design of the Rotor

To reduce the weight of the rotor, the electrical characteristics and mechanical strength would be considered. Because the magnet is inserted into the rotor of IPMSM, the rib is existed to prevent the magnet fall from the rotor. The rib is the significant design parameters which affect the efficiency of the motor. If the thickness of the rib is enough, the mechanical strength is high but the leakage flux is increased. In opposite case, although the leakage flux is decreased, the mechanical strength is so weak that the rib can be broken. So, the design considering the mechanical strength and electromagnetic force is positively necessary at the rib design.



(a) Mechanical characteristics (b) Electrical characteristics

Figure 9. Stress distribution of the Rotor

In this section, the thickness of the rib is decided at the point which met both the safety structural strength and the low leakage flux despite the worst condition (high speed). The maximum stress is 171MPa, the safety rate is 2.3. The figure 9 shows the analysis model.

III. Conclusion

In this paper, the traction motor for the electric vehicle is designed using the hairpin winding method. The hairpin winding is advantage of high efficiency and the high power density of the motor due to high space factor. It is very important design parameter for the EV to increase the driving distance. However, hairpin winding has the some constraints due to formed hairpin coil. To solve these problems, this paper explains some design parameter for motor design using hairpin winding. The DOE is applied to the design of the traction motor to improve THD of back EMF, the average torque and torque ripple. In the optimal design step 1, the design parameters are analyzed by the level 2 full factorial method. In the optimal design step 2, the regression analysis and the routine for optimal design are derived by the RSM (Response Surface Method) and the optimal model is designed.

In this paper, the mechanical strength and electromagnetic features are considered at the same time for the rib design and the stress concentrated at the rib is distributed. The optimal model minimized the thickness of rib and secured the safety rate of the rotor. This paper can be useful to design the hairpin winding and optimize the traction motor.

REFERENCES

[1] Y. Honda, T. Higaki, S. Morimoto, Y. Takeda, "Rotor Design Optimisation of a Multi-layer Interior Permanent Magnet Synchronous Motor," IEE Proc. Electric Power Appl. Vol. 145, No. 2, 1998

[2] Wen L. Soong, David . Staton, T.J. E. Miller, "Design of a New Axially-Laminated Interior Permanent Magnet Motor", IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 31, NO. 2, MARCH/APRIL 1995.