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Optimization Design of an Interior Permanent Magnet Motor for Electro Hydraulic Power Steering

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Abstract

This paper shows the optimization design of an interior permanent magnet motor for EHPS (Electro Hydraulic Power Steering). The effect of the design parameters of the motor on the output characteristics were analyzed through a simulation of a finite element method. In addition, according to temperature of during operation it was due to the differences in the demagnetization characteristics of the permanent magnet. Therefore, it used the magnetic properties in the actual operating temperature for designing order to be not appeared demagnetization. Depending on the design parameters, final model was analyzed for the total harmonic distortion ratio of the back electromotive force, torque ripple, cogging torque. The authors derive the optimal design for system requirements.

Keywords: Design Optimization, EHPS, Motor Design

1. Introduction

Figure 1. Electro hydraulic power steering system.

As shown in Figure 1, EHPS is the handle system of the method using motor for driving the hydraulic pump to assist the steering wheel. The vibration of the drive motor used for automobile steering has a direct effect on the steering. Therefore, the motor applied to the power steering is designed in a direction for reducing the torque ripple of the main factors of vibration[1].

In addition, there is a need for optimal design to reduce the size of components used in the vehicle according to a strategy for improving the fuel economy of the automobile. Thus, the preferred motor type with a high power density and is a model for the IPM type motor. Recently, it situated in the main trend of the automotive electric component for motor vehicles. Unlike the SPM type motor, IPM type motor has a structure that is inserted into the magnet inside the rotor2–5. This structure ensures the robust core structure to prevent separating the magnet during high speed operation. Furthermore, additional torque during high speed operation is generated to the reluctance torque in addition to the complement output. This paper contains information that the optimal design to the IPM

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motor EHPS system and the characteristics to maximize the torque through the rotor and stator design elements by analyzing torque ripple, THD and etc6,7.

2. Motor Design Analysis

2.1 Required Specification

The pole slot combinations for the IPM motor of EHPS was designed into the three-phase 6-pole 9-slot to use the existing control system. Table 1 shows the constraints for the design. Conditions to be most careful in the constraint is the size constraints of the outer diameter of a stator with housing. Considering the size of the stator outer diameter 96mm, it was determined core design specifications of the stator and the rotor. Also select the maximum value of all the constraints to satisfy the worst case of specification. That is, the stator outer diameter is 96mm, stack length is designed to 36mm.

Table 1. Motor design specification

Motor Design Specification	
Number of Phase	3-phases
Number of Poles	6
Number of Slots	9
Winding Connection	Star(Y)
Stack Length	36 mm
Stator Diameter	96 mm
Winding Pattern	Concentric
Core Material	S14
Magnet Material	NdFeB 42H

In addition, the winding of the motor can take a space factor more than 80%, because of the chosen concentric winding method and the split-core. Table 2 shows the design conditions for the operating environment and the rating the motor performance.

Table 2. Motor operation specification

Motor Operation Specification	
Working temperature range	-40^{0}C ~ + 120^{0}C
Rated Speed	3500 rpm
Maximum Speed	5500 rpm
Rated Torque	3.27 Nm
Maximum Torque	3.82 Nm

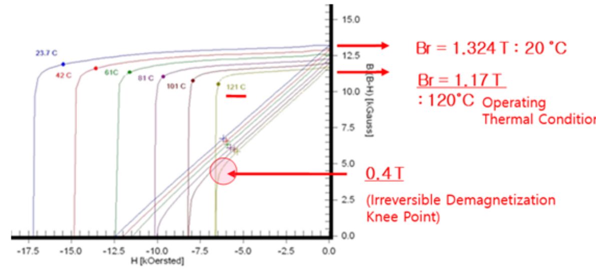

Figure 2. Magnetic characteristics of the operation point in consideration of the temperature condition.

Motor design was determined the number of coil turns and the permanent magnet size by considering the worst case of the drive temperature. As shown in Figure 2, it was determined the specifications of the permanent magnet in the worst of the driving temperature at 120 ^{0}C based on the B-H curve of the temperature of the permanent magnets. In addition, the motor base speed is 3500rpm and torque is 2.08Nm considering the rated output. In simulations of motor design, it has about 15% margin of the rated torque, because it cannot take into account the output reduction due to mechanical loss or the stray loss exactly.

The back electromotive force is generated by the magnetic flux change through the coil when the electric motor drive. If the value of the back electromotive force is larger than the voltage limit value, the current cannot be further applied to the coil from the power supply. Therefore, it is important to design such that the peak value of the back electromotive force is generated in the load operation to be smaller than the applied voltage.

2.2 Determine the Stator and Rotor Size

In order to determine the size of the stator and the rotor, it is determined the number of turns per slot per phase and the thickness of the yoke. The size of the permanent magnet and the number of turns of the coil to maximize torque is determined by the maximum in the range that does not exceed a back electromotive force limit. The number of turns of coil is set by 20 turns. The space factor of the slot is more than 80% since it is possible for using a split core. By calculating a slot area in consideration of the space factor and number of coil turns was set to the optimal size of the stator.

2.3 Determine Teeth Width and Yoke Width

The teeth width and the yoke width are closely related to the magnetic saturation of the core. Therefore, the magnetic flux density be set to an appropriate value according to the amount of magnetic flux in the core. First, the total amount magnetic flux was determined as the teeth 1.6T by generated an electric loading and a magnetic loading. And the teeth width is 8.6mm. The width of the yoke had determined the percentage value from teeth width. Figure 3 shows the back-EMF THD analysis of the teeth and oak rate. Figure 4 illustrates the torque and Figure 5 shows the optimum size, which is designed to minimize the torque ripple.

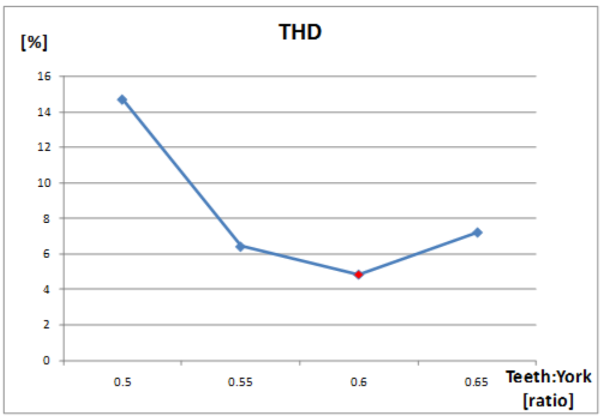

Figure 3. Back electromotive force THD according to the ratio of the teeth and the yoke.

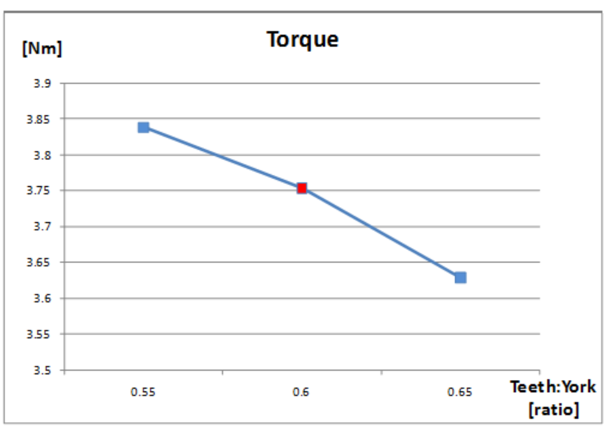

Figure 4. Torque according to the ratio of the teeth and the yoke.

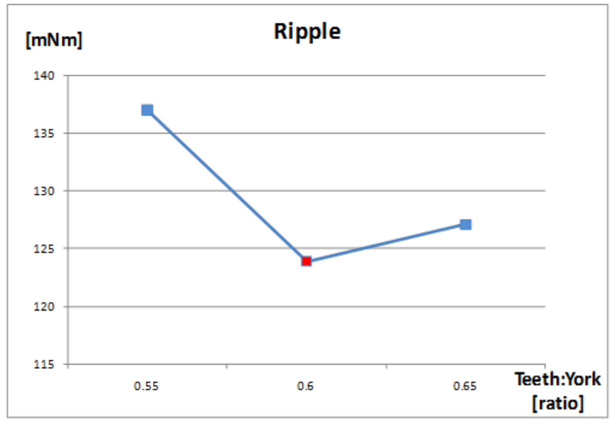

Figure 5. Torque ripple according to the ratio of the teeth and the yoke.

2.4 Determine Slot Open

The motor used normal core has absolutely necessary slot open for inserting the winding machine. However, in the case of the motor studied in this paper, there is no design restriction due to the opening of the slot to produce the stator core with split. The smaller opening slot has reduced cogging torque and torque ripple, but the average torque is reduced. Figure 6 shows the variation of the cogging torque according to the slot opening. Figure 7 shows the trend of the average torque.

Slot opening to a design placed the average torque margin is larger, but because of the cogging torque is increased proportionally, the slot opening width is selected for optimal performance.

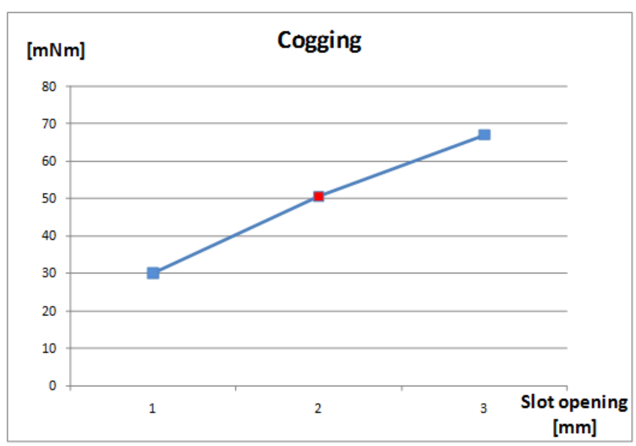

Figure 6. The variation of the cogging torque according to the slot opening.

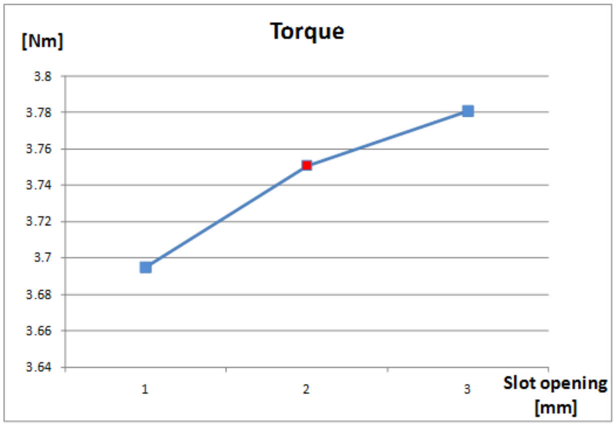

Figure 7. The trend of the average torque.

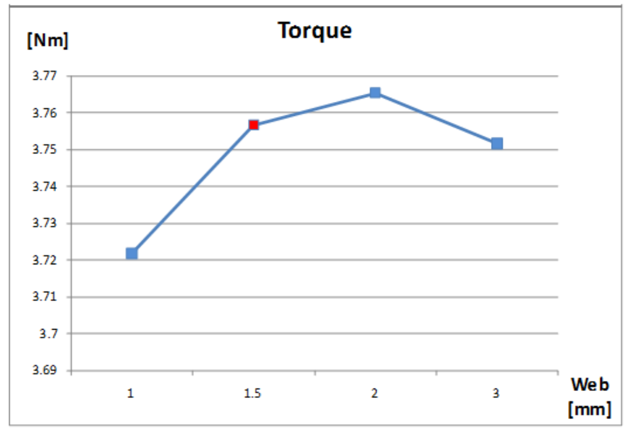

Figure 8. Torque according to web width.

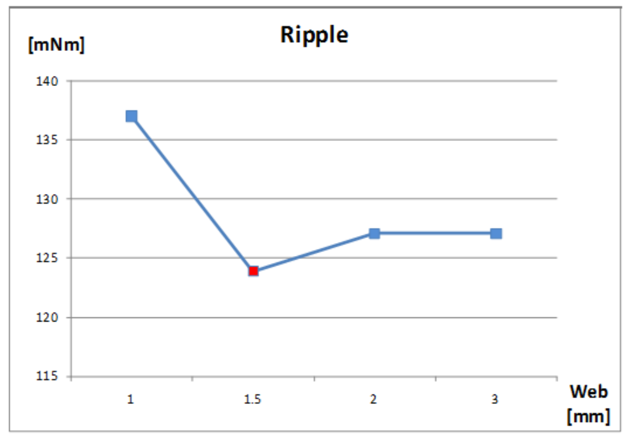

Figure 9. Torque ripple according to web width.

2.5 Rotor Design

In the IPM motor Rotor design considers the size of the permanent magnet, Web width, Rib thickness, the barrier shape. It can be determined the size of the permanent magnet according to the pole arc ratio of permanent magnet. Therefore, if the pole arc ratio is increased, because the magnetic flux amount increases. In other words, the torque can be increased.

However, if the amount of magnetic flux increases, the back electromotive force is increased more largely than the input voltage. Therefore, the electric motor optimizing in this paper has selected the pole arc ratio of the magnet so that the peak value of the back EMF is not exceeding the input voltage. Thus, the pole arc ratio is designed at 136° electric degrees.

Because the thinner Rib can reduce the leakage flux, normal designed Rib is thinned as possible in order to increase the motor output. However, if the rib thickness is too thin, the core can be torn. In addition, the barrier is designed by considering the Web width and the pole arc ratio of the permanent magnet.

2.6 Determine Web Width

Size of the web is one of the parameters that significantly change the characteristics of the motor. In other words, the web size increases the reluctance torque which affects the current phase angle to provide the maximum torque. When the web is 0.6mm when the beta angle is 21 degrees and the web is 1.5mm when 26 degrees. And as seen in Figure 8 and 9, the web width is determined, when it generates larger torque and low torque ripple at an appropriate value.

2.7 Determine Rotor Tapper

So far, upper progress design a basic model of the IPM motor. By applying the tapper design to the rotor for reducing additional cogging torque and torque ripple. The tapper design of the rotor is a cut rotor of q-axis to control with the web. Variable is placed in the slope of the difference in length of the air gap in the d-axis and q-axis. Figure 10, 11, 12, and 13 are parameter analysis for comparing the back EMF THD, the cogging torque, torque, and torque ripple analysis according to the airgap length difference in the two axes. As a result, the tapper is determined 0.2mm when the average torque is not much reduced and the reduction of cogging torque and torque ripple is much.

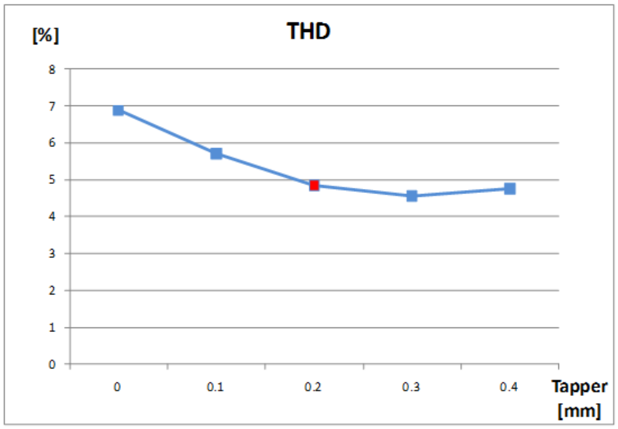

Figure 10. The back EMF THD in accordance with tapper.

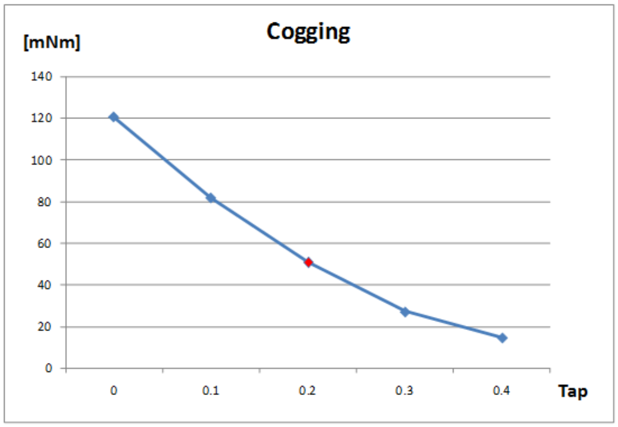

Figure 11. Cogging torque in accordance with tapper.

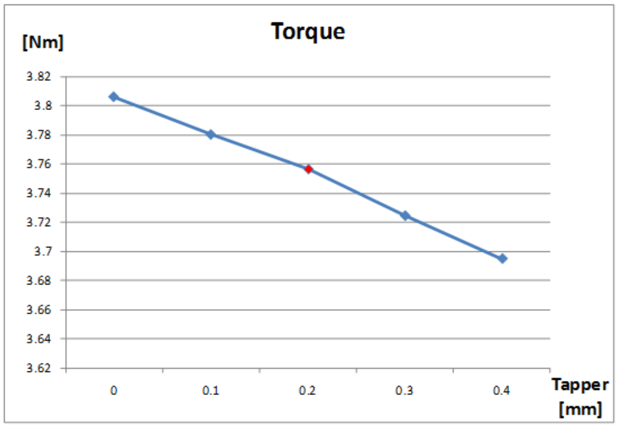

Figure 12. Torque in accordance with tapper.

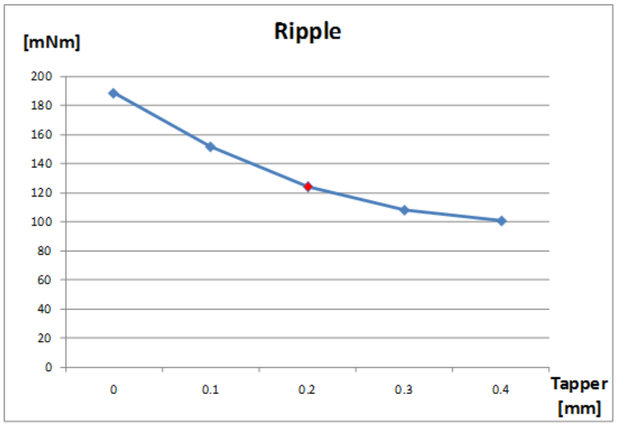

Figure 13. Torque ripple in accordance with tapper.

3. Evaluation for Final Optimal Model

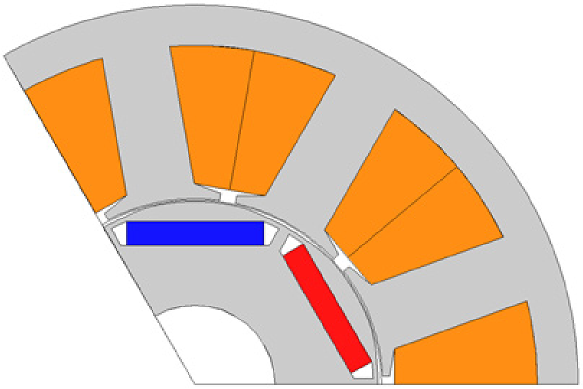

Figure 14. Final optimal IPM model.

The final design model by FEM analysis is shown in Figure 14. Figure 15, 16, 17, 18 and 19 is the evaluation results. At 3500 RPM and 5500RPM, the results are compared to such cogging torque, back-EMF and torque. The average rated torque 3.75Nm, torque ripple is 124 mNm rms, and Cogging Torque_rms is 50.61mNm. These results were satisfied with the performance specification. As well as line-to-line back-EMF peak value as 18.69V is satisfied for limit of the voltage supply.

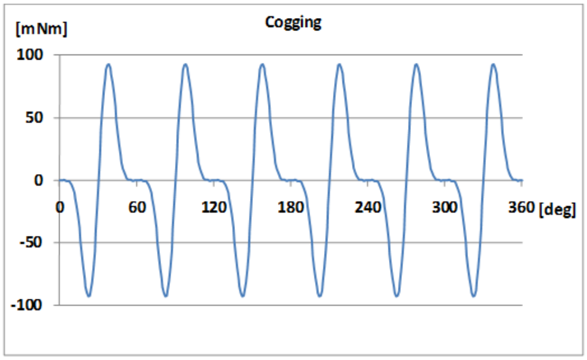

Figure 15. Cogging torque simulation (3500RPM).

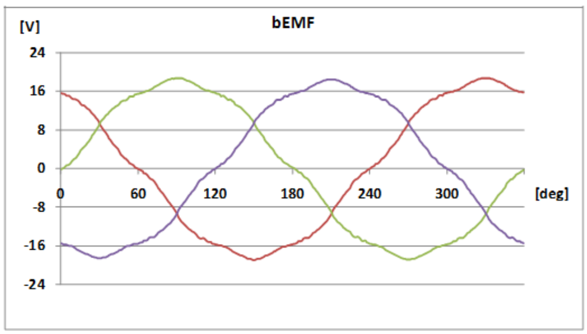

Figure 16. Line-to-line back EMF simulation (3500RPM).

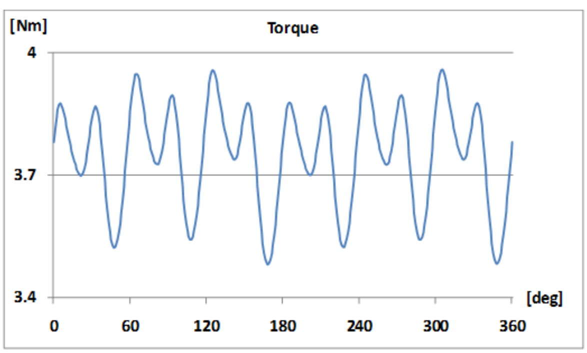

Figure 17. Torque simulation (3500RPM).

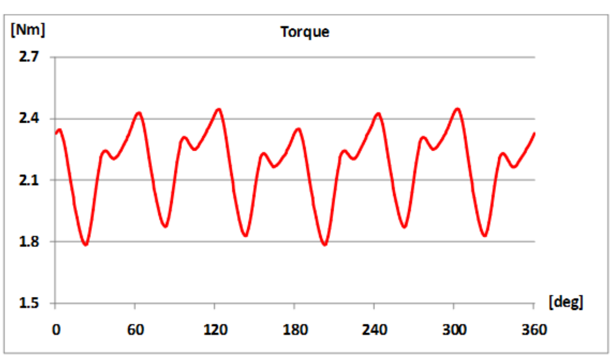

Figure 18. Torque simulation (5500RPM).

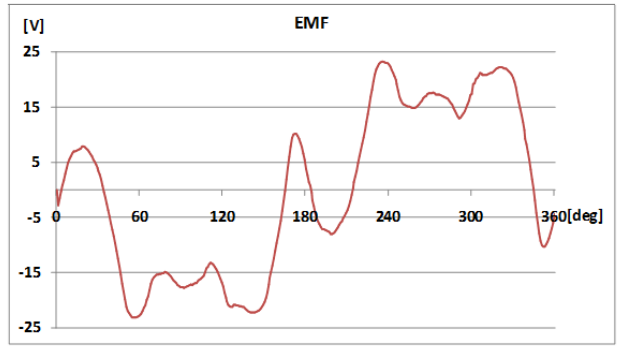

Figure 19. Line-to-line back EMF simulation (5500RPM).

4. Conclusion

IPM motor has a large torque ripple of the output torque characteristics due to use reluctance torque characteristics. But IPM motors can be designed for high power density and wide area high-speed driving. For these advantages, the IPM motor is a very suitable model for the vehicle component requiring weight reduction, compact size. In particular, power steering on the driving, which have a direct effect on the operation of the driver, EHPS have an extremely big impact on the quality of the vehicle. Therefore, it is possible to reduce the torque ripple of the motor that is the main vibration factors a very important design goal. This study employed the structure of the IPM motor to a high power density designs. The key design factors were analyzed to minimize the torque ripple. This could lead to an optimized IPM motor designs.

5. Acknowledgment

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6. References

1. Hendershot JR, Jr Miller THE. Design of Brushless Permanent-Magnet Motors; 1994.
2. Bianchi N, Bolognani S. Design techniques for reducing the cogging torque in surface-mounted PM motors. Industry Applications Conference; 2000, 2002. p. 1259–65.
3. Huang S, Aydin M, Lipo TA. Torque quality assessment and sizing optimization for surface mounted permanent magnet machines. Industry Applications Conference; Chicago, IL, USA. 2001 Sep 30-Oct 4. P. 1603–10.

4. Islam R, Husain I, Fardoun A, McLaughlin K. Permanent-magnet synchronous motor magnet designs with skewing for torque ripple and cogging torque reduction. IEEE Transactions on Industry Applications. 2009; 45(1):152–60.
5. Yang SC, Yang YP, Liu JJ. Design and control optimization of surface-mounted permanent-magnet machines with high torque and lowripple. The 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON); Taipei. 2007. p. 198–203.
6. Zhu L, Jiang AZ, Zhu ZQ, Chan CC. Comparison of alternate analytical models for predicting cogging torque in surface-mounted permanent magnet machines. IEEE Vehicle Power and Propulsion Conference; Harbin. 2008 Sep 3-5. p. 1–6.
7. Hur J. Characteristic analysis of interior permanent-magnet synchronous motor in electrohydraulic power steering systems. IEEE Transactions on Industrial Electronics. 2008; 55(6):2316–23.