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Research paper

Study on Improvement of Torque Characteristics of IPM BLDC Motor for Electric Water Pump using Ferrite Magnet

Soo-Whang Baek

Dept. of Automotive Engineering, Honam University, Korea
**Corresponding author E-mail: swbaek@honam.ac.kr*

Abstract

Background/Objectives: The objectives of this study are to propose a design method to replace the permanent magnets of brushless DC (BLDC) motors used in electric water pumps (EWPs) with ferrite materials and to improve the torque characteristics.
Methods/Statistical analysis: Using the proposed design algorithm presented in this study, the shape of the ferrite permanent magnet used in the rotor was changed, and the output at the same level was confirmed when compared with that of the conventional model that uses rare-earth magnet. In addition, finite element (FE) analysis verified that the cogging torque and torque-ripple characteristics of the proposed model using a ferrite material improved.
Findings: An EWP operated by a BLDC motor is used to improve the engine performance of a vehicle. Applying permanent magnets made of a ferrite material is necessary, which is advantageous in terms of cost in the design of BLDC motors. In particular, ferrite permanent magnets have a good demagnetization characteristic at high temperature compared with rare-earth magnets. By improving the cogging torque and torque ripple of the motor, achieving robust characteristics from disturbance and precisely controlling the system become possible. In this study, BLDC motors for EWPs were designed by replacing the rare-earth permanent magnets with low-cost ferrite permanent magnets. The shape design of the rotor using ferrite permanent magnet was implemented to make the output characteristics of the proposed model conform to the output characteristics of the conventional model, and simultaneously, the cogging torque and torque-ripple characteristics improved. To verify the suitability of the proposed design method, the design results were analyzed using 2D FE-analysis.
Improvements/Applications: The proposed design algorithm is suitable for cost reduction and performance improvement of BLDC motors that drive EWPs for automobiles.
***Keywords*: Brushless DC, Motor, Ferrite, Cogging Torque, Torque Ripple, Automobile.

1. Introduction

Recently, to improve the fuel efficiency of automobiles, systems that use motors have increased to reduce unnecessary energy consumption. Among them, an electric water pump (EWP) driven by a motor is used to improve engine efficiency and for effective heat management. The conventional water pump connected to the fan belt of an engine acts as an engine load, resulting in efficiency reduction. EWP has been developed to solve these problems. EWP is a device that circulates cooling water only when the engine needs to be cooled, thereby reducing unnecessary power loss[1,2]. EWP is an indispensable device for cooling of the battery systems, drive motors, and electronic control devices of hybrid vehicles as well as internal combustion engines. The EWP operating conditions depend on the operating mode and operate only in conditions that require driving, thus improving the fuel efficiency of the vehicle. As a result, EWP is expected to improve fuel efficiency by 2% compared to conventional mechanical water pump[3]. EWP is driven by motor power and mainly uses a brushless DC (BLDC) motor with high efficiency and reliability. In general, a BLDC motor is provided with a permanent magnet (PM) attached to the rotor surface or inserted into the rotor. Therefore, the losses in the rotor are reduced, and the efficiency is high. Permanent magnets used in BLDC motors generally use NdFeB (rare earth) materials with high magnetic-flux density[4]. However, because the unbalanced resource supply and demand are prone to NdFeB price fluctuation, a motor design that uses relatively inexpensive ferrite (non-rare earth) materials is needed. Ferrite magnets have lower residual magnetic-flux density than NdFeB magnets but have lower cost and superior stability to temperature[5]. BLDC motors are classified into surface permanent magnets (SPM) and internal permanent magnets (IPM) depending on the position of the PM of the rotor. In the IPM BLDC motor, the PM is inserted in the rotor and is structurally stable and strong compared with the SPM. In addition, the IPM BLDC motor is widely used in automotive applications because it can be operated at high torque and high speed condition. However, because the difference in the magnetic reluctance is large, the cogging torque and torque ripple suffer from a large disadvantage, which are difficult to control. Therefore, if the cogging torque and the torque ripple of the IPM BLDC motor are reduced, stable performance of the EWP can be expected[6]. In this paper, we first describe the structure of the EWP and propose a design method for an IPM BLDC motor using ferrite magnets. By replacing the permanent-magnet material with ferrite magnets, achieving output characteristics equivalent to those of conventional BLDC motors that use NdFeB becomes possible. The mechanical dimensions of the stator outer diameter are designed under the same conditions. To improve the EWP driving stability, the shape of the rotor magnet is designed to improve the cogging torque and torque-ripple characteristics. Finally, we compare its performance with that of the conventional model and verify the suitability of the proposed design algorithm.

2. Electric Water Pump

The conventional water pump is mechanically connected to the engine to circulate the coolant as long as the engine is warmed up regardless of the driving conditions of the vehicle. The conventional water pump, which mechanically operates, suffers from the disadvantage in that efficient control cannot be performed because the discharge rate of the coolant is determined in proportion to the number of revolutions of the engine. Figure 1 shows the structure of the EWP mounted on an engine. The EWP consists of a pump for circulating the coolant, a BLDC motor for generating torque, and a controller for driving the BLDC motor. The cooling flow path is closed so that the coolant is not circulated until the engine is warmed up to a set temperature. When the temperature of the engine has sufficiently warmed up, the cooling flow path is opened to perform the cooling process. Figure 2 shows the overall structure of the EWP system. Three conditions are necessary for the EWP to perform engine cooling: first is when the temperature of the cooling water is higher than the set temperature, second is when the engine oil temperature is higher than the set temperature, and third is when the engine rotates at a speed higher than the set speed. These conditions make possible improvement in the fuel efficiency of the vehicle because running the EWP at a high speed is unnecessary in a region where the cooling load is small.

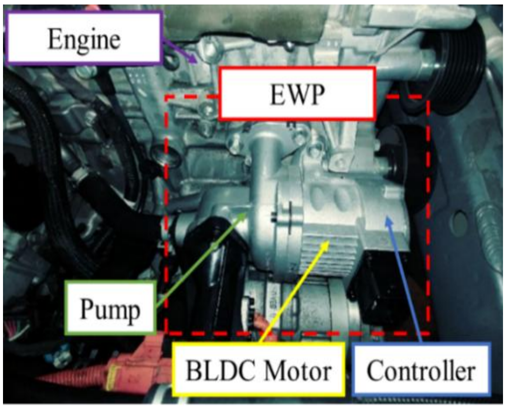

Figure 1: Structure of the EWP mounted on an engine

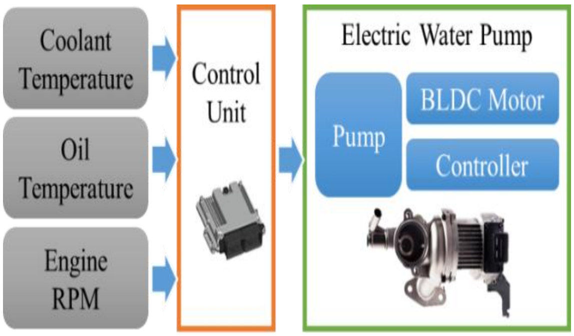

Figure 2: Overall structure of the EWP system

3. BLDC Motor and Proposed Design Algorithm

3.1. Conventional IPM BLDC Motor that uses NdFeB Magnet

The conventional model of the BLDC motor is shown in Figure 3. The distributed winding of the stator is wound in 24 slots. The rotor-magnet arrangement contains four poles. The conventional model is an IPM BLDC motor that uses NdFeB as a permanent-magnet material. Table 1 lists the specification of the conventional model.

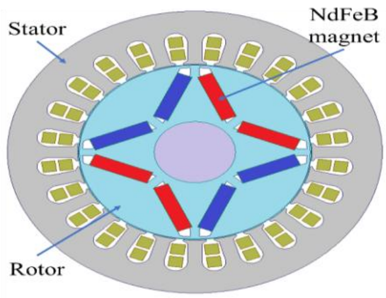

Figure 3: Cross section of an IPM BLDC motor (Conventional model)

Table 1: Specification of the conventional model

Items		Value	Unit
Stator	Number of slots	24	-
	Winding	Distributed	-
	Outer diameter	60	mm
	Inner diameter	36	mm
	Stack length	35	mm
Rotor	Number of poles	4	-
	Outer diameter	35	mm
	Inner diameter	10	mm
	Stack length	35	mm
Air gap length		0.5	mm
Magnet		NdFeB(N40SH)	

3.2. Proposed Design Algorithm

The proposed BLDC motor in this study is an IPM BLDC motor that uses a ferrite magnet. The proposed design algorithm of the BLDC motor for an EWP is shown in Figure 4. First, design specification of the BLDC motor is decided. The dimensions of the magnet for the IPM rotor design are then determined. Determine the diameter and turn of stator winding parameters and calculate the air gap magnetic flux density. The dimensions of the magnet for the IPM rotor design are then determined. Determine the stator winding number and diameter parameters and calculate the air gap magnetic flux density. Finally, the characteristics of the proposed model are compared with the conventional model and the design specifications are determined to satisfy the design goals. Through the proposed design algorithm, a ferrite magnet material was selected to replace the conventional NdFeB magnet. Table 2 lists the comparison of the ferrite permanent magnets selected in this study with the NdFeB permanent magnets used in the conventional model. A non-oriented silicon steel sheet with the same characteristics as the conventional iron core material was used. We used finite element (FE) method to analyze the BLDC motor, and the design of the proposed BLDC motor was carried out.

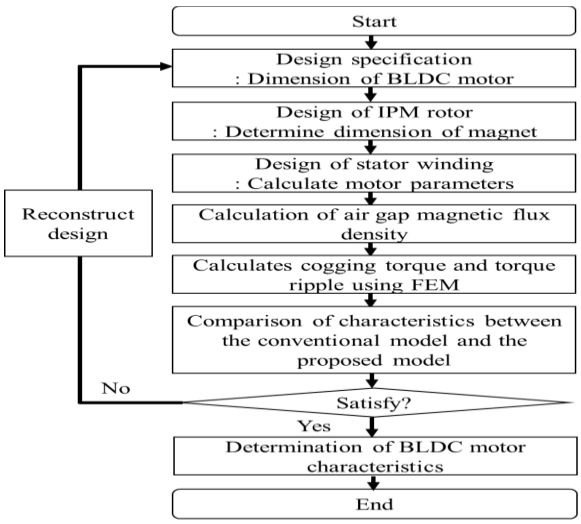

Figure 4: Proposed design algorithm of the BLDC motor for an EWP

Table 2: The specification of the conventional model

Items		Value	Unit
Magnet of Conventional model	NdFeB	N40SH	-
		Br: 1.24~1.28	T
		Hc : < -939	kA/m
Magnet of the proposed model	Ferrite	Y35	-
		Br: 0.40~0.44	T
		Hc: -176~224	kA/m
Core sheet		35PN270	-
		Thickness of sheet: 0.35	mm
		Non-oriented silicon steel sheet	

3.3. Proposed IPM BLDC Motor Using Ferrite Magnet.

The proposed model has the same air-gap length and slot/pole combinations as the conventional model. However, because the residual magnetic-flux density of the ferrite magnets is approximately one-third that of the NdFeB magnets, the characteristics of the back electromotive force are inevitably reduced. Therefore, to compensate for the reduced characteristics of the back-EMF, the design parameters such as the number of turns and diameter of the stator winding were modified. In addition, the coil diameter of the proposed model was increased to raise the coil fill factor in the slot compared with the conventional model. The shape of the rotor of the proposed model is a ferrite magnet with two layers inserted in the rotor, as shown in Figure 5. In addition, parameters such as the back-EMF constant, inductance, and resistance were calculated using finite element analysis. The design parameter results of the conventional and proposed models are compared, as listed in Table 3.

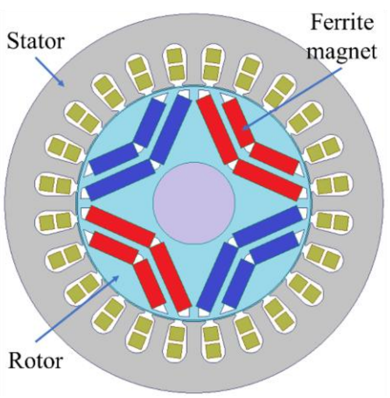

Figure 5: Proposed model of the IPM BLDC motor

Table 3: Design parameter comparison of BLDC motors

Items	Value		Unit
	Conventional model	Proposed model	
Rated speed	3500		rpm
Rated output	150		W
Number of slots	24		-
Number of pole	4		-
Air gap length	0.5		mm
Number of turns	26	34	-
Diameter of coil	0.5	0.6	%
Slot fill factor	32	48	%
Back-EMF constant	0.0038	0.0038	-

4. Comparisons of Characteristics

As described in the previous section, the proposed model that uses ferrite magnets compared with the conventional model that uses NdFeB magnets reduces the back-EMF because the residual magnetic-flux density of the PM is approximately three times smaller. The degradation in the back-EMF causes degradation in the output and efficiency characteristics of the BLDC motor. Therefore, we improve the proposed model by changing the permanent-magnet array to two layers and increasing the coil fill factor in the slot. Figure 6 shows the comparison of the back-EMF characteristics.

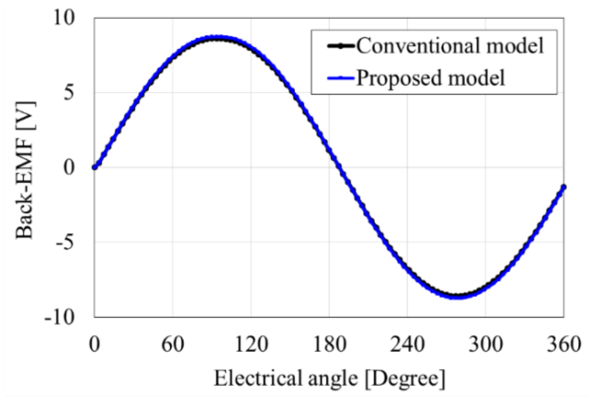

Figure 6: Comparison of the back-EMF characteristics

In general, if the back-EMF characteristic of a BLDC motor has a sinusoidal waveform, unnecessary losses can be electromagnetically reduced, thereby improving the output and efficiency of the motor. Therefore, analyzing and comparing the total harmonic distortion (THD) of the back-EMF characteristics are necessary. Figure 7 shows the THD of the back-EMF characteristic, which shows that the back-EMF fundamental-wave component of the proposed model is higher than that of the conventional model. In addition, the back-EMF value of the harmonic-order component of the proposed model is lower than that of the conventional model. As a result, we can see that the value of the fundamental-wave component is increased, and the magnitude of the harmonic component is reduced; thus, the loss is reduced and the efficiency improves. Further, we expect that the stability and control performance of the BLDC motor drive will be increased because of the decrease in the torque ripple.

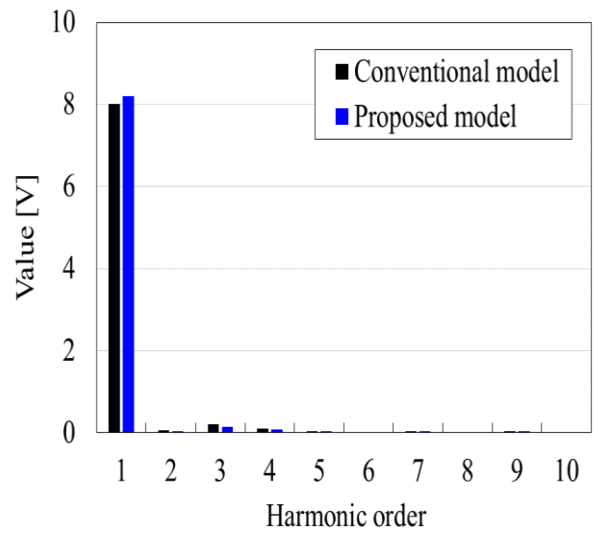

Figure 7: Comparison of the THD characteristics of the back-EMF

Figure 8 shows the comparison of the cogging torque characteristics. The peak-to-peak values of the cogging torque of the conventional and proposed model are 0.02533 Nm and 0.00683 Nm, respectively. Therefore, the cogging-torque characteristic of the proposed model is reduced by 74% compared with that of the conventional model because the magnet used in the proposed model is a ferrite material with a low residual magnetic-flux density.

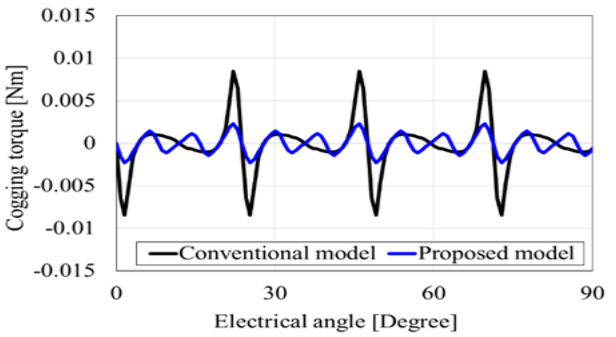

Figure 8: Comparison of the cogging torque characteristics (no-load condition)

Figure 9 shows the comparison of the torque ripple characteristics. The proposed characteristic is a torque ripple waveform that operates at rated condition (3500 rpm and 150 W). Generally, the torque ripple is proportional to the harmonic component of the back-EMF waveform. The THD characteristic of the proposed model back-EMF is 4% lower than that of the conventional model; thus, it is close to a sinusoidal waveform. Therefore, the peak-to-peak characteristic of the torque ripple of the proposed model is confirmed to be reduced by 8% compared with the conventional model. We expect that stable operation and control precision of the BLDC motor will be improved by decreasing the peak-to-peak values of the cogging torque and torque ripple characteristics.

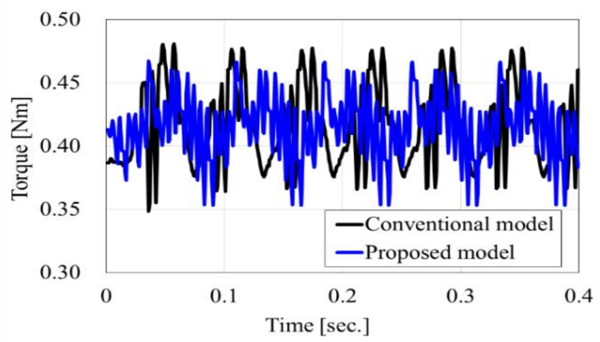

Figure 9: Comparison of the torque ripple characteristics (rated torque: 0.41 Nm)

The proposed model, which is designed using the BLDC motor-design algorithm proposed in this paper, should provide satisfactory performance to obtain the same output and efficiency to be able to replace the conventional model. To confirm these characteristics, the efficiency characteristics of the proposed model are derived, and the characteristic results compared with the conventional model are shown in Figure 10. At an operating speed of 3500 rpm (rated), the efficiency values of the conventional and proposed models are 60.2% and 60.9%, respectively. We can see that the efficiency is the same as that of the conventional model. Instead of using the existing NdFeB magnet, a BLDC motor for EWP is designed to replace the ferrite material. Finally, Table 4 lists the performance and specifications of the BLDC motors.

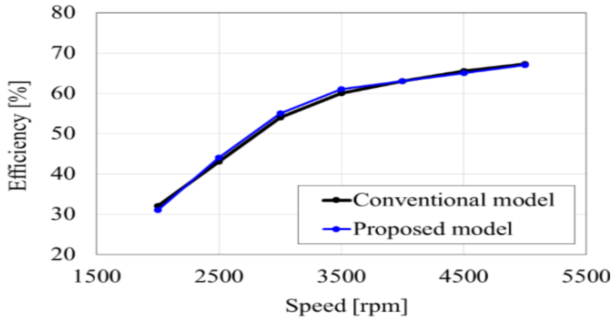

Figure 10: Comparison of the efficiency characteristics

Table 4: Comparison of the performance and specifications

Items	Value		Unit
	Conventional model	Proposed model	
Input voltage	13.5		V
Rated speed	3500		rpm
Rated torque	0.41		Nm
Rated efficiency	60.2	60.9	%
Cogging torque	0.02533	0.00683	Nm
Torque ripple	0.13229	0.12322	Nm
Current	6	5.4	A

5. Conclusion

In this study, we proposed the design algorithm of a BLDC motor to drive an EWP for automobiles. To solve the price instability factor of rare-earth permanent magnets, research was carried out to replace the permanent magnets of EWP BLDC motors that use NdFeB permanent magnets with ferrite materials. The output and efficiency characteristics, which are the main design conditions, were set at the conventional model level, and the design results of the proposed model were derived through FE analysis. In particular, the control stability of the EWP operated by a BLDC motor is expected to improve with the improvement in the cogging torque and torque-ripple characteristics. In the future, miniaturizing the EWP would be possible by improving the performance of the BLDC motor through selection of the design parameters of the stator and the rotor and using an optimal design that considers the objective function and constraints.

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