Characteristics of a Radial Flux Type Slotless Brushless DC Motor for No Cogging Torque

Sun-Ki Hong*

Abstract - BLDCMs are widely used in many industries. In certain specialized areas, they need to have high efficiency, high power rate and produce a low volume of noise, etc. In this study, a new type of slotless BLDCM is proposed that has no cogging torque, low iron loss and low volume as compared to commonly used BLDCMs. With a high performance magnet and coreless compact winding structure similar to those employed in linear synchronous motors, motor volume is reduced. The proposed motor has been put been through various experiments and has demonstrated acceptable results for industry applications.

Keywords: slotless, brushless DC motor, cogging torque, high efficiency

1. Introduction

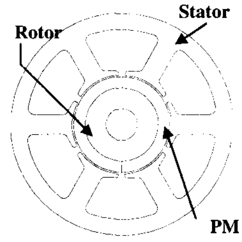
Slotless motors have commonly been used in axial flux type BLDCMs for small fan motors and capstan motors, etc. In radial type motors, slotless motors are less commonly utilized due to their high production costs. High efficiency and low noise vibration are basically required, especially in the case of certain home and automobile applications. To reduce the problems of noise and vibration, the elimination of motor cogging is required first. A skewing rotor can be applied in induction motors, however in BLDCMs, this is not a viable solution because of the winding and manufacturing costs. One possilbe answer to these problems is the low cost slotless type BLDCM. In this study, a radial flux type slotless motor is studied, which adopts the slotless linear synchronous motor winding method. With relatively little effort, this motor can be fabricated. The motor windings are molded to secure them on the stator frame. The rotor structor is similar to the common SPMSM. The experiments performed on the slotless motor show good performance in all areas including efficiency and noise, etc.

2. Slotless Brushless DC Motor

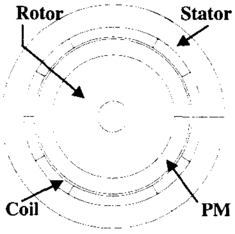
The radial type slotless brushless DC motors are not common in industrial areas because they are usually expensive to manufacture, despite their high performance ability in such areas as low noise, high efficiency, and high power rate [1-3]. Recently, slotless BLDC motors have been tried to be applied to certain industrial areas in which specialized performances are needed, such as in the case of the EPS system. In this study, we attempt to confirm the superiority and the practicality of a radial flux slotless brushless DC motor that has a simple structure, demonstrates high performance and requires low costs to produce. This type of motor can be applied not only to specialized areas but also to more generalized areas, making it desirable as a replacement for the current commonly used BLDC motors.

2.1 Basic Structure of the Analyzed BLDCM

Fig. 1 shows the structure of a BLDC motor. Fig. 1(a) illustrates the slot type BLDCM, which is very commonly used, having coils wound in the slots. This type of BLDC motor possesses cogging torque because of the relation between the slot structure and the rotor magnets. Many researchers have attempted to reduce or remove the cogging torque using various methods, however it is either very difficult to remove it completely or very expensive to do so. Fig. 1(b) depicts a slotless BLDCM.



(a) Slot type BLDC motor



(b) Slotless BLDC motor

Fig. 1 Two types of BLDC motors

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As can be seen in this Fig., there is no slot in the stator and the winding coils are bonded on the inner surface. Next they are molded to affix them to the stotor yoke. This stucture is very simple and the production costs are relatively inexpensive. Since there are no slots, no cogging torque can exist.

2.2 Characteristics of Slotless BLDCM

The slotless BLDC motor in this study has the following features. First, there are no teeth on the stator, which normally cover the winding coils. Therefore the magnetic resistance between the rotor and stator becomes uniform for the circumferential direction, making it possible for the motor to rotate softly without cogging torque. In addition, it reduces the vibration and noise and enhances the ability of uniform speed. Second, this motor has an efficient heat radiation structure because the coil is attached to the surface of the stator yoke and the molding material in use has a high heat transfer rate. Therefore, the motor structure has the necessary features to enhance the output density relative to other structures. Third, there is no air gap in the stator so the magnetic inductance becomes smaller than the other slot type BLDCM. The system response time becomes faster because the electric time constant becomes smaller than in the common slot type BLDC motors. The fourth characteristic is that there are no stator teeth where the dominant iron loss is arised, which decreases the iron losses in the BLDCM. In addition, this motor has lower magnetic saturation, which enhances the torque linearity and controllability according to the input currents.

3. Simulation and Experiment

Table 1 shows the specifications of the motor. The desired maximum efficiency is 85%, which is much higher than the common BLDCM with its small output. In order to achieve the following aims, high performance permanent magnet and high density winding are required. The permanent magnet in this study is NdFeB and it is used to increase the air-gap flux density within a limited volume and the stator winding is concentric with a high fill factor.

Table 1 Specification of slotless BLDCM

Voltage [V]	42
Output [W]	250
Efficiency [%]	85
Max. Torque [Nm]	3

Fig. 3(a) shows the structure of the proposed slotless BLDC motor. The number of poles is 8, the winding is consequent concentric and the winding arrangement is similar to the linear PM synchronous motor to decrease the air gap and to make winding easy.

3.1 Simulation

For the principle of the slotless BLDCM is the same as with DC motors, the analytical equations of voltage, back EMF and torque are as follows.

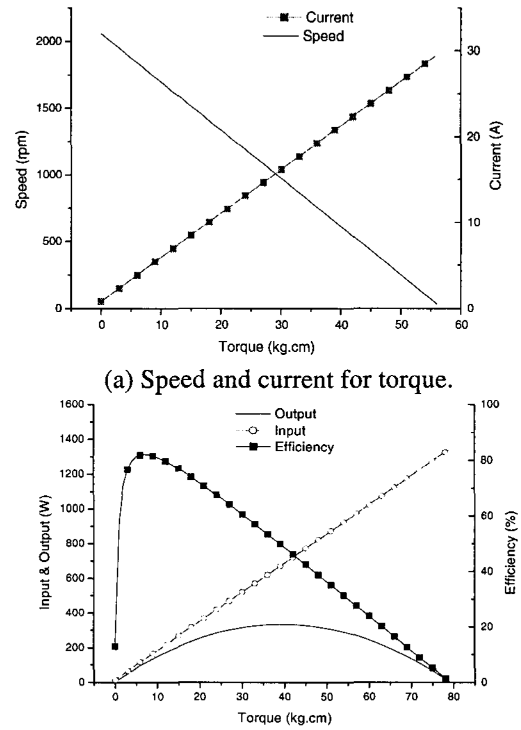
$$V_a = E_a + I_a R_a \tag{1}$$

$$E_a = \frac{P}{a} Z\Phi \frac{N}{60} = k_e \Phi \omega_r \tag{2}$$

$$T = \frac{Z}{2\pi} \frac{P}{a} \Phi I_a = k_t \Phi I_a \tag{3}$$

where E_a is back EMF, P is the number of poles, Z is the number of conductors, a is the number of parallel circuits, k_e is the back EMF constant, k_t is the torque constant and Φ is the flux per pole.

With equations (1) to (3), the slotless BLDC motor can be simulated for torque, current, input, output and efficiency to speed. Fig. 2 shows the simulation results for the efficiency, input and output according to the torque. As



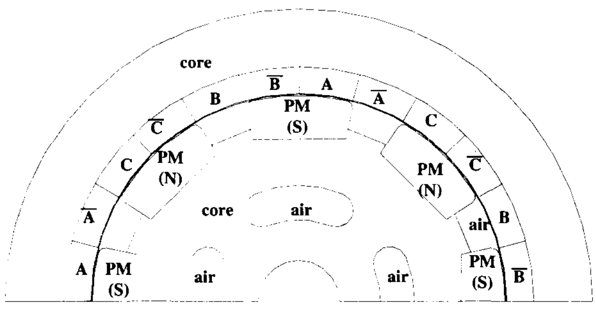
(a) Speed and current for torque.

(b) Output, efficiency and input for torque.

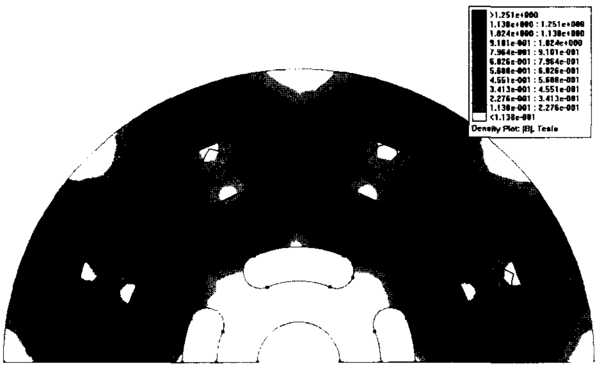
Fig. 2 Simulation results of slotless BLDCM.

predicted, the current and the speed variation according to the torque are linear from no load to full load, signifying a high level of controllability in this motor. Therefore, one of the applications for this motor can be in the EPS system, which needs no cogging torque for torque control with high linearity. This motor can also be applied to general servo systems.

Fig. 3 shows the analysis results according to FEA. As can be seen, Fig. 3(a) depicts the structure of the slotless motor and it is analyzed for half plane because of its symmetry. The number of poles is 8 and the winding is concentric. Fig. 3(b) shows the equi-potential. Because the equivalent air-gap is large, there is no saturated part in the stator or rotor core and the linearity of torque to current is increased.



(a) Motor structure.



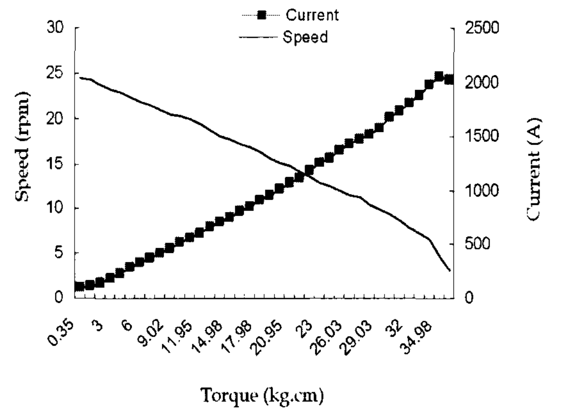
(b) Diagram of the equi-potential.

Fig. 3 The finite element analysis of slotless BLDCM for equi-potential.

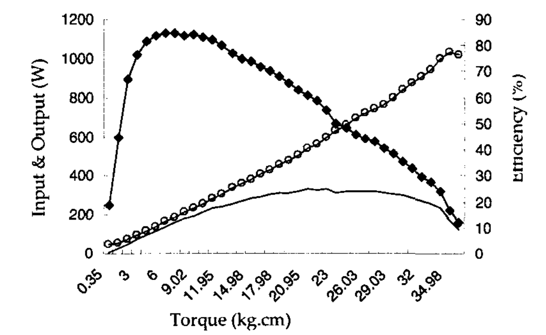
3.2 Experimental results

Fig. 4 shows the experimental results of the slotless BLDC motor. The speed and current to torque are almost linear even though the torque is a little larger than the full torque load. The maximum efficiency is about 85% and the maximum output is about 300W. These results are agreeable compared with the simulation results.

One of the most significant factors about this motor is, as mentioned, the cogging torque. Fig. 5 shows the measured cogging torques. Fig. 5(a) is the measured data for a slot type BLDCM and Fig. 5(b) is that for the slotless BLDCM. As we can see, there is no cogging torque in the slotless BLDCM. On the contrary, the slot type BLDCM has some cogging torque, about 3% compared to the rated torque. In certain applications like the EPS system, it is said that this amount of cogging torque can affect a certain degree of uncomfortability to the hands. In the case of some applications like servo motors, the cogging torque prevents the driver from achieving accurate control.



(a) Speed and current for torque.



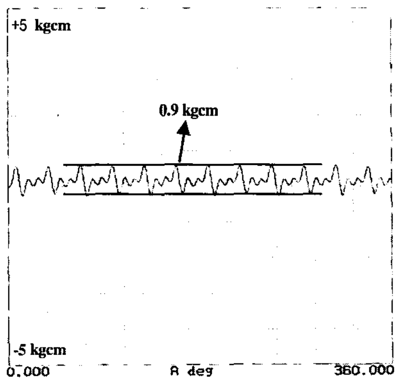
(b) Output, efficiency and input for torque.

Fig. 4 Experimental results of slotless BLDCM

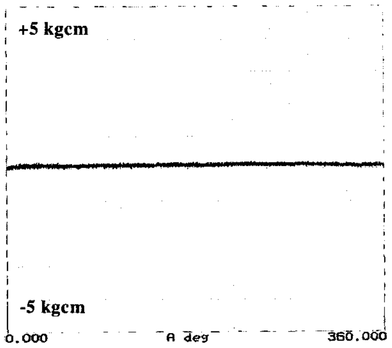
Table 2 shows the comparison of the noise level between slot type and slotless type BLDC motors having almost identical volumes. As predicted before, the slotless BLDCM is much quieter because there is no cogging torque. This comparison is measured using the same driver. Because the flux distribution of the slotless BLDCM is sinusoidal, if the driver output voltage for the slotless BLDCM is sinusoidal, the noise level will be reduced even more.

Table 2 Measured noise level

Speed[rpm]	Slotless BLDC	Common BLDC
500	42.3	46
1000	42.9	48.2
1300	43.4	49.5



(a) Cogging of slot type BLDCM



(b) Cogging of slotless BLDCM

Fig. 5 Comparison of cogging torque between slot and slotless BLDCM

4. Conclusion

BLDCM is widely used in various industries. For some specialized areas, these motors must provide a high level of efficiency, high power rate, emit a low level of noise and low torque ripple, etc. In this study, a radial flux slotless type BLDCM is proposed with no cogging torque, low iron loss and low volume rather than the commonly used BLDCMs. With high performance magnets and coreless compact winding, motor volume is decreased and efficiency is increased. The proposed motor has been put through various experiments and has demonstrated acceptable results for industry applications like the EPS system.

Acknowledgements

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