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Field-Winding Claw-Pole Type Motor Characteristics Analysis Using Additional Ferrite Magnets

Jin-Seok Kim[1], Dae-Woo Kim[1], Yong-Jae Kim[2], and Sang-Yong Jung[1]*

[1]*Sungkyunkwan University, Korea*
[2]*Chosun University, Korea*

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The magnetic flux density of a rotor core is increased on the basis of the B-H characteristics of the core when the field current of a field-winding claw-pole type motor (FWCPM) is increased. However, owing to the saturation of the rotor core caused by the increase in magnetic flux density, the magnitude of the electromotive force relative to the field current increase in a nonlinear direction. Therefore, to improve the performance of the FWCPM, it is necessary to reduce the leakage flux and rearrange the source of the rotor in order to supply additional magnetic flux. In this paper, three types of ferrite assisted field-winding claw-pole type motors (FAFWCPM) are proposed to improve the nonlinearity and performance of the FWCPM field current. The magnets applied to the FAFWCPM are located between the claws, at the front of the claws, and at the tops and bottoms of the claws. Further, to ensure analytical accuracy, the amount of magnets used in the motor is equally limited. Finally, the magnitude of the electromotive force under a no-load condition and the average torque under the load condition are studied through three-dimensional finite element analysis.

Keywords : Synchronous Motor, Permanent Magnet, Claw-Pole type Motor

1. Introduction

Permanent magnet synchronous motors are used in various industrial fields owing to their structural robustness and high output power density. However, the materials used in permanent magnets have disadvantages in that their prices fluctuate rapidly with respect to the market demands, and the manufacturing cost of such magnets is high owing to limited availability of the materials. In addition, it is difficult to control the intensity of the magnetomotive force (MMF) generated in a rotor; therefore, a weak field control technique is applied under high-speed operation, which degrades performance [1]. A motor whose MMF can be varied has been recently developed, namely, a variable flux memory motor. This type of machine uses a low coercive force magnet to increase the rate of a variability of the magnet. However, due to such characteristics, this machine has a disadvantage wherein the magnets are demagnetized under the load conditions by the stator MMF [2].

A field-winging claw-pole type motor (FWCPM) has a relatively simple structure and low manufacturing cost compared to a permanent-magnet-type motor. In addition, the FWCPM has the advantage of easily controllable the field flux and is used in various industrial fields because of its easy torque control. In particular, the coil can be easily excited and has a high MMF and high output density. FWCPMs are therefore applied to vehicle generators. Hybrid-type claw-pole motors have recently been studied to increase the motor output density by adding magnets to the FWCPM [3]. In this study, we compare the hybrid-type claw-pole motors with ferrite magnets based on type to improve the nonlinearity of the field current due to rotor core saturation in the FWCPM. First, a ferrite magnet is applied to the rotor to increases the amount of total magnetic flux generated in the field and improve the no-load characteristics of the FWCPM. Further, the ferrite assistant FWCPM (FAFWCPM) with a three type of structure has been proposed. The magnet positions of the proposed model are located between the claws, at the front of a claw, and at the top and bottom claws. To verify the validity of the analysis, the usage

*Corresponding author: Tel: +82-31-299-4952
Fax: +82-31-299-4918, e-mail: syjung@skku.edu

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magnet applied to the three types of FAFWCPM is maintained, and finally the positions of the magnets used to maximize the no-load and load characteristics are investigated using a three-dimensional finite element analysis.

2. Field-Winding Claw-Pole Type Motor

The design dimensions of the FWCPM are shown in Fig. 1 and Table 1, respectively. When a rotor current is applied, the flux flows according to the claw. Therefore, the polarity of the claw changes depending on the direction of attach to the upper or lower core body. As shown in Fig. 1, after the current direction is set, the claw connected to the upper core body has an N-pole characteristic, and the claw connected to the lower frame is driven with an S-pole characteristic. Therefore, the polarities of the driving directions and claw are determined according to the direction of the current applied to the rotor winding and the arrangement of the claw, respectively. In addition, the amount of magnetic flux coupled to the stator varies depending on the magnitude of the current applied. Furthermore, the magnitude of the electromotive force (EMF) of the motor is determined based on the rotor speed and the amount of magnetic flux linking the windings. The value of the EMF induced in the coil can be calculated using equation (1).

$$\mathrm{EMF} = -d\lambda/dt \quad (1)$$

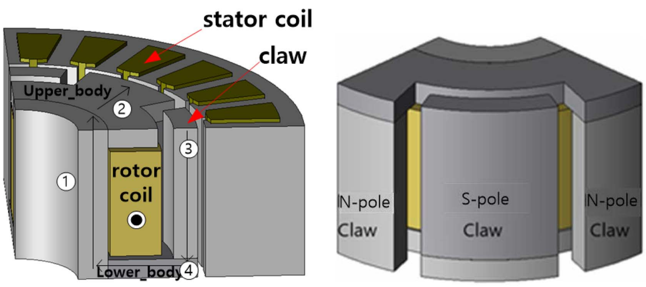


Fig. 1. (Color online) Shape of FWCPM.

2.1. No-Load Characteristics of FWCPM by changing the Field Current

As Fig. 2 shows that the saturation degree of the rotor core increases as the field current increases. For an accurate study, the point of high saturation in the core was set to point A, and the magnitude of the magnetic flux density was analyzed. As the field current increases, the value of the magnetic flux density of the core increases continuously, whereas the value of the magnetic flux density distributed in the air gap decreases when the field current exceeds a certain value, owing to the leakage flux. When point A is highly saturated by the field current, the flux from the rotor winding does not link to the stator, and the main flux path is lost, as shown in Fig. 1. Thus, the magnitude of the EMF, which is closely related to the air-gap magnetic flux density, decreases when the field

Table 1. Design specifications of FWCPM.

Outer diameter	Stator	144 mm	Number of turns	Stator	10
	Rotor	90 mm		Rotor	50
Air-gap width		2 mm	Speed		3000 rpm
Motor height		40 mm	Steel type		50PN470
Poles and slots		8 / 24			

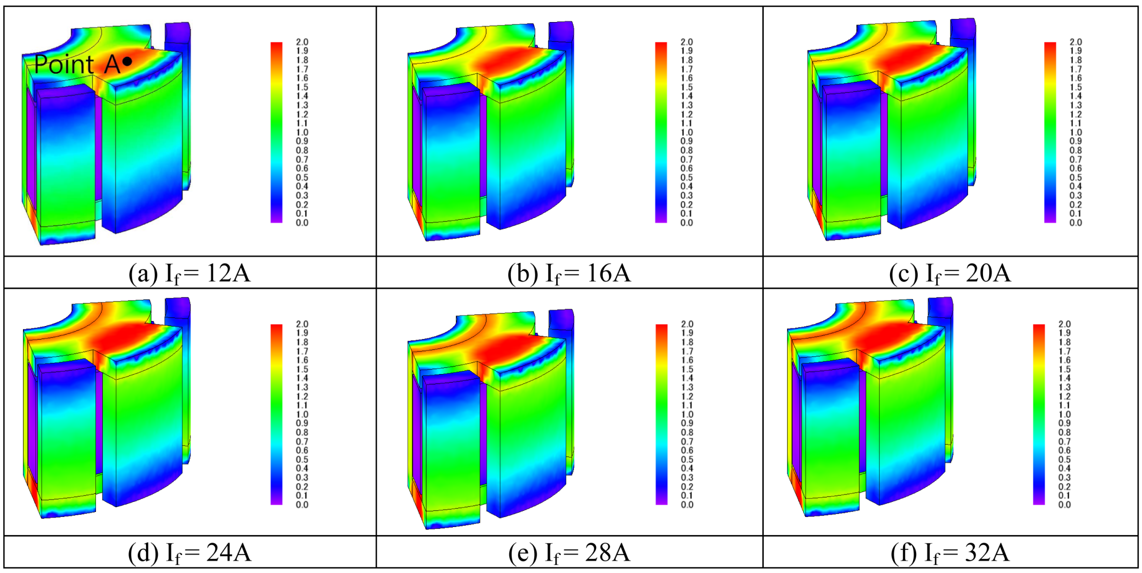
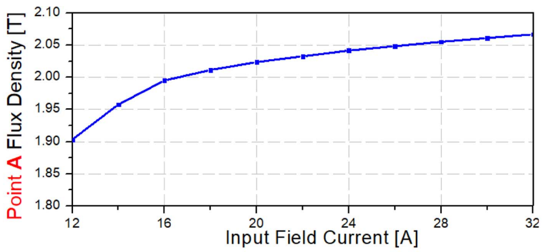
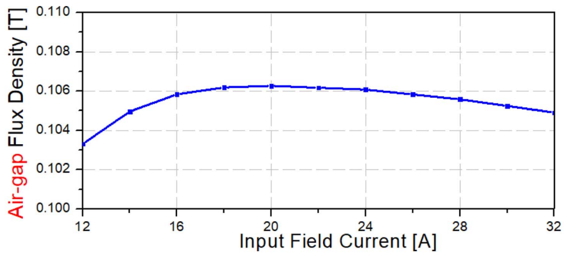


Fig. 2. (Color online) Flux density of rotor core.



(a) Point A flux density based on field current



(b) Air-gap flux density based on field current

Fig. 3. (Color online) Flux density of core and air-gap parts.

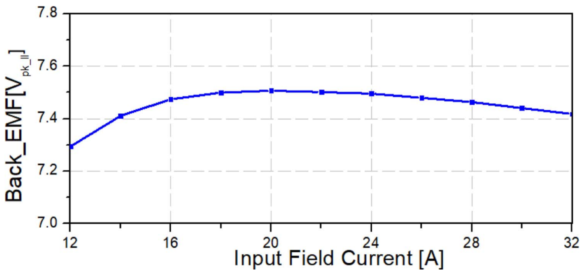


Fig. 4. (Color online) Magnitude of EMF by field current.

current exceeds a certain value, as shown in Figs. 3 and 4. Therefore, a method for applying the ferrite magnets to improve the characteristics of an FWCPM was studied.

3. Ferrite-Assisted FWCPM

In this study, an additional ferrite magnet is utilized to increase the EMF and torque characteristics by increasing the field current of the FWCPM. The specifications of the ferrite magnets are shown in Table 2. As Fig. 5 indicates, the magnets are located at three positions, namely, between the claws, at the front of the claw, and the top and bottom claws. In model 1, the magnets magnetized toward the N-pole claw are placed between the claws. Therefore, the magnetic flux generated from the rotor winding and magnet are added, as shown in Fig. 5(a). The magnets of model 2 are attached according to the polarity of the claw, as shown in Fig. 5(b). The N-pole magnets magnetized in

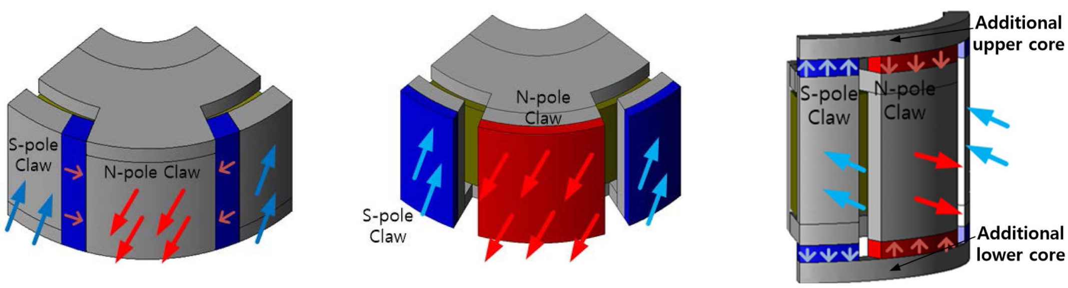
Table 2. Specifications of ferrite magnet.

Usage of the ferrite magnet per pole		2693 mm^3
Spec. of magnet	Br	0.37 T
	Hc	279657.97 A/m

the direction of radiating rotor to the stator are attached in front of the N-pole claw and S-pole magnets magnetized in the opposite direction of the N-pole magnet are attached to the front face of the s-pole claw. In Model 3, the magnets are arranged in the axial direction, as shown in Fig. 5(c). The magnets placed on the N-pole are magnetized in the direction of the N-pole claw, and the magnets placed in the S-pole are magnetized in the opposite direction. An additional core is placed on the magnet to create a new path for the magnetic flux generated from the magnet. Finally, the magnets are arranged in a direction that increases the polarity of the claw, thereby increasing the total amount of magnetic flux generated in the motor.

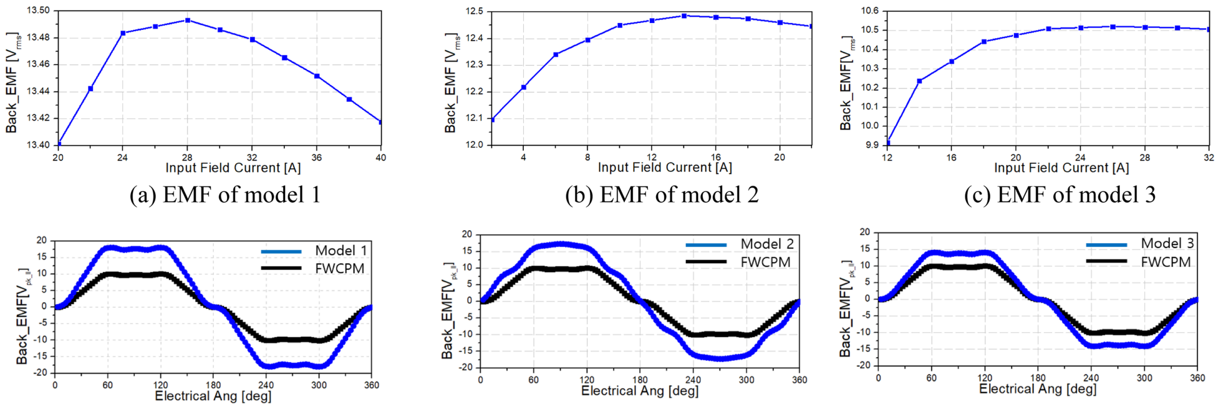
3.1. Ferrite-Assisted FWCPM No-Load Analysis

In model 1, a magnet magnetized in the N-pole claw direction is placed between the claws, as shown in Fig. 5(a). Therefore, the total flux generated by the rotor is increased by adding the magnetic flux. The added magnet serves to improve the magnitude of the EMF by 44.2 % by increasing the magnetic flux passing from the rotor to the gap while blocking the leakage flux path from claw to



(a) Model 1 (b) Model 2 (c) Model 3

Fig. 5. (Color online) Three types of FAFWCPM.



(a) EMF of model 1 (b) EMF of model 2 (c) EMF of model 3

(d) EMF wave form of model 1 (e) EMF wave form of model 2 (f) EMF wave form of model 3

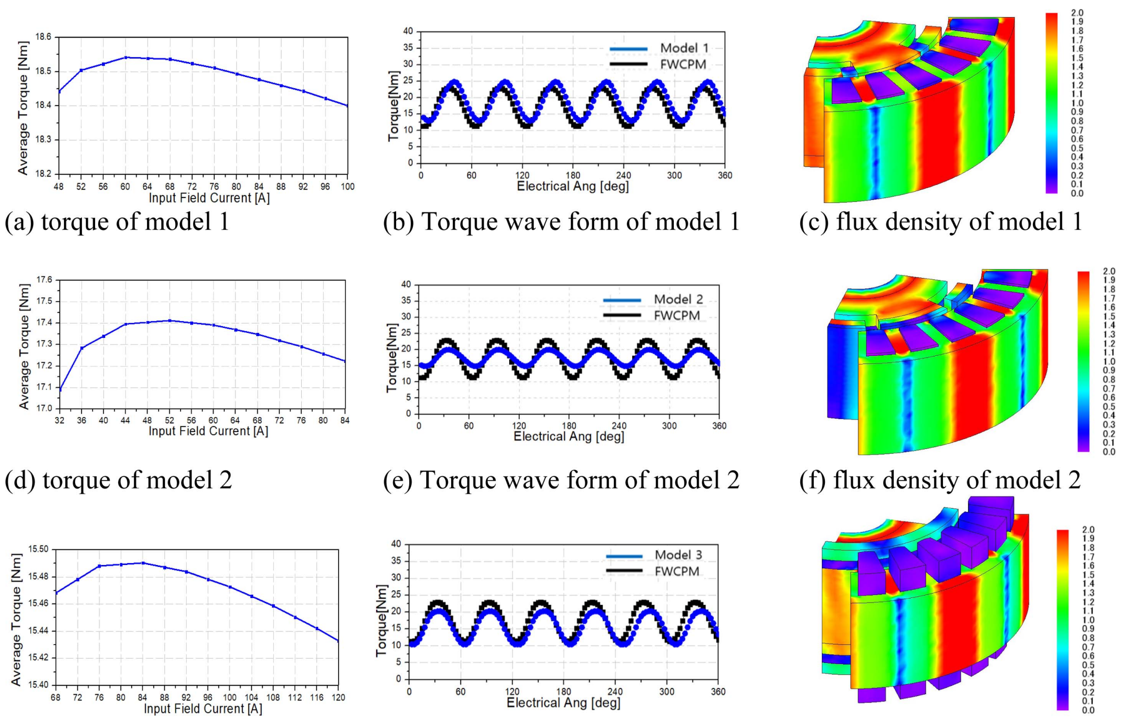
Fig. 6. (Color online) No-load characteristics of the FAFWCPM.

Table 3. Increasing ratio of EMF based on the field current.

Model	Field current	RMS value of EMF	Increase ratio
FWCPM	20 A	7.5 V_{rms}	-
1	36 A	13.5 V_{rms}	44.2 %
2	16 A	12.5 V_{rms}	39.9 %
3	26 A	10.5 V_{rms}	28.6 %

claw. In addition, owing to the position and shape of the EMF has a trapezoid appearance. The change in the rms value of the EMF due to the field current and the waveform of the EMF are shown in Fig. 6(a).

Model 2 increases the amount of magnetic flux by placing the magnet at the front of the rotor claw, and the shape of which is shown in Fig. 5(b). Similar to the basic model, the leakage flux is easily generated between the claws, and the magnitude of the EMF is reduced because the amount of flux linkage is smaller than that of model 1. However, due to the magnet located on the surface of the claw, the EMF is generated irrespective of the field current. Therefore, when the field current is relatively small, the EMF which is 39.9 % higher than that of a conventional FWCPM model can be obtained. Further,



(a) torque of model 1 (b) Torque wave form of model 1 (c) flux density of model 1

(d) torque of model 2 (e) Torque wave form of model 2 (f) flux density of model 2

(g) torque of model 3 (h) Torque wave form of model 3 (i) flux density of model 3

Fig. 7. (Color online) Load characteristics of FAFWCPM.

Table 4. The variation ratio of average torque by the field current.

Model	Field current	Average torque	Increase ratio
FWCPM	76 A	17.39 Nm	-
1	60 A	18.69 Nm	7.45 %
2	52 A	17.49 Nm	0.53 %
3	84 A	15.49 Nm	-10.9 %

the shape of the EMF owing to the position of the magnet resembles a square wave more than model 1. Table 3 indicates the change in the rms value of the EMF according to the field current and the waveform of the EMF shown in Fig. 6(c).

3.1. Ferrite-Assisted FWCPM Load Analysis

The load condition analyzes the characteristics according to the field current when $282A_{rms}$ is applied to the stator equally. If the magnetic field of the Claw-Pole type motor is large, the performance tends to decrease as compared with the field current input due to the saturation of the core at point A. The torque waveform according to the field current when comparing the conventional FWCPM and the FAFWCPM models at the operating point generating the maximum torque, and the saturation degree are shown in Fig. 7. The model with the best torque characteristics is model 1, whose increased is 7.5 %. Moreover, the torque results and the rate of increase in the other models are shown in Table 4.

4. Results

In this paper, we proposed three types of FAFWCPMs using ferrite magnets to improve the no-load and load characteristics of motor and compared to the performance of the basic FWCPM and each model. The role of the magnets applied to the proposed models is to improve the performance of the motor by reducing the leakage of the magnetic flux as the field current increases. The magnets of an FAFWCPM are located between the claws (model 1), at the front of a claw (model 2) and at the top and bottom of claws (model 3). Among the proposed models, the performance of model 1 was confirmed to be 44.2 %, and the average torque was increased by 7.45 %.

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