

Design of Vernier Motor Considering PM Irreversible Demagnetization for Abnormal Operating Condition

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This study investigates the design of a flux modulation pole (FMP)-type vernier motor considering irreversible demagnetization in a permanent magnet (PM). The FMP-type vernier motor, which has a distinct configuration compared to the conventional vernier motor, is taken into account because the PM placed at its stator is vulnerable to irreversible demagnetization. The demagnetization ratio of the PM is analyzed and compared using two different types of flux barrier, namely the bar- and delta-type barriers with varying design parameters. To guarantee reliability of the motor performance, both normal and abnormal operating conditions are considered for each type of flux barrier. Finally, selected models are compared to the base FMP-type vernier motor model in terms of demagnetization ratio and output torque.

Keywords : permanent magnet synchronous motor, vernier motor, irreversible demagnetization, flux barrier

1. Introduction

Recently, research on low-speed and high-torque operation for direct-drive applications such as robotics, electric propulsion, and wind power generators has gained interest. Consequently, focus on permanent magnet (PM) motors, which are known for their high torque density, and are suitable for direct-drive applications, has been growing ever since [1]. The vernier motor, which is a type of PM motor that utilizes flux harmonics, is also a flux modulation machine that operates on a mechanism similar to that of magnetic gears, thereby acquiring high torque density [2, 3]. Owing to these operating characteristics, the vernier motor is considered as a potential candidate for low-speed and high-torque motor applications.

In this study, a flux modulation pole (FMP)-type vernier motor with a PM placed at its stator is coupled with a surface PM rotor for analysis. Different types of flux barriers are applied to reduce the irreversible demagnetization ratio of the stator PM and to improve the output

torque [4, 5]. Although the PM placed at its stator teeth can generate a higher output torque, it is vulnerable to irreversible demagnetization under both normal and abnormal operating conditions because the magneto-motive force produced by the stator coil affects it directly. Therefore, the FMP-type vernier motor is analyzed using two different types of flux barrier for different design parameter values, under both normal and abnormal operating conditions. Finally, selected models are compared to the base model in terms of irreversible demagnetization and output torque.

2. Operating Principle of the Vernier Motor

The performance characteristics of a conventional PM motor are determined by its air-gap flux density derived from the fundamental MMF wave and average air-gap permeance. The MMF and air-gap permeance equations are given as follows.

$$F_m(\theta, \theta_m) \approx F_1 \cos Z_r(\theta - \theta_m) \quad (1)$$

$$P(\theta) \approx P_0 - P_1 \cos Z_s(\theta) \quad (2)$$

where θ and θ_m are the mechanical angles of the stator and rotor, respectively, and Z_r and Z_s denote the number of rotor pole pairs and stator slots, respectively. P_0 is the average air-gap permeance, and P_1 is the permeance

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considering the slot harmonics.

From Eq. (1) and (2), the air-gap flux density of a conventional motor is derived as follows.

$$B(\theta, \theta_m) = F_m(\theta, \theta_m)P(\theta) \approx F_1P_0 \cos Z_r(\theta - \theta_m) \quad (3)$$

For conventional motors, only the fundamental term that concerns Z_r is considered, while the harmonic terms of the air-gap flux density are neglected. However, the vernier motor adopts an additional flux density component developed from magnetic field modulation, also known as the vernier effect [3, 6].

The rotor of the vernier motor operates according to the relationship between the number of rotor pole pairs and the dominant harmonics of the magnetic field generated by the stator winding. The fundamental equation for the vernier motor is as shown below.

$$Z_r - Z_s = \pm p \quad (4)$$

where p is the number of winding pole pairs. When Eq. (4) is satisfied, the dominant harmonic component of the air gap flux density is matched to the number of pole pairs of the rotor. Eq. (1) and (2) represent the MMF of the PM and the air-gap permeance of the vernier motor, respectively. The air-gap flux density for the vernier motor is derived as follows.

$$B(\theta, \theta_m) \approx F_1P_0 \cos Z_r(\theta - \theta_m) - \left(\frac{F_1P_1}{2}\right) \cos((Z_r - Z_s)\theta - Z_r\theta_m) \quad (5)$$

The first component of Eq. (5) is the air-gap flux density component that corresponds to the one generated in the conventional PM motors. The second component, however, is the flux element generated from the harmonic coefficient related to the air-gap permeance due to its vernier structure [2, 7]. The second and first components of Eq. (5) are the fundamental and harmonic terms of the air-gap flux density, respectively. Accordingly, the additional air-gap flux density produces an additional electromotive force (EMF) that generates an additional torque as compared to conventional PM synchronous motors. The equation for the EMF of the vernier motor is as follows.

$$e_{ph}(t) = k_{1q} N_{ph} D_g l_{stk} w_m \left(F_1P_0 + \frac{Z_r}{2p} F_1P_1 \right) \cos(Z_r\theta_m - p\theta_{ph}) \quad (6)$$

where k_{1q} is the winding factor, N_{ph} is the number of turns per phase, w_m is the mechanical speed of the rotor, and θ_{ph} represents the phase angle of the phase winding. D_g and l_{stk} denote the air-gap diameter and stack length of the motor, respectively. The fundamental EMF component adds to the induced EMF component, as the vernier motor

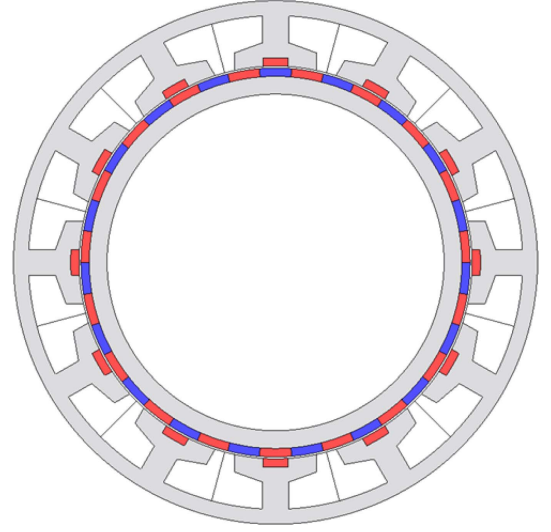


Fig. 1. (Color online) Base configuration of the FMP-type vernier motor.

uses higher-order terms for the EMF as a major component for torque generation.

3. Design and Analysis

In this study, an FMP-type vernier motor is analyzed using the base model shown in Fig. 1. The distinct feature of the FMP-type vernier motor is the modulation teeth of the stator, which alters the number of effective slots, denoted as k in this study. For the base model shown in Fig. 1, the value of k is 2, allowing the base model to have 24 effective slots despite 12 slots being available for winding. For analysis, a ferrite-type PM with a residual flux density of 0.39 T and a coercive force of -290 kA/m was applied in this study, because a ferrite PM undergoes irreversible demagnetization unlike the neodymium type. The configuration of the FMP-type vernier motor is determined with (4), while its specific design parameters and values are as listed in Table 1.

Table 1. Design parameter of the FMP-type vernier motor.

Parameter	Unit	Value
Number of Pole / Effective slot	-	38 / 24
Stator Inner / Outer Diameter	mm	210.0 / 280.0
Rotor Inner / Outer Diameter	mm	180.0 / 208.0
Stack Length	mm	50.0
Airgap Length	mm	1.0
Rotating Speed	rpm	200
Magnet B_r	T	0.39
Magnet H_c	kA/m	-290

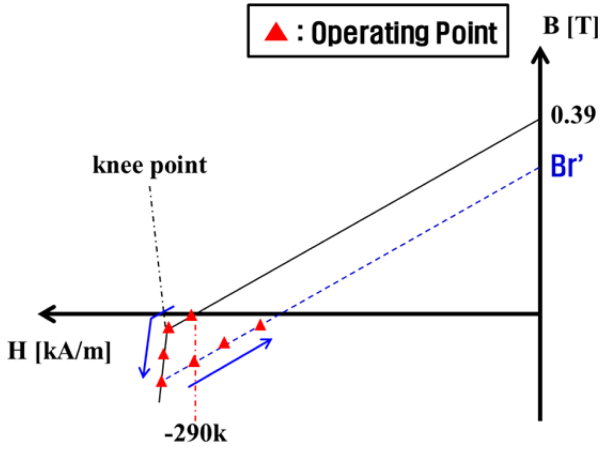


Fig. 2. (Color online) B-H curve under irreversible demagnetization.

3.1. Calculation of Irreversible Demagnetization in PMs

Irreversible demagnetization is an undesired characteristic that may have a critical effect on the performance of the motor. It occurs when the operating point of a PM is established beyond the knee point, as shown in Fig. 2. The flux density (B) and magnetic field strength (H) are important parameters in the analysis of the irreversible demagnetization ratio in the PM. In Fig. 2, the solid line represents the original B-H curve of the PM while the dotted line shows a curve affected by the irreversible demagnetization. The shift of the PM operating point, depicted by the triangle plot in Fig. 2, shows the process of irreversible demagnetization for the ferrite PM, whose parameters are listed in Table 1. The irreversible demagnetization ratio is calculated based on the residual flux density (B_r) of 0.39 T, and its demagnetized value (B_r') derived using the equations below.

$$B = \sum_n (B_x \times \cos \theta + B_y \times \sin \theta) / n \quad (7)$$

$$H = \sum_n (H_x \times \cos \theta + H_y \times \sin \theta) / n \quad (8)$$

where θ denotes the magnetization angle of the PM and n is the number of elements within it. B_x and H_x represent the x-axis components while B_y and H_y represent the y-axis components. Using Eq. (7) and (8), the average values for B and H are calculated for each mesh of the demagnetized PM. As the PM is locally demagnetized, the values of B and H for all meshes are averaged in reference to the magnetization direction. Using the derived operating point of the PM, B_r' is derived with a recoil line according to the value of the original B-H curve. The irreversible demagnetization ratio is calculated using the calculated B_r' with the following equation.

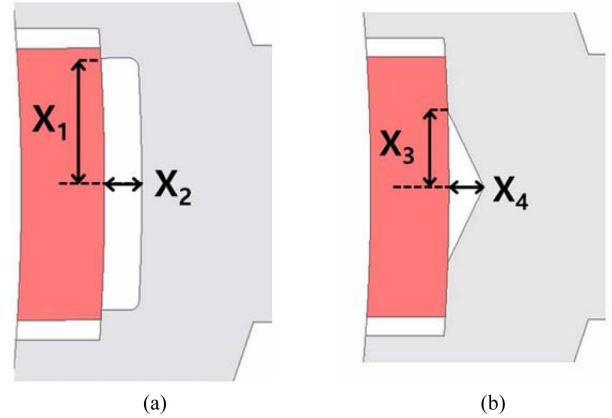


Fig. 3. (Color online) Flux barrier configuration for stator PM: (a) bar type and (b) delta type.

$$\text{Demagnetization ratio} = \frac{B_r - B_r'}{B_r} \times 100 \quad (9)$$

3.2. Analysis Conditions: Barrier Type and Operating Conditions

To avoid demagnetization in the PM and to improve the motor performance, two different types of flux barrier are applied, namely, bar- and delta-type barriers, as shown in Fig. 3(a) and (b), respectively. The width and height of the bar-type flux barrier are denoted as X_1 and X_2 while X_3 and X_4 denote the width and height of the delta type, respectively. The assigned values for the design parameters are listed in Table 2. The flux barrier is positioned between the stator core and the PM to prevent irreversible demagnetization by blocking the MMF generated by the stator coil. In addition, the position of the flux barrier is selected such that it does not interfere with the main flux path during its operation.

In this study, two different operating conditions are considered to investigate the irreversible demagnetization characteristics. The normal operating condition with a 4 A_{pk} input current applied to the q-axis is considered. Under normal operating conditions, the PM placed in the stator of the FMP-type vernier motor should not be irreversibly demagnetized in order to maintain its performance. However, the motor may encounter abnormal operating conditions in cases such as inverter failure.

Table 2. Flux barrier design parameters.

Design variables		Value	Unit
Bar	X_1	4 / 6	mm
	X_2	1 / 2 / 3 / 4	
Delta	X_3	4 / 6	
	X_4	2 / 4 / 6 / 8	

Table 3. Demagnetization ratios and output torques for bar- and delta-type flux barriers applied to the FMP-type vernier motor.

FMP vernier motor	Torque [Nm]	Torque Ripple [%]	Demagnetization ratio [%]		
			4 A_{pk} q-axis	8 A_{pk} d-axis	
Base model	10.07	3.86	0.782	3.623	
Bar type (X_1, X_2) [mm]	(6, 1)	10.63	2.31	0.053	3.255
	(6, 2)	10.74	2.25	0.122	3.259
	(6, 3)	10.81	2.26	0.185	3.265
	(6, 4)	10.85	2.26	0.230	3.269
	(4, 1)	10.58	2.15	0.003	2.407
	(4, 2)	10.63	2.17	0.004	2.326
	(4, 3)	10.66	2.19	0.007	2.303
	(4, 4)	10.68	2.15	0.009	2.324
Delta type (X_3, X_4) [mm]	(6, 2)	10.63	2.27	0.014	2.341
	(6, 4)	10.72	2.19	0.045	2.342
	(6, 6)	10.77	2.24	0.071	2.348
	(6, 8)	10.80	2.19	0.087	2.357
	(4, 2)	10.57	2.26	0.003	2.391
	(4, 4)	10.62	2.17	0.004	2.355
	(4, 6)	10.64	2.18	0.005	2.341
	(4, 8)	10.65	2.10	0.006	2.333

Therefore, abnormal conditions with an 8 A_{pk} input current applied to the d-axis is also considered. When the current is applied in phase with the d-axis, the MMF generated by the coil directly opposes the flux direction of the PM, thereby significantly affecting the PM in terms of irreversible demagnetization.

3.3. Analysis and Results

The irreversible demagnetization ratio of the stator PM and its output torque in the flux barriers and the operating

conditions are listed in Table 3. The combinations of the design parameters for each type of flux barrier are indexed as coordinates with its values. For the base model, the irreversible demagnetization ratios of the PM are 0.78 % and 3.63 % for the normal and abnormal operating conditions, respectively, with an output torque of 10.07 Nm.

To ensure the performance of the vernier motor, the stator PM should not experience irreversible demagnetization when operated under the normal condition. Therefore, the flux barrier is applied to prevent irreversible demagnetization. Under normal operating condition, the bar- and delta-type flux barriers with respective design parameters (X_1, X_2) and (X_3, X_4) are applied, and the resulting irreversible demagnetization ratios are plotted in Fig. 4(a). The square and triangle legends represent bar- and delta-type flux barriers, respectively, whereas the hollow and solid plots represent widths of 4 mm and 6 mm, respectively. From Fig. 4(a), it is inferred that the demagnetization ratio is more sensitive for the bar-type flux barrier on account of its height than that for the delta-type flux barrier.

The analysis for the abnormal operating condition is conducted using the same parameter values applied to that for normal operating condition. Its irreversible demagnetization ratio is plotted in Fig. 4(b), denoted by the same legend used in Fig. 4(a). From Fig. 4(b), it is inferred that the delta-type flux barrier is less dependable in terms of the design parameter values regarding its demagnetization ratio. For the bar-type flux barrier, however, the demagnetization ratio is highly affected by its width, but the height parameter is not considered as an important factor.

Based on the analysis, the bar-type (4, 3) and delta-type (4, 8) models are compared with the base model. The PM

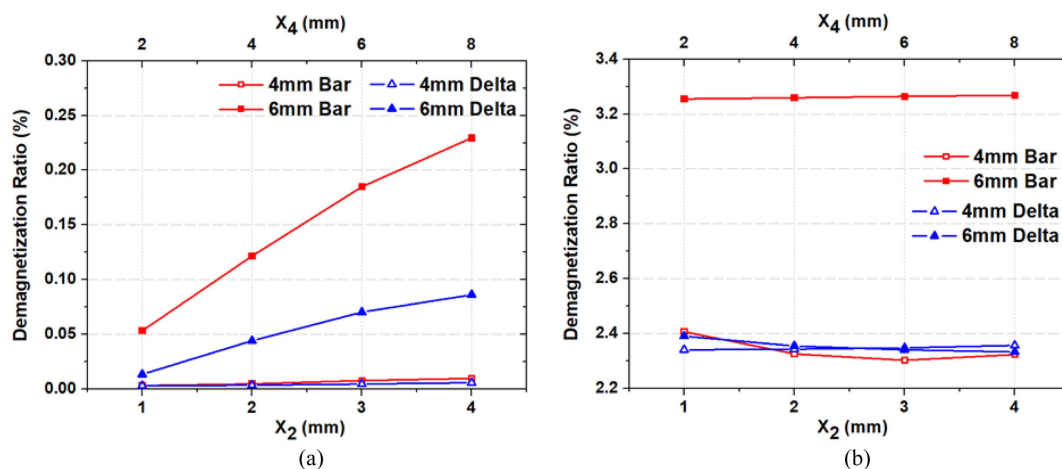


Fig. 4. (Color online) PM demagnetization ratio for the bar- and delta-type flux barriers under (a) normal operating condition and (b) abnormal operating condition.

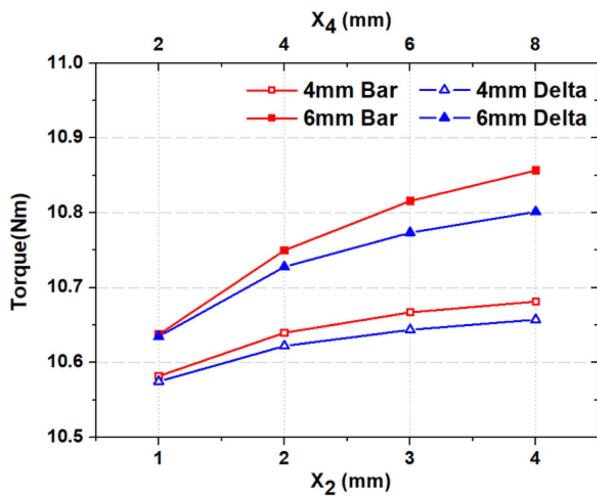


Fig. 5. (Color online) Output torques for the bar- and delta-type flux barriers.

demagnetization ratio under the normal operating conditions is reduced by 0.775 % and 0.776 % for the bar- and delta-type models, respectively, thereby reducing the demagnetization ratio to approximately zero percent. Under the abnormal operating conditions, the demagnetization ratio is reduced by approximately 1.319 % and 1.289 % for the bar-type (4, 3) and delta-type (4, 8) models, respectively. For the vernier motor analyzed in this paper, the fundamental air-gap flux component utilized for torque generation is the fifth-harmonic component based on (4). When the radial air-gap flux component is analyzed using fast Fourier transform, the amplitude of the fifth component is $7.04e^{-2}$ for the base model, and is $7.11e^{-2}$ and $7.10e^{-2}$ for the bar-type (4, 3) and delta-type (4, 8) models. Because the amplitude of the fundamental component is closely related to the output torque, it is inferred that the presence of the flux barrier generates a higher torque. The output torque was improved due to the demagnetization ratio reduction as well as leakage flux minimization, as shown in Fig. 5. Consequently, the torque improved by 5.86% and 5.76% for the selected models for the bar- and delta-type flux barriers, respectively.

According to the analyzed results, the FMP-type vernier motors with the delta-type flux barriers achieved low and stable PM demagnetization ratios, even when the design parameter values were altered. Conversely, the FMP vernier motors with the bar-type flux barriers generated higher output torques, although their demagnetization ratios were highly affected by the design parameter values

as compared to those of the delta-type barriers.

4. Conclusion

In this study, the design of flux barriers for FMP-type vernier motors was investigated considering irreversible demagnetization in a stator PM. Analysis of the irreversible demagnetization ratio of the PM with varying design parameters for the flux barriers under different operating conditions was performed. Under normal operating conditions, the demagnetization ratio of the stator PM was 0.78 % for the base model while it is reduced to approximately 0 % for both the bar- and delta-type flux barriers in the selected models considered in this study. Under abnormal operating conditions, the irreversible demagnetization ratio dropped by approximately 1.3 % for both the bar- and delta-type flux barriers applied to the vernier motors. Finally, the output torque improved by 5.86 % and 5.76 % for the bar- and delta-type flux barriers, respectively, as compared to that in the base FMP-type vernier model.

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References

- [1] L. Wu, R. Qu, and Y. Gao, *IEEE Trans. Magn.* **51**, 15456646 (2015).
- [2] K. Okada, N. Niguchi, and K. Hirata, *IEEE Trans. Magn.* **49**, 13486955 (2013).
- [3] A. Toba and T. Lipo, *IEEE Trans. Ind. Appl.* **36**, 6786041 (2005).
- [4] S. Niu, S. L. Ho, and W. N. Fu, *IEEE Trans. Magn.* **50**, 14128083 (2014).
- [5] S. Jia, R. Qu, D. Li, and J. Li, *IEEE VPPC*, Hangzhou, 16558110 (2016).
- [6] B. Kim and T. Lipo, *IEEE Trans. Ind. Appl.* **50**, 14758961 (2005).
- [7] B. Kim, *IEEE Trans. Elec.* 16154846 (2016).