Design of Vernier Motor considering Irreversible Demagnetization in Permanent Magnet

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Introduction

- As demand for high-torque direct drive motor is increasing, interest in vernier motor is gaining its importance
- Vernier motor is a type of permanent magnet (PM) motor, targeted for low speed and high torque operation applications
- PM used in vernier motor should be prevented from irreversible demagnetization in both operating and abnormal conditions, for its consistency
- Flux Modulation Pole(FMP) type vernier motor that has PM placed in its stator coupled with SPM type rotor is selected as base model for analysis
- Bar and delta type flux barrier is applied to the stator PM to prevent its irreversible demagnetization for different operation conditions
- Vernier motor is analyzed with different design parameters regarding flux barrier, as its PM irreversible demagnetization ratio and output performance characteristic is compared to that of the base model

Operating principle of VM

- Vernier motor utilizes magnetic flux harmonics to develop additional torque component with harmonic flux component
- Vernier motor operates with characteristic analogous to the magnetic gear
  - The magnetic gear ratio of vernier motor is determined by ratio of the stator winding pole pair number and the rotor pole pair number
- The vernier motor adopts additional flux density component developed from magnetic field modulation, also known as the vernier effect
- MMF of PM and air-gap permeance for the vernier motor is as follows

$$F_m(\theta, \theta_m) \approx F_1 \cos Z_r(\theta - \theta_m) \qquad P(\theta) \approx P_0 - P_1 \cos Z_s(\theta)$$

- *ϑ and ϑ_m : mechanical angle on the stator and the rotor*
- *Z_r and Z_s : the number of rotor pole pair and stator slot*
- *P_0 and P_1: average air-gap permeance and permeance considering slot harmonic*

- Using the derived MMF and air-gap permeance, the air-gap flux density of vernier motor is derived as follows

$$B(\theta, \theta_m) \approx F_1 P_0 \cos Z_r(\theta - \theta_m) - \left(\frac{F_1 P_1}{2}\right) \cos((Z_r - Z_s)\theta - Z_r\theta_m)$$

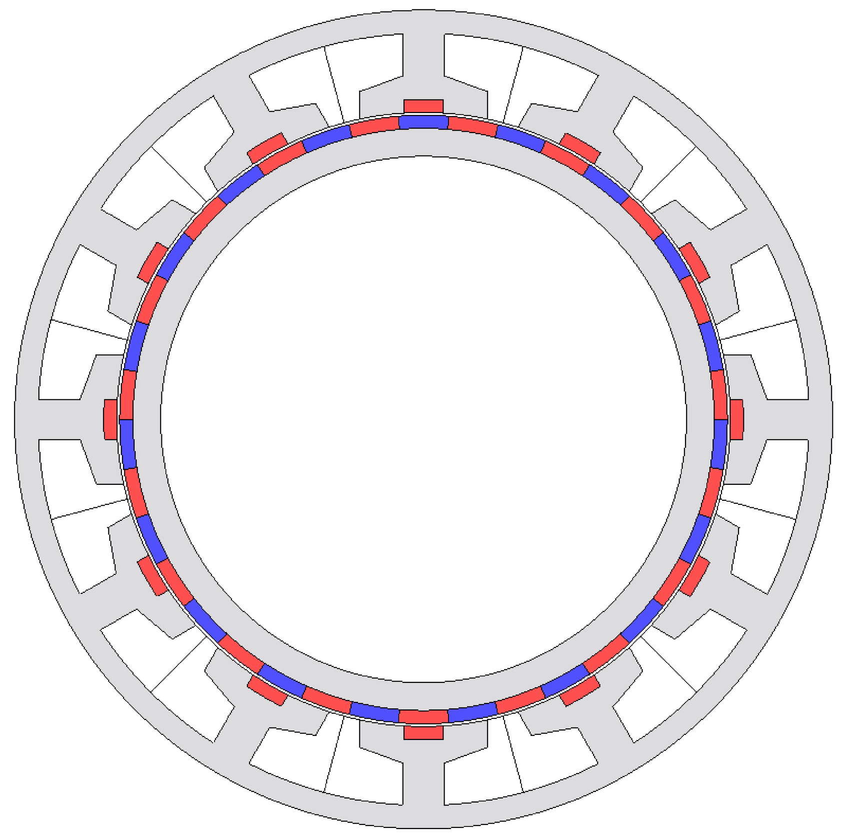
- *First term: air-gap flux density component (equal to conventional PM motor)*
- *Second term: flux element generated by harmonic component (additional)*

- Due to the second term of air-gap flux density component, additional torque component is generated, compared to that of the conventional PM motor
- The pole-slot combination of vernier motor is determined by the equation shown below, which is derived from the air-gap flux density equation above

$$Z_r - Z_s = \pm P_0$$

- *p : the number of winding pole pair*

Specification of VM



< Base model of FMP vernier motor >

- FMP type vernier motor, which modulates numbers of stator teeth by altering number of divided teeth tip(k)
  - Since k is 2 for the analyzed base model, it has 24 effective slots, despite that it has 12 slots available for winding
- Ferrite PM is used for both stator and SPM type rotor

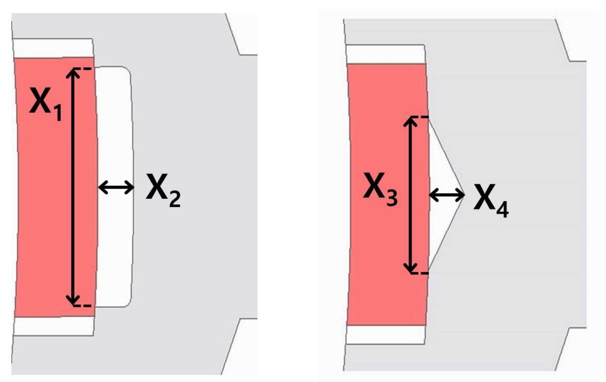
Parameter	Unit	Value
Number of Pole / Effective Slot	-	38 / 24
Stator Inner / Outer Diameter	*mm*	210.0 / 280.0
Rotor Inner / Outer Diameter	*mm*	180.0 / 208.0
Stack Length	*mm*	50.0
Air-gap Length	*mm*	1.0
Rotating Speed	*rpm*	200
Magnet Br / Hc	T / $^{A}/_{m}$	0.39 / -290*k*

< Base FMP vernier motor specification >

Analysis & Results

Conditions for analysis

- $4A_{pk}$ is assigned as operation current in phase with q-axis, for the FMP type vernier motor
- However, abnormal conditions when larger current is supplied in phase with d-axis should be taken into account, to assure reliability of the motor
- Two conditions are taken into account for PM irreversible demagnetization analysis
  1) **4A input current in phase with q-axis (normal operation)**
  2) **8A input current in phase with d-axis (abnormal operation)**
- To ease irreversible demagnetization and to improve performance of the motor, 2 different type of flux barriers are selected for analysis



a) Bar type b) Delta type

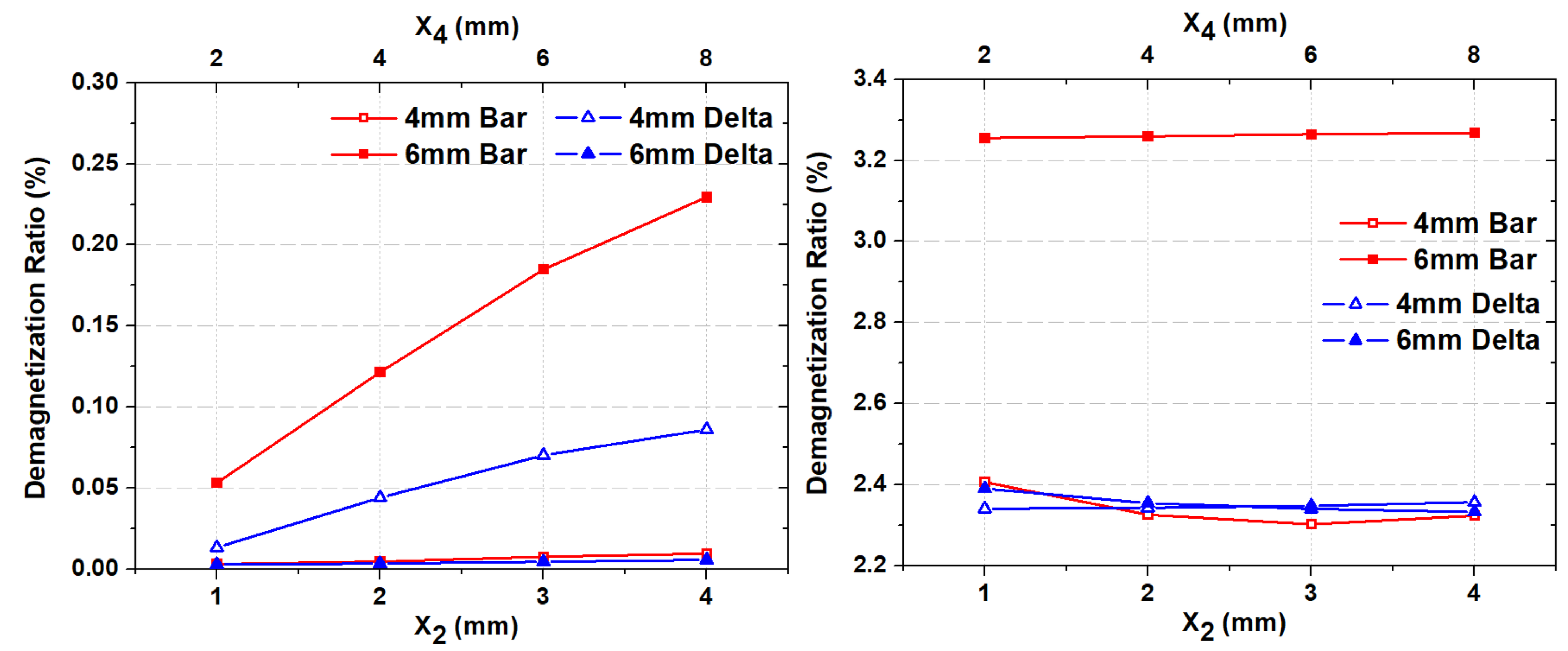
< Flux barrier configuration >

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	

< Flux barrier design parameter >

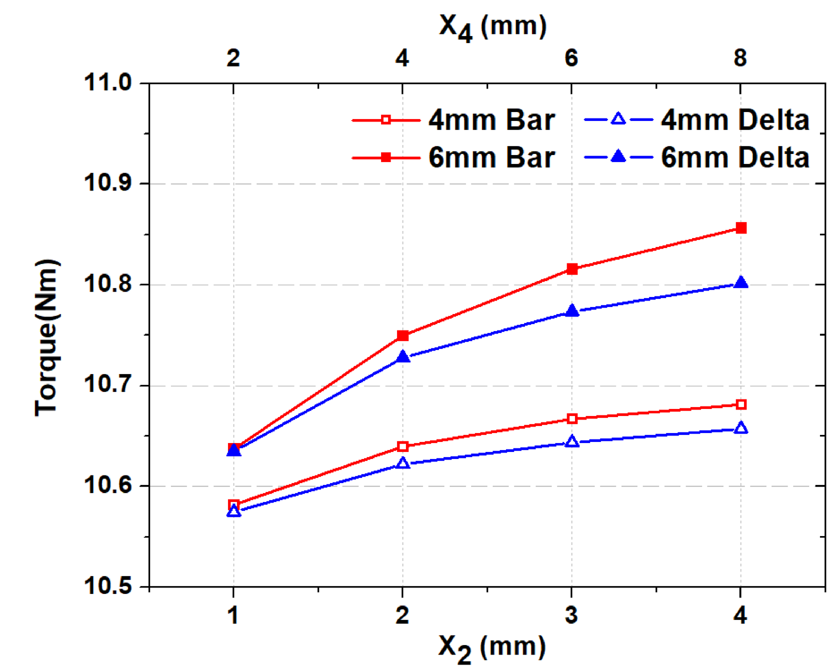
Model			Torque [Nm]	Demagnetization ratio [%] 4Apk q-axis	8Apk d-axis
Base model			10.07	0.782	8.070
Bar type	X_1 (6mm)	X_2 (1mm)	10.63	0.053	3.255
		X_2 (2mm)	10.74	0.122	3.259
		X_2 (3mm)	10.81	0.185	3.265
		X_2 (4mm)	10.85	0.230	3.269
	X_1 (4mm)	X_2 (1mm)	10.58	0.003	2.407
		X_2 (2mm)	10.63	0.004	2.326
		X_2 (3mm)	10.66	0.007	2.303
		X_2 (4mm)	10.68	0.009	2.324
Delta type	X_3 (6mm)	X_4 (2mm)	10.63	0.014	2.341
		X_4 (4mm)	10.72	0.045	2.342
		X_4 (6mm)	10.77	0.071	2.348
		X_4 (8mm)	10.80	0.087	2.357
	X_3 (4mm)	X_4 (2mm)	10.57	0.003	2.391
		X_4 (4mm)	10.62	0.004	2.355
		X_4 (6mm)	10.64	0.005	2.341
		X_4 (8mm)	10.65	0.006	2.333

< Demagnetization ratio and output torque for bar and delta type flux barrier >



a) $4A_{pk}$ in phase with q-axis b) $8A_{pk}$ in phase with d-axis

< Demagnetization ratio for bar and delta type flux barrier >



< Torque generated for each flux barrier >

- To make comparison of demagnetization ratio to the base model, two models were selected as highlighted in table on the left hand side
  - **Bar type:** Demagnetization ratio was reduced by approximately 0.78% and 5.77% for operation and abnormal condition, respectively
  - **Delta type:** Demagnetization ratio was reduced by approximately 0.78% and 5.74% for operation and abnormal condition, respectively
- Due to the flux barrier, both irreversible demagnetization ratio and leakage flux of stator PM was reduced
  - Output torque increased by 5.86% and 5.76% for Bar and Delta type flux barrier applied vernier motor, respectively

Conclusion

- In this paper, design of flux barrier for FMP type vernier motor considering irreversible demagnetization in PM is studied
- Analysis on demagnetization ratio of FMP vernier motor is carried out, with different design parameters applied
  - In operation condition, demagnetization ratio of stator PM is reduced to approximately 0%, as it dropped by approximately 5.7% for both bar and delta type flux barrier applied FMP vernier motor
- Applied flux barrier not only reduced the demagnetization ratio of PM in stator, but also reduced its leakage flux
  - Output torque is improved by 5.86% and 5.76% for bar and delta type flux barrier, respectively
- **Delta type:** Advantageous in achieving low and stable PM demagnetization ratio, regarding change in its design parameter
- **Bar type:** Advantageous in generating higher output torque, although demagnetization ratio is effected by its design parameter