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Design Techniques for Reducing Cogging Torque in Permanent Magnet Flux Switching Machine

Daohan Wang[1], Xiuhe Wang[1], and Sang-Yong Jung[2]*

[1]*School of Electrical Engineering, Shandong University, Jinan 250061, China*
[2]*School of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon 440-746, Korea*

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Permanent magnet flux switching motor (PMFSM) is a novel double salient machine which employs PMs instead of field winding for excitation. PMFSM contains only one set of armature winding, thereby features simple control strategy, low cost power inverter and substantial high efficiency. Due to the unique double salient structure and operation principle, the generated cogging torque in PMFSM is critical and quite different compared to the traditional PM machines. This paper presents and investigates various design techniques for reducing cogging torque in PMFSM. Firstly, an analytical model is proposed to study the influence of different methods on cogging torque. Then the optimal design parameters for minimizing cogging torque are determined by the analytical model, which significantly reduces the computational efforts. At last, the cogging torque with different design approaches are simulated by FEA along with the average output electromagnetic torque, which validates the analysis above.

Keywords : permanent magnet flux switching machine, cogging torque, machine design, analytical model

1. Introduction

Permanent magnet flux switching machine (PMFSM) is a new type brushless permanent magnet machine which is derived from the Flux Switching Machine (FSM) with electric winding excitation [1]. In PMFSM, the permanent magnets are housed in the stator side and there are neither coils nor PMs in the rotor as shown in Fig. 1, so it retains the robustness and ruggedness of switch reluctance motor (SRM), and benefits from permanent magnet machine to achieve high efficiency [1]. PMFSM gains an advantage over FSM because it exhibits low copper loss, high power density and high efficiency [3-5]. PMFSM has been a potential candidate for taking the place of BLDC in some applications, such as fans, vacuum cleaner and air ventilation machines. In these applications, the machines are usually required to exhibit low level of vibration and acoustic noise. However, torque ripple is inherent in PMFSM due to the double salient structure which is similar as SRM. Furthermore, the existing PMs housed inside interact with rotor core, thus produces cogging torque even with the windings no-excitation, thereby, the situation is getting worse. As mentioned above, the cogging torque in PMFSM is a critical issue even in case of light or no-load condition, so it must be considered in machine design. However, we are not able to find any relevant studies or researches reported on this topic regarding the cogging torque reduction of PMFSM.

In this paper, various design techniques for reducing cogging torque in PMFSM are presented. An analytical model of cogging torque is proposed. With the assistance of the analytical model, the appropriate design parameters which can minimize the cogging torque are determined. The cogging torque with different design schemes are calculated by using FEA, which can give preciseness of calculations. The average output torque with different design schemes are also examined.

2. Analytical Model of Cogging Torque in PMFSM

Referring to the definition of cogging torque in traditional PM machines, the cogging torque in PMFSM is

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*Corresponding author: Tel: +82-31-299-4952
Fax: +82-31-290-7231, e-mail: syjung@ece.skku.ac.kr

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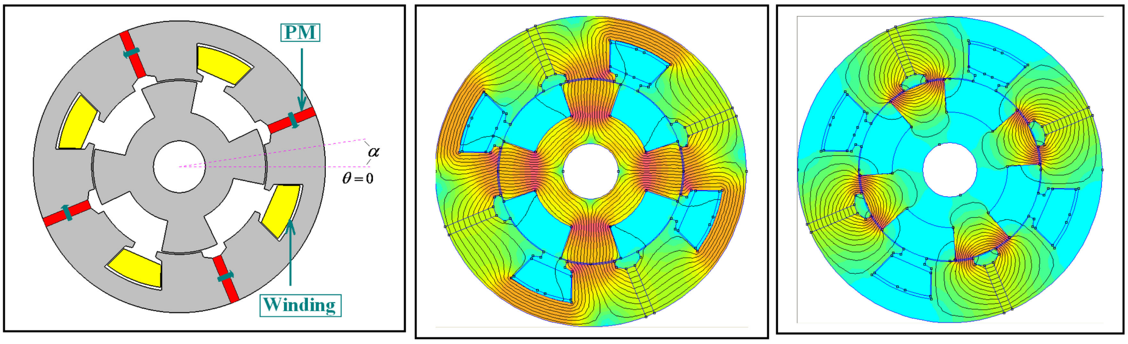

Fig. 1. (Color online) Sketch of PMFSM and field distributions with different rotor position.

defined as the no-load torque without winding excitation, which can be described as [2, 6, 7]

$$T_\alpha = -\frac{\partial W_{ft}}{\partial \alpha} = -\frac{\partial (W_{gap}+W_{pm})}{\partial \alpha} \approx -\frac{\partial W_{gap}}{\partial \alpha} \tag{1}$$

Where W_{ft} is the magnetic energy of the machine, W_{gap} and W_{pm} the energy of the air-gap and magnets, α the rotor movement.

$$W_{gap} = \frac{1}{2\mu_0}\int_V B_\delta^2(\theta)dV = \frac{1}{2\mu_0}\int_V B_r^2(\theta)\left(\frac{h_m(\theta)}{h_m(\theta)+\delta(\theta,\alpha)}\right)^2 dV \tag{2}$$

The Fourier expansions of $B_r^2(\theta)$ and $\left(\frac{h_m(\theta)}{h_m(\theta)+\delta(\theta,\alpha)}\right)^2$ can be derived as

$$B_r^2(\theta) = B_{r0} + \sum_{n=1}^{\infty} B_{rn}\cos N_s n\theta \tag{3}$$

Where $B_{r0} = \frac{\beta_s B_r^2}{\tau_s}$, $B_{rn} = \frac{2}{n\pi}B_r^2 \sin\frac{n\beta_s}{\tau_s}\pi$, β_s the stator pole arc width, τ_s the pole pitch of the stator, N_s the stator pole number, B_r the residual flux density ofPMs.

$$\left(\frac{h_m(\theta)}{h_m(\theta)+\delta(\theta,\alpha)}\right)^2 = G_0 + \sum_{m=1}^{\infty} G_m \cos mN_r(\theta+\alpha) \tag{4}$$

Where N_r is the rotor number, G_m the Fourier coefficients. The analytical expression can be deduced as

$$T_{cog}(\alpha) = \frac{\pi N_r l_{Fe}}{4\mu_0}(R_2^2 - R_1^2)\sum_{m=1}^{\infty} nG_n B_{r\frac{nN_r}{N_s}} \sin nN_r\alpha \tag{5}$$

Where l_{Fe} the stack length, R_1 and R_2 the radius of outer rotor and inner stator, μ_0 the permeability of the air.

3. Design Techniques for Cogging Torque Reduction in PMFSM

3.1. Rotor skewing

In general, skewing, either rotor or stator skewing is usually employed to reduce the cogging torque. When rotor skewing is adopted in PMFSM, the cogging torque can be expressed as

$$T_{cog}(\alpha, Q_r) = \frac{\pi l_{Fe}}{2\mu_0 Q_r \tau_r}(R_2^2 - R_1^2)\sum_{m=1}^{\infty} G_n B_{r\frac{nN_r}{N_s}} \sin\frac{nN_r Q_r \tau_r}{2} \sin nN_r\left(\alpha + \frac{Q_r\tau_r}{2}\right) \tag{6}$$

Where Q_r is the teeth pitches of axially skewing, τ_r the rotor pitch.

For minimizing the cogging torque, obviously, $\sin\frac{nN_rQ_r\tau_r}{2}$

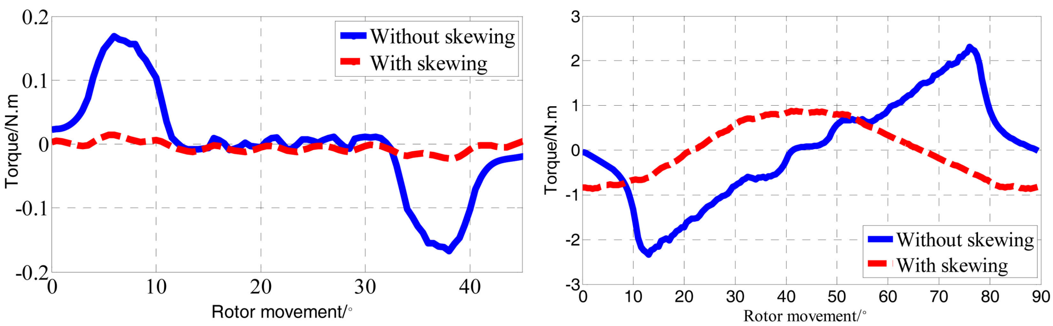

Fig. 2. (Color online) Comparison of results calculated by FEM (a) Cogging torque with and without skewing (b)Torque v.s angle.

= 0 should be satisfied. Then we can calculate the suitable value of Q_r, which should be $Q_r = 1/2$. That means the machine should be axially skewed 0.5 rotor pitch for minimizing the cogging torque. Fig. 2 shows the results of cogging torque and torque v.s angle characteristics calculated by FEM. It can be seen that although the cogging torque has been significantly reduced, the electro-magnet torque has also been reduced.

3.2. Changing pole arc width of stator and rotor

While changing the pole arc width of stator, the Fourier expansions of B_{rn} can be deduced as

$$B_{rn} = \frac{2}{n\pi}B_r^2 \sin n\alpha_{ps}\pi \tag{7}$$

Where α_{ps} is the pole arc to pole pitch ratio of the stator. Fig. 3 gives the curves of B_{rn} changing with α_{ps}. It can be seen that there is not a zero point which can make all the components B_{rn} zero but all components B_{rn} is getting to be zero as α_{ps} is being close to 1. Fig. 4 shows the cogging torque and electro-magnetic torque calculated by FEM.

While changing the pole arc width of rotor, the Fourier expansions of G_m can be deduced as

$$G_m = (2/m\pi)g_s \sin \alpha_{pr} m\pi \tag{8}$$

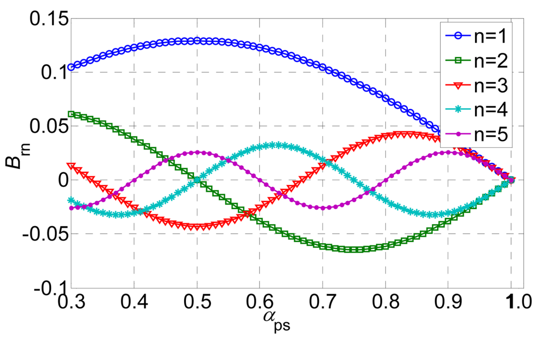

Fig. 3. (Color online) B_{rn} changing with α_{ps} calculated analytically.

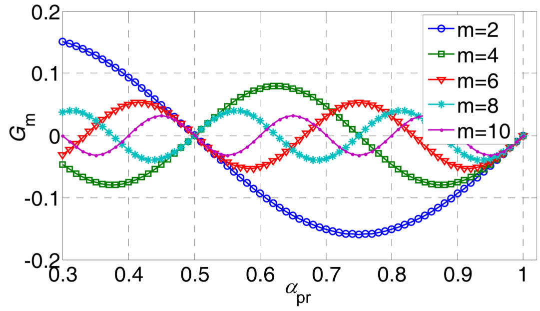

Fig. 5. (Color online) G_m changing with α_{pr} calculated analytically.

α_{pr} is the pole arc to pole pitch ratio of the rotor. Fig. 5 gives the curves of G_m changing with α_{pr}. It can be seen that when α_{pr} is 0.5, all components of G_m are made zero, which indicates that the cogging torque can be greatly reduced by $\alpha_{pr} = 0.5$. Fig. 6 gives the cogging torque and electro-magnetic torque calculated by FEM.

3.3. Rotor teeth pairing

When adopting rotor teeth paring. the Fourier expansions $\left(\frac{h_m(\theta)}{h_m(\theta)+\delta(\theta,\alpha)}\right)^2$ can be derived as

$$\left(\frac{h_m(\theta)}{h_m(\theta)+\delta(\theta,\alpha)}\right)^2 = G_0 + \sum_{m=1}^{\infty} G_m \cos\frac{N_r}{2}m(\theta+\alpha) \tag{9}$$

$$G_m = \frac{2g_s}{m\pi}\left[2\sin\frac{mN_r}{8}(\beta_{ra}+\beta_{rb})\cos\frac{mN_r}{8}(\beta_{ra}-\beta_{rb})\right] \tag{10}$$

For minimizing cogging torque, G_m should be made zero, hence the following should be satisfied

$$\begin{cases} \beta_{ra}-\beta_{rb} = \dfrac{k\pi}{4} \\ \quad\text{or} \\ (\beta_{ra}+\beta_{rb}) = \dfrac{k\pi}{2} \end{cases} \qquad k = 1, 2, 3\ldots \tag{11}$$

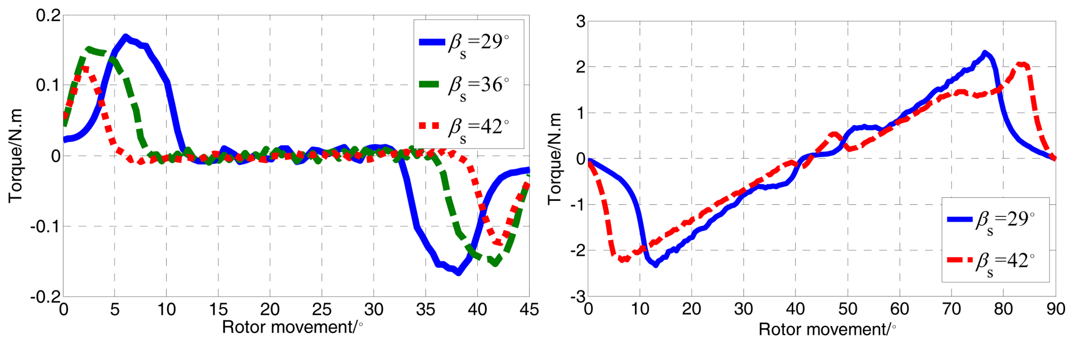

Fig. 4. (Color online) Comparison of results calculated by FEM (a) Cogging torque with different pole arc width (b) Torque v.s angle.

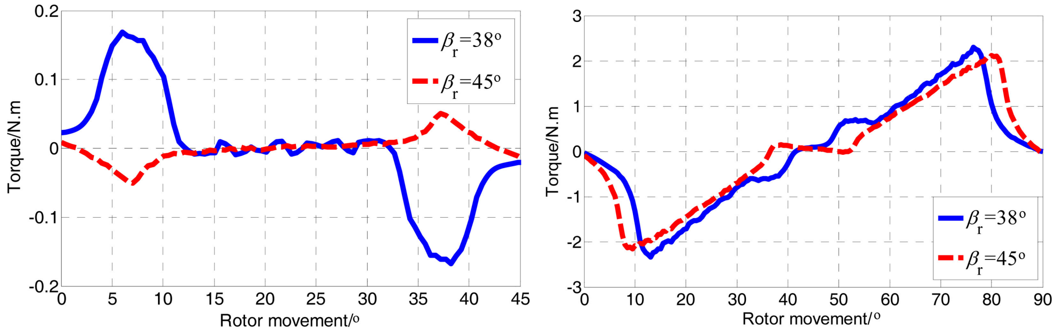

Fig. 6. (Color online) Comparison of results calculated by FEM (a) Cogging torque with different pole arc width (b) Torque v.s angle.

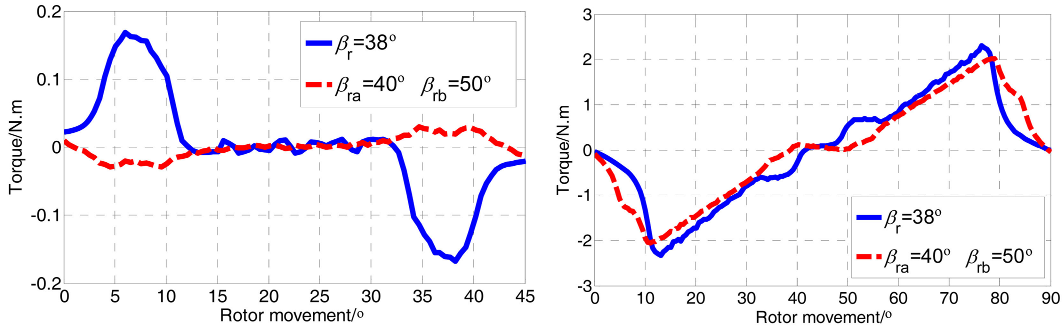

Fig. 7. (Color online) Comparison of results calculated by FEM (a) Cogging torque with and without teeth pairing (b) Torque v.s angle.

According to (11), $\beta_{ra}+\beta_{rb}=\frac{\pi}{2}$ should be satisfied. β_{ra} and β_{rb} are the pole arc angle of the rotor. Fig. 7 shows the cogging torque results of the machine with β_{ra} = 40° and β_{rb} = 50° together with the electro-magnetic torque.

4. Conclusions

In this paper, an analytical model is presented to investigate the principle of cogging torque in PMFSM. Different design techniques, viz. skewing, changing stator and pole arc width, rotor teeth paring are described and used to reduce the cogging torque. With the assistance of the presented analytical model, the optimal design parameters are determined. Finite Element Method, which can give high preciseness to calculation, is used to calculate the cogging torque, which validates the correctness and effectiveness of the analysis and methods we have presented. The results reveal that both taking into account of the cogging torque reduction and machine running performance, β_{ra} = β_{rb} = 45°, viz. β_{pr} = 0.5 is the best solution in PMFSM.

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