Analysis of Cogging Torque Reduction Techniques in Axial Field Flux-Switching Permanent Magnet Machine

Li Hao, Mingyao Lin, Da Xu, Nian Li, and Wei Zhang

Abstract—**An axial field flux-switching permanent magnet machine (AFFSPMM) is suitable to be used in wind power generation and electric vehicles. But the cogging torque (Tcog) is large. For obtaining high performance AFFSPMM, the reduction of Tcog in AFFSPMM is investigated. The theoretical Tcog expression is deduced. Based on 3-D finite element method, the influences of the design parameters on the Tcog and the reduction methods of Tcog, such as rotor tooth skewing (RTS), rotor tooth circumferential pairing (RTCP), and rotor tooth notching (RTN), are analyzed. The design parameters except the axial length of rotor have influences on Tcog and optimizing the design parameters can decrease Tcog. Tcog can reduce greatly by RTS for AFFSPMM with parallel stator tooth and fan-shape permanent magnet (PST-FSPM) structure. However, RTS is no effective in reducing Tcog for AFFSPMM with fan-shape stator tooth and parallel PM (FSST-PPM) structure. Tcog decreases greatly by RTN and RTCP for FSST-PPM stator structure. Moreover, the reduction effect of Tcog with RTN is better than that with RTCP.**

***Index Terms*—permanent magnet machine, flux-switching, cogging torque, rotor tooth structure.**

I. Introduction

In recent years, the axial field flux-switching permanent magnet machine (AFFSPMM) [1], which can be used in wind power generation and electric vehicles (EVs), has been proposed and investigated. AFFSPMM combines the merits both of the axial field and flux-switching machines, owns sinusoidal flux and EMF, good capability of flux weakening, and large torque capability. But the cogging torque (Tcog) in AFFSPMM is higher than that in the traditional axial field PM machine, which causes torque ripple and affects the control accuracy. Hence, the reduction of Tcog is very important for designing high performance AFFSPMM.

For traditional PM machines, Tcog has been thoroughly investigated and many reduction methods of Tcog [2-13], such as magnet shift, slot skew, pole skew, combination number optimization of slots and poles, optimization of pole arc coefficient and slot opening, tooth notching, and tooth paring, etc., are effective in reducing Tcog of traditional PM machines.

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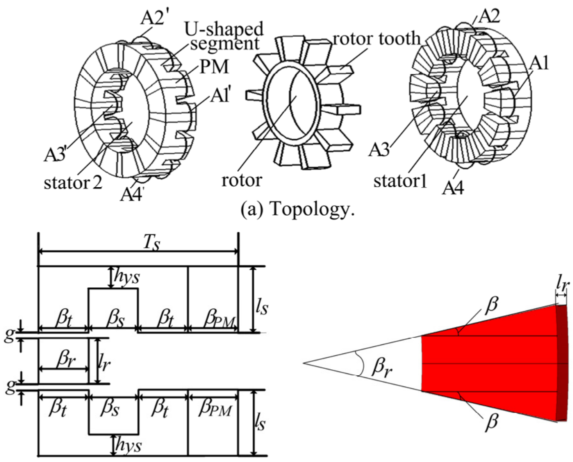
Li Hao is with School of Automation, Southeast University, Nanjing, China. (phone: +8613951820510; e-mail: haoli1226@sina.com).

Mingyao Lin is with School of electrical Engineering, Southeast University, Nanjing, China. (e-mail: mylin@seu.edu.cn).

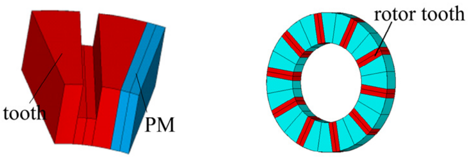
Da Xu, Nian Li, and Wei Zhang are with School of electrical Engineering, Southeast University, Nanjing, China.



(a) Topology.

(b) Dimensioning figure.

Fig. 1. AFFSPMM.



(a) Stator tooth and PM. (b) Rotor.

Fig. 2. Original design structure.

For flux-switching PM machine (FSPMM), Tcog analysis is focused on the radial field FSPMM [10-13] and the Tcog in AFFSPMM is seldom studied.

Tcog reduction of AFFSPMM is investigated in this paper. The theoretical Tcog expression of AFFSPMM is deduced. The influences of the tooth arc of stator, PM thickness of stator, yoke width of stator, axial length of stator, tooth arc of rotor, rotor tooth shape, and axial length of rotor on the cogging torque are analyzed by 3-D finite element method (FEM). The reduction methods of Tcog, such as rotor tooth skewing (RTS), rotor tooth notching (RTN), and rotor tooth circumferential pairing (RTCP), are investigated.

II. Cogging Torque Analysis of AFFSPMM

AFFSPMM, shown in Fig.1, has two doubly-salient outer stators and one inner rotor. In each stator, there are 12 U-shaped stator teeth, PMs, and concentrated coils. Both the PMs and coils are located in the stator and the rotor structure is very simple. The material both of the stator teeth and rotor teeth are silicon steels. In the initial design, the stator and the rotor are designed as fan-shape stator tooth and parallel PM (FSST-PPM) structure and parallel rotor tooth, respectively, as shown in Fig.2. The main parameters of AFFSPMM are listed in Table I.

TABLE I
MAIN ORIGINAL DESIGN PARAMETERS

Description	Original	Optimal
Rated output power (w)	600	
Rated speed (r/min)	750	
Rated output torque (N.m)	7.64	
Outer radius of stator, R_{so} (mm)	70	
Inner radius of stator, R_{si} (mm)	40	
Axial length of rotor, l_r (mm)	17.5	
Axial length of air-gap, g (mm)	1	
Tooth arc of stator at inner radius, β_t (°)	7.5	
Slot arc of stator at inner radius, β_s (°)	7.5	
PM thickness of stator at inner radius, β_{PM} (°)	7.5	
Axial Length of stator, l_s (mm)	20	17
Yoke width of Stator, h_{ys} (mm)	6	3
Tooth arc of rotor at inner radius, β_r (°)	7.5	12.5
Tooth fan-shaped angle of rotor, β (°)	0	5

Tcog is expressed

$$T_{cog} = -\frac{\partial W}{\partial \alpha} \quad (1)$$

where W is the magnetic co-energy and α is the rotor position angle.

The magnetic co-energy stored in the PMs and the air-gap is much larger than that stored in the stator iron core. Moreover, the variation of the co-energy stored in PMs is ignored because the PMs are located in the stator. So, AFFSPMM magnetic co-energy W may be expressed

$$W \approx W_{gap} = \frac{1}{2\mu_0}\int_V B^2 dV = \frac{1}{2\mu_0}\int_V B_r^2(\theta)\left(\frac{h_m}{h_m+g(\theta,\alpha)}\right)^2 dV \quad (2)$$

where μ_0 and V are the air permeability and the air-gap volume, respectively. θ is the air-gap circumference angle. $B_r(\theta)$ is the circumference distribution of the air-gap flux density at mean radius. h_m and $g(\theta,\alpha)$ are the PM magnetization length and the distribution of effective axial air-gap length, respectively.

The Fourier expansions of $B_r^2(\theta)$ is expressed

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

where $B_{r0} = b_m^2 B_r^2 / \alpha_p \tau^2$, $B_{rn} = 2b_m^2 B_r^2 \sin n\pi\alpha_p / n\pi\alpha_p^2\tau^2$. B_r is the PM remanence. α_p is the coefficient of the effective pole-arc. b_m and τ are the PM thickness and the pole pitch, respectively. P_s is the number of stator tooth.

$(h_m/(h_m+g(\theta,\alpha)))^2$ can be approximately expanded

$$\left(\frac{h_m}{h_m+g(\theta,\alpha)}\right)^2 \approx 1 - 1.646\frac{g(\theta,\alpha)}{h_m} + \left(\frac{g(\theta,\alpha)}{h_m}\right)^2 \quad (4)$$

$g(\theta,\alpha)$ is expressed

$$g(\theta,\alpha) = g + \frac{3P_s\beta_s + 2l_r(2\pi-\beta_rP_r)}{8\pi} + \sum_{i=1}^{\infty}\frac{12\times(-1)^i\cos iP_s\theta}{\pi i^2\beta_s}\cos iP_s\theta$$
$$+\sum_{m=1}^{\infty}\frac{g(P_r-\pi)}{l_rP_r\pi}\sin l_r\beta_rP_r\cos mP_r(\theta-\alpha) \quad (5)$$
$$+\sum_{m=1}^{\infty}\frac{2((-1)^m-\cos l_r\beta_rP_r)}{l_rP_r(\pi-\beta_rP_r)}\cos mP_r(\theta-\alpha)$$

where P_r is the number of rotor tooth.

Substituting (2)-(4) into (1), T_{cog} of AFFSPMM is expressed

$$T_{cog} = -\frac{g}{4\mu_0}(R_{so}^2 - R_{si}^2) \quad (6)$$
$$\times\int_0^{2\pi}\sum_{n=0}^{\infty}B_{rn}\frac{2g(\theta,\alpha)-1.646}{h_m}\frac{\partial g(\theta,\alpha)}{\partial\alpha}\cos nP_s\theta d\theta$$

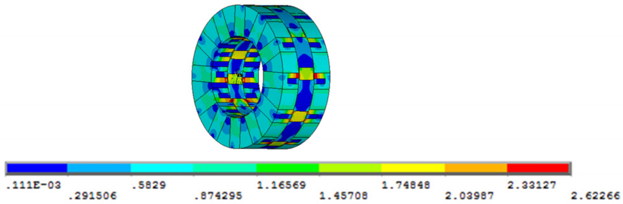


Fig. 3. The magnetic field distribution.

where B_{rn} is the Fourier coefficient of $B_r^2(\theta)$.

III. INFLUENCES OF DESIGN PARAMETERS ON COGGING TORQUE

According to the theoretical analysis, Tcog in AFFSPMM is influenced by the design parameters and the flux density distribution of the air-gap. Based on 3-D EFM, the influences of the tooth arc of stator, PM thickness of stator, yoke width of stator, axial length of stator, tooth arc of rotor, rotor tooth shape, and axial length of rotor on Tcog are analyzed for FSST-PPM structure. The 3-D magnetic field distribution of AFFSPMM is shown in Fig.3. Fig.4 shows the normalized cogging torque T_{cog}/T_{cog_orig}, where $T_{cog\_orig.}$ is the original Tcog and T_{cog} is the cogging torque changing with the design parameters.

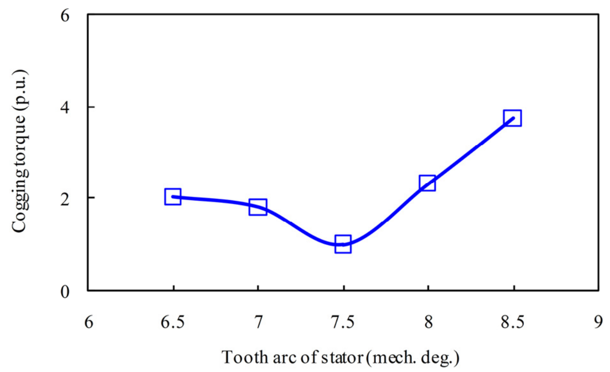
Tcog in AFFSPMM is influenced greatly by the design parameters except the rotor axial tooth length. Decreasing the yoke width and axial length of stator can decrease Tcog, and increasing the tooth arc and tooth fan-shaped angle β of rotor will also decrease Tcog. Hence, Tcog in AFFSPMM can be reduced by the optimization of the design parameters. Considering other static characteristics of AFFSPMM, the optimized design parameters are list in Table I and the Tcog value comparison between the original design and the optimal design is shown in Fig.5. After the optimization of the parameters, Tcog is reduced by ~52%.

IV. COGGING TORQUE REDUCTION BY ROTOR DESIGN TECHNIQUES

Though Tcog in AFFSPMM decreases by the optimization of the design parameters. However, the peak value of Tcog is about 1.1N.m and still large. Hence, Tcog should be reduced further. Considering the structure of rotor is simple and easy to manufacture, the reduction methods of Tcog by different rotor tooth design techniques are analyzed.

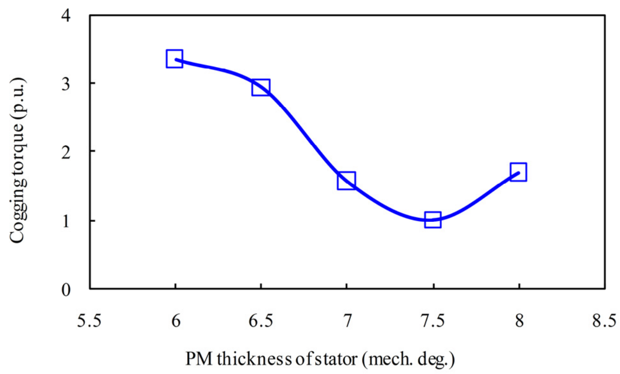
A. Rotor Tooth Skewing

For AFFSPMM, the RTS, shown in Fig.6(a), can change the distribution of the air-gap flux density. Hence, the cogging torque will be influenced. The influence of the RTS angle α on Tcog, which is expressed in normalized mode, is shown in Fig. 7. RTS method is invalid for AFFSPMM with FSST-PPM structure. However, when the stator is designed as parallel stator tooth and fan-shape permanent magnet (PST-FSPM) structure, shown in Fig.6(b), the cogging torque can decrease greatly by RTS method. As seen from Fig.7(b), Tcog for PST-FSPM structure decreases by ~56% when the skewing angle is designed as 6°. Then, Tcog almost keeps unchanged with the increasing of the rotor tooth skewing angle α.

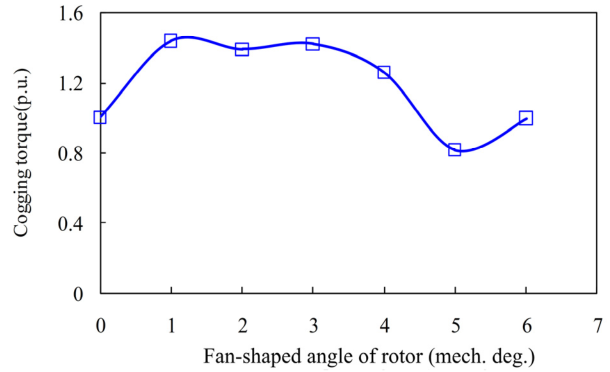


(a) Tooth arc of stator.

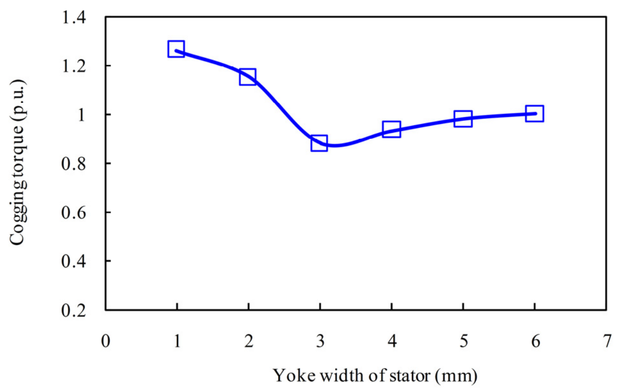
(e) Tooth arc of rotor.



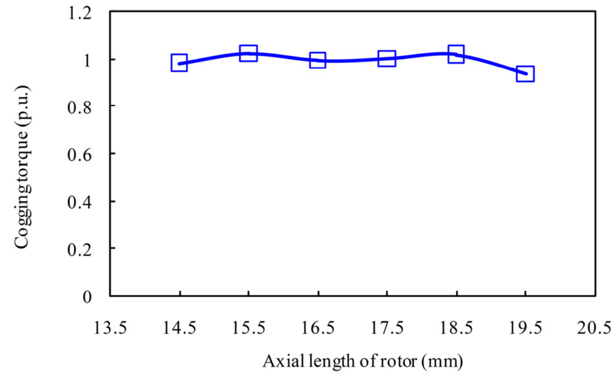
(b) PM thickness of stator.



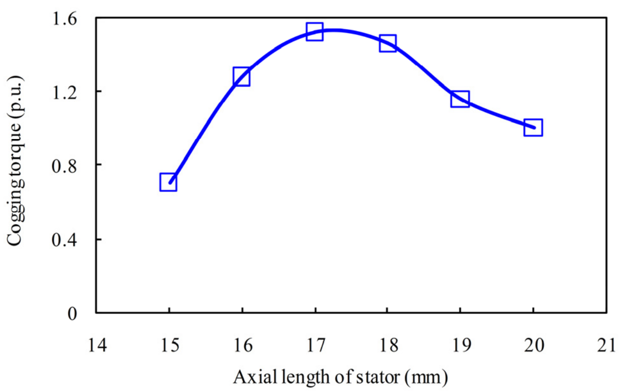
(f) Fan-shaped angle of rotor.



(c) Yoke width of stator.



(g) Axial length of rotor.



(d) Axial length of stator.

Fig. 4. Influences of main design parameters on Tcog.

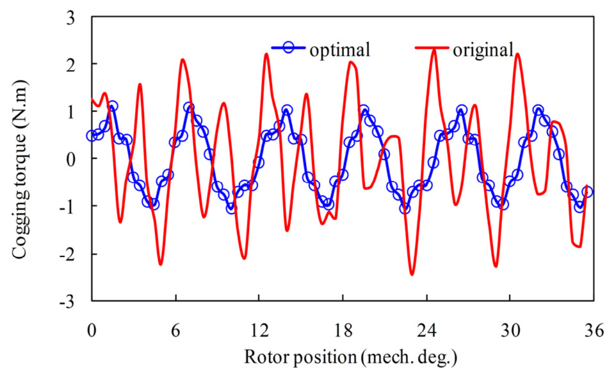
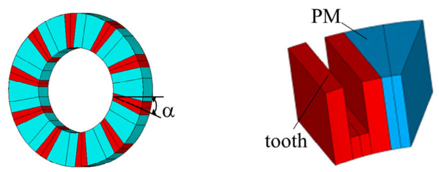
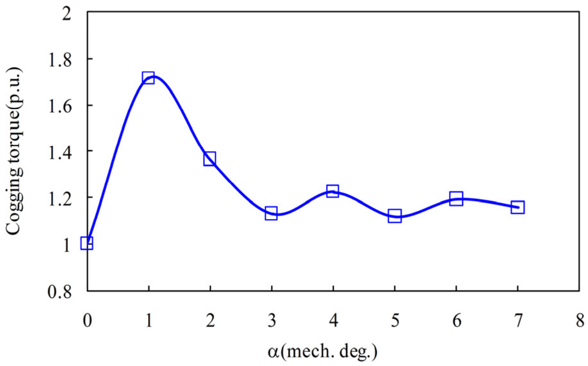


Fig.5. Tcog comparison between the original and optimal design.

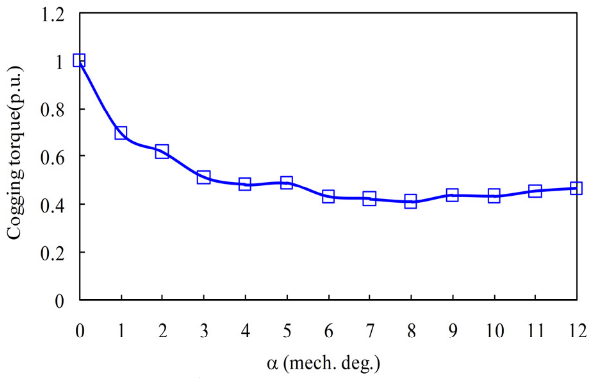


(a) Rotor tooth skew. (b) PTPS stator.

Fig. 6. Rotor teeth skewing schematic and PTPS stator.

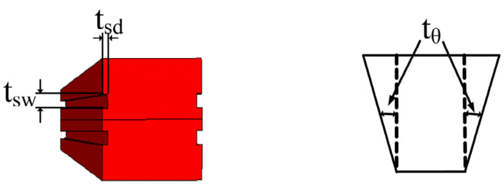


(a) FSST-PPM structure.



(b) PST-FSPM structure.

Fig. 7. Influences of the rotor tooth skewing angle α on Tcog.



(a) Rotor tooth notching. (b) Dummy slot shape.

Fig.8. Rotor tooth notching schematics.

RTS method is no effective for FSST-PPM structure in reducing Tcog. Hence, RTN and RTCP methods are investigated to reduce the Tcog for FSST-PPM structure.

B. Rotor Tooth Notching

The combination between the stator tooth and rotor tooth is changed when the dummy slots are added in the rotor tooth. So, Tcog will be influenced. Fig.8 shows a rotor tooth with two dummy slots. For FSST-PPM structure, Tcog can be reduced by RTN method. Fig.9 compares the Tcog value between having and no two dummy slots in the rotor tooth for FSST-PPM structure. The minimum Tcog is obtained and reduced by ~43% when the width of dummy slot t_{sw}=2.6°, depth of dummy slot t_{sd}=1.65mm, and shape angle of dummy slot t_θ=1°, respectively.

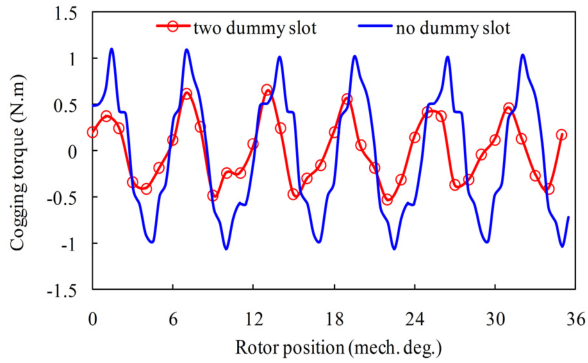


Fig.9. Tcog comparison between dummy slot and no dummy slot.

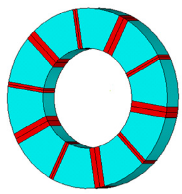


Fig.10. Schematic diagram of rotor teeth pairing in AFFSPMM.

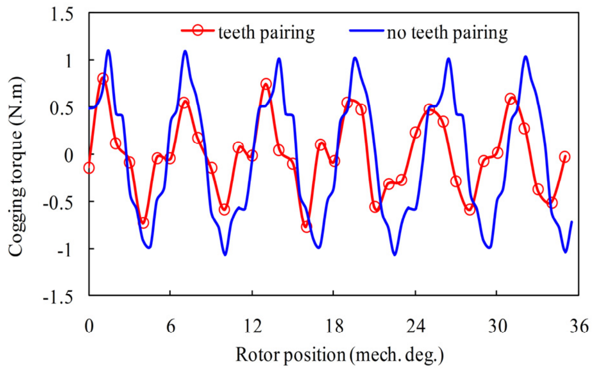


Fig.11. Cogging torque Comparison between teeth pairing and no teeth pairing.

C. Rotor Tooth Circumferential Pairing

Fig.10 and Fig.11 show the schematics diagram of RTCP and Tcog comparison between tooth pairing and no tooth pairing for FSST-PPM structure. Tcog is the minimum and reduced by ~21% when the big rotor tooth and small rotor tooth are designed to 12.5° and 5.5°, respectively.

V. CONCLUSION

The Tcog and three different Tcog reduction methods in AFFSPMM are investigated. The theoretical Tcog expression is deduced and the influences of the main design parameters on Tcog are analyzed by 3-D FEM. The tooth arc of stator, PM thickness of stator, yoke width of stator, axial length of stator, tooth arc of rotor and tooth shape of rotor have great influences on Tcog. However, the axial length of rotor almost has no influence on Tcog. In three different reduction methods of Tcog, RTS is no effective to the cogging torque reduction for FSST-PPM. For PST-FSPM, the Tcog will decrease greatly by RTS method. However, Tcog can be decreased by RTN and RTCP for FSST-PPM structure. Moreover, the cogging torque reduction effect of RTN is better than that of RTCP.

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