

# A Partition Stator Flux Switching Permanent Magnet Machine with Consequent-Pole Flux Reverse Effect

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This paper presents a novel partitioned stator flux-switching permanent magnet (PS-FSPM) machine aimed at overcoming the limitations in torque enhancement. The proposed design employs consequent-pole PMs (NN-SS-NN) arranged alternately within the outer stator. This dual-PM configuration combines the effects of flux-switching and flux-reverse. Through equivalent magnetic circuit analysis, the strong coupling of flux contributions under both effects is demonstrated. Then the torque ripple characteristics and torque contribution mechanisms under load conditions is analyzed, revealing the principles of torque improvement. Finally, a comparative analysis with regular machine shows improvements in back-EMF, torque performance and power factor.

**Index Terms**—PS-FSPM, torque, consequent-pole, flux-reverse effect.

## I. INTRODUCTION

WITH a smaller volume of permanent magnets, the torque density of the partition stator flux-switching permanent magnet (PS-FSPM) machine is still higher than that of the machine before stator separation. This improvement is mainly attributed to the further increase in winding space and the effective utilization of the stator structure [1]. However, to minimize the magnetic reluctance and maximize the torque density, the centerlines of the inner stator PMs must align with the centerline of the outer stator teeth [2]. Therefore, further enhancement of the torque density in the PS-FSPM machine presents a critical challenge for its development.

In [3], a method is proposed to enhance the torque performance through the integration of DC windings for hybrid excitation. However, this approach necessitates a complex control system and introduces additional costs due to the incorporation of electrical excitation components [4]. Alternatively, some researchers have employed an H-shaped PMs structure on the inner stator to augment the magnetic flux density within the air gap [5]. Nonetheless, this results in a substantial increase in the required volume of PMs. Consequently, enhancing the torque performance of the PS-FSPM machine through topological design remains a significant and challenging task.

## II. TOPOLOGY AND OPERATION PRINCIPLE

This paper proposed a novel PS-FSPM machine, as shown in Fig. 1. In contrast to regular model with tangentially magnetized PMs embedded in inner stator teeth, the proposed design incorporates radially magnetized PMs arranged in an NN-SS consequent-pole configuration on the outer stator teeth. Furthermore, the pole-arc coefficient of inner rotor PMs has been reduced compared to regular model to compensate for the additional PM volume in the outer stator.

Base on the permeance-magnetomotive force model, the flux switching and flux reverse effects of the proposed machine are

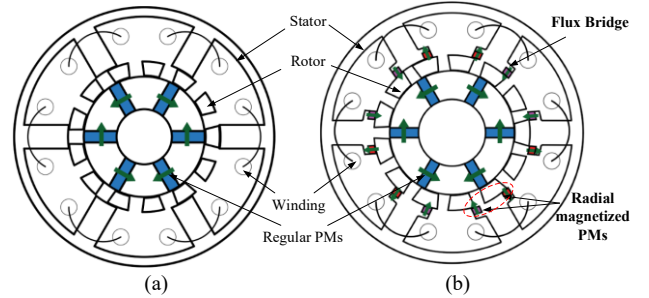


Fig. 1. Topology of PS-FSPM machine. (a) Regular. (b) Proposed

derived and analyzed [6]. The corresponding PM magnetomotive force  $F_{SPM}$  and  $F_{RPM}$  of the flux switching and flux reverse effects are as follows:

$$F = F_{SPM} + F_{RPM} = \sum_{n=1,3,5,\dots}^{\infty} F_n \sin(nP_s\theta) + \sum_{m=1,3,5,\dots}^{\infty} F_m \sin(mP_r\theta) \quad (1)$$

where  $F_n$  and  $F_m$  represent the Fourier coefficients of the equivalent magnetomotive forces.  $P_s$  and  $P_r$  are the pole pairs of the inner and outer PMs, respectively. In this paper,  $P_s = P_r = 3$ .

$$\Lambda(\theta, t) = \Lambda_0 + \sum_{k=1}^{\infty} \Lambda_k \cos(kN_r\theta - N_r\omega_r t) \quad (2)$$

where  $N_r$  the number of rotor teeth, the DC term of specific permeance  $\Lambda_0$  is stationary and does not induce back EMF in the armature windings. The air-gap flux density components generated by higher-order harmonics of relative permeance  $\Lambda_k$  ( $k \neq 1$ ) rotate at  $k$  times the synchronous speed ( $\omega_r$ ). Consequently, these harmonics contribute neither to the fundamental back EMF nor to the average torque production. Therefore, the formulation can be simplified by considering only the fundamental harmonic component ( $k=1$ ).

$$B_{PM}(\theta, t) = F_{sys} \Lambda(\theta, t) = \sum_{n,m=1,3,5,\dots}^{\infty} F_n \Lambda_1 \sin[(nP_s \pm N_r)\theta - N_r\omega_r t] + F_m \Lambda_1 \sin[(nP_r \pm N_r)\theta - N_r\omega_r t] \quad (3)$$

Based on the equivalent magnetic circuit method, the increase in the magnetic flux linkage of each coil is calculated using the harmonic components of the effective air-gap flux density. Combining with the winding function  $N(\theta)$ , the magnetic flux contribution is calculated as follows:

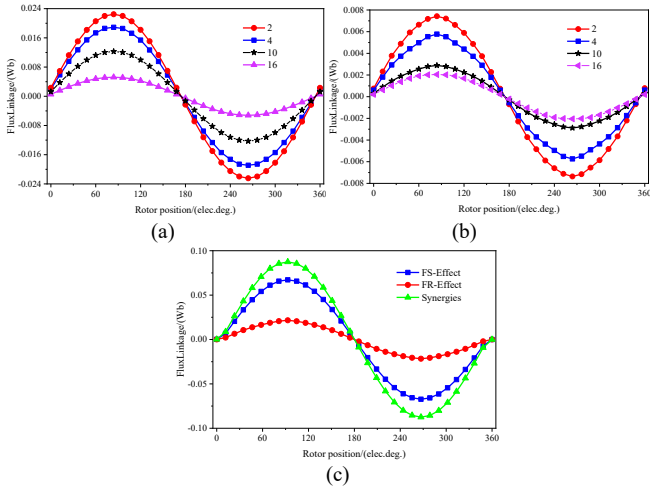


Fig. 3. No-load flux linkage of phase A. (a) Flux switching effect. (b) Flux reverse effect. (c) Synergistic effect.

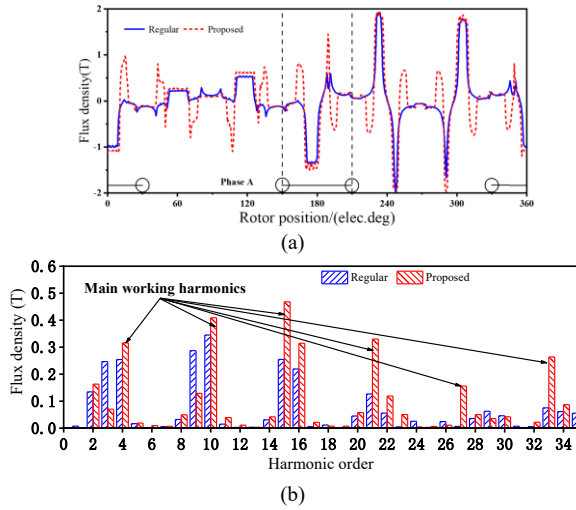


Fig. 4. Outer air gap flux density. (a) Waveforms. (b) Spectrum.

$$\begin{aligned}
 \psi(t) &= k_w r_g l_s \int_0^{2\pi} B_{PM}(\theta, t) N(\theta) d\theta \\
 &= k_w r_g l_s \int_0^{2\pi} \sum_{\substack{n=1,3,5,\dots \\ j=1,2,3,\dots}}^{\infty} F_n \Lambda_1 N_{wj} \sin[(nP_s \pm N_r)\theta - N_r \omega_r t] \cos(jP_w \theta) d\theta \\
 &\quad + k_w r_g l_s \int_0^{2\pi} \sum_{\substack{m=1,3,5,\dots \\ j=1,2,3,\dots}}^{\infty} F_m \Lambda_1 N_{wj} \sin[(mP_r \pm N_r)\theta - N_r \omega_r t] \cos(jP_w \theta) d\theta
 \end{aligned} \quad (4)$$

As shown in Fig. 3(a) and (b), the primary contributing pole pairs are the 2nd, 4th, and 10th harmonics, respectively. Under both effects, the contribution of these harmonics to the fundamental magnetic flux of phase A reaches over 90% of the total contribution. Furthermore, as shown in Fig. 3(c), the contributions of both effects to the total magnetic flux exhibit strong coupling.

### III. ELECTROMAGNETIC PERFORMANCE ANALYSIS

#### A. No-load magnetic field

In Fig. 4(a), compared with the regular model, the proposed model exhibits a significant enhancement in magnetic flux density in the reverse-effect region of the waveform. Through modulation of the rotor teeth, the outer air-gap magnetic density exhibits a richer harmonic content, as shown in Fig. 4 (b).

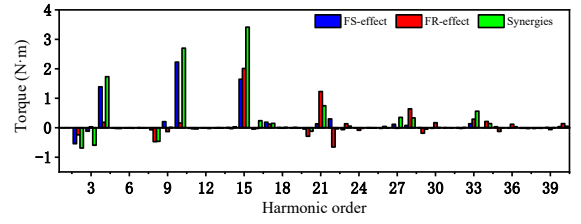


Fig. 5. Torque contribution.

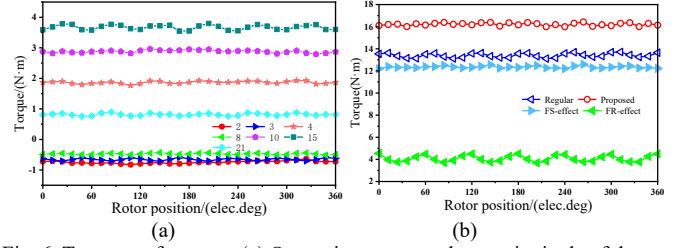


Fig. 6. Torque performance (a) Outer air-gap torque harmonic ripple of the proposed model. (b) Output torque.

According to Equation (3), the amplitudes of 15th-order harmonic and higher-order harmonics at the 27th and 33rd orders are significantly enhanced. Meanwhile, other working harmonics show slight improvements.

#### B. Torque performance

Fig. 5 illustrates the torque contributions under two different effects. These results align with the no-load harmonic analysis. Fig. 6(a) presents the pulsation characteristics of the dominant harmonic components contributing to the torque in the proposed model. Although the flux reverse effect introduces relatively higher torque ripple, the harmonic phases under this effect oppose those of the 3rd and 8th-order harmonics generated by the flux switching effect. This phase opposition results in partial cancellation of torque harmonic ripple [7]. Consequently, compared to regular model, the proposed design enhances the output torque from 13.43N·m to 16.10N·m while reducing torque ripple to 3.2%.

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