

Electromagnetic Force Analysis of Permanent Magnet Synchronous Motors With Opposing Unequal Magnetic Poles

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The method of optimizing rotor magnetic pole is usually used to suppress the torque ripple and electromagnetic vibration of PMSM. However, unbalanced magnetic pull and new electromagnetic vibration components may be introduced. This paper proposes a new rotor structure with opposing unequal magnetic poles, and its electromagnetic force wave is systematically analyzed. The symmetrical magnetic poles can avoid the radial unbalanced magnetic pull. Moreover, the general analytical expressions of air gap flux density and electromagnetic force are derived, and the spatial-temporal characteristics of radial electromagnetic force are investigated. Then, the finite element analysis model is established, and the correctness of the theoretical analysis is verified by finite element analysis. The results show that the proposed rotor structure can weaken the related electromagnetic force component, which is conducive to the improvement of the electromagnetic vibration characteristics of the motor.

Index Terms—Permanent magnet motor, air gap flux density, electromagnetic force, vibration.

I. INTRODUCTION

TORQUE ripple and electromagnetic vibration noise as inherent problems of permanent magnet synchronous motors (PMSMs), which reduce the operational reliability of motor drive systems. The method of optimizing the pole-arc coefficients of the rotor poles can optimize the magnetic field distribution by changing the amplitude and order distribution of the air-gap magnetic field, weakening the cogging torque and electromagnetic vibration [1]–[3]. The single pole unequal width rotor structure is often used in the existing literature to effectively suppress the cogging torque of PMSM. However, this structure cannot avoid the unbalanced magnetic pull caused by the magnetic pole asymmetry of the non-segmented rotor motor, which is not conducive to the durability of the bearing.

To obtain a smoother torque output and lower vibration level, a novel PMSM with opposing unequal magnetic poles is proposed in this paper. A general electromagnetic force analysis method is proposed and compared with the finite element results to verify the weakening and suppression effect of the proposed rotor structure with relatively unequal magnetic poles on the electromagnetic force wave component and electromagnetic vibration.

II. TOPOLOGY OF THE PROPOSED MOTOR

The comparison of the rotor structure of the original motor proposed motor structure is shown in Fig. 1. Different from the original equal pole arc width motor, the width of a pair of poles in the proposed motor is always wider than that of other poles. However, the distance between magnetic poles does not change. The symmetrical magnetic poles can avoid the radial unbalanced magnetic pull. The shape and size of each permanent magnet of the proposed rotor structure applied to the surface mounted PMSMs will be changed, but the total magnet steel usage remains the same. When applied to interior PMSMs, this structure can be realized by changing the size of the rotor core punches only, thus achieving improved motor performance without increasing the processing cost.

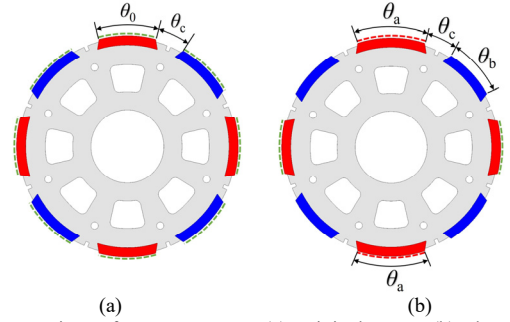


Fig. 1. Comparison of rotor structures. (a) Original motor. (b) The proposed motor.

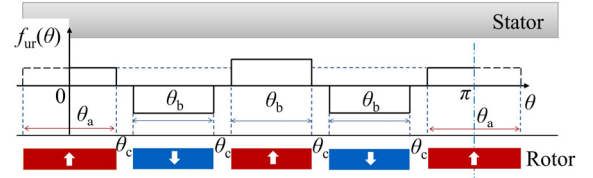


Fig. 2. Schematic diagram of the magnetomotive force distribution of the proposed motor.

III. ELECTROMAGNETIC FORCE WAVE ANALYSIS

Electromagnetic force waves are the excitation source of electromagnetic vibration of the motor. By analyzing the order and amplitude of the electromagnetic excitation force, the geometrical parameters can be adjusted during the design of the motor so as to weaken the excitation force component that causes the resonance of the motor.

The magnetomotive force generated by the permanent magnets of the proposed rotor is distributed along the circumference for a period of π , as shown in Fig. 2, and the Fourier expansion of the magnetomotive force distribution function is given by

$$f_{ur}(\theta, t) = \sum_{v=1,2,3,\dots} F_{urv} \cos(2v\theta - \frac{2v}{p} \omega_l t) \quad (1)$$

The air-gap magnetic density of the surface-mounted PMSM with opposing unequal magnetic poles is obtained from the magnetic potential-permittivity method as

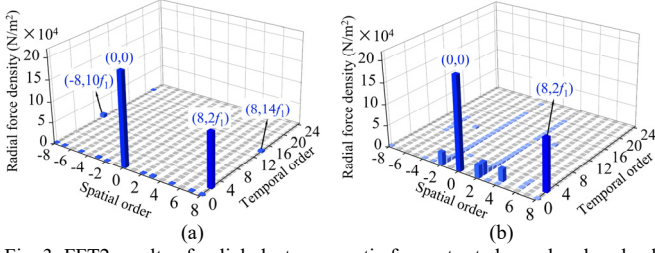


Fig. 3. FFT2 results of radial electromagnetic force at rated speed and no load. (a) Original motor. (b) The proposed motor.

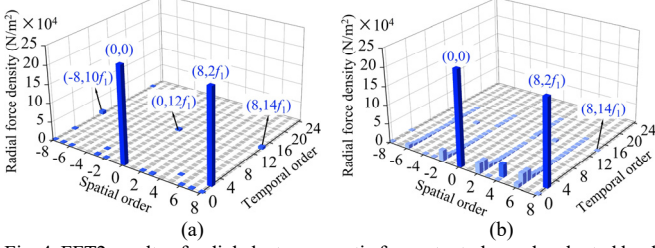


Fig. 4. FFT2 results of radial electromagnetic force at rated speed and rated load. (a) Original motor. (b) The proposed motor.

TABLE I

RADIAL ELECTROMAGNETIC FORCE AMPLITUDES UNDER NO LOAD			
Electromagnetic force component	No load		
	The original motor (Pa)	The proposed motor (Pa)	Percentage Change
(0, 0)	216737	214735	-0.92%
(0, 24f)	230	87	-62.17%
(8, 2f)	126403	121005	-4.27%
(8, 14f)	4537	191	-95.78%
(-8, 10f)	8492	116	-98.64%

TABLE II

RADIAL ELECTROMAGNETIC FORCE AMPLITUDES UNDER RATED LOAD			
Electromagnetic force component	Rated load		
	The original motor (Pa)	The proposed motor (Pa)	Percentage Change
(0, 0)	253503	248235	-2.08%
(0, 24f)	943	185	-80.38%
(8, 2f)	244528	224665	-8.12%
(8, 14f)	6814	1044	-84.67%
(-8, 10f)	8844	442	-95.01%

$$b_{ur}(\theta, t) = \sum_{v=1,3,5,\dots} F_{rv} \cos(vp\theta - v\omega_1 t) \cdot \Lambda_{r0} \quad (2)$$

$$= \sum_{v=1,2,3,\dots} B_{urv} \cos(2v\theta - \frac{2v}{p}\omega_1 t)$$

where the magnetic permeability of the surface-mounted PMSM is represented by the constant Λ_{r0} . Combined with Maxwell stress tensor method, the analytical equation for the electromagnetic force wave is obtained as

$$p_{ur}(\theta, t) = \frac{[b_{ur}(\theta, t)]^2}{2\mu_0} \quad (3)$$

The above electromagnetic force components can be simplified and expressed as $(2k, 2kf_i/p)$, where $k=0,1,2,3, \dots$, and the order and frequency characteristics of the main EMF of the proposed motor are reduced to $1/p$ of the original equal pole width motor.

Considering the stator slotting, the radial air gap magnetic density can be expressed as

$$b_{urs}(\theta, t) = b_{ur}(\theta, t) \cdot [\Lambda_{s0} + \sum_{l=1,2,3,\dots} \Lambda_{sl} \cos(lZ\theta)] \quad (4)$$

$$= \sum_{v=1,2,3,\dots} \sum_{l=0,1,2,\dots} B_{urvl} \cos[(2v \pm lZ)\theta - \frac{2v}{p}\omega_1 t]$$

The electromagnetic force wave considering the effect of the stator slotting is

$$p_{urs}(\theta, t) = \frac{[b_{urs}(\theta, t)]^2}{2\mu_0}$$

$$= \sum_{v_1} \sum_{v_2} \frac{B_{urv_1} B_{urv_2}}{4\mu_0} \cos[2(v_1 \pm v_2)\theta - \frac{2}{p}(v_1 \pm v_2)\omega_1 t]$$

$$+ \sum_{v_1} \sum_{v_2} \sum_l \frac{B_{urv_1} B_{urv_2}}{2\mu_0} \cos\left\{ \left[2(v_1 \pm v_2) \pm lZ \right] \theta - \frac{2}{p}(v_1 \pm v_2)\omega_1 t \right\} \quad (5)$$

$$+ \sum_{v_1} \sum_{v_2} \sum_{l_1} \sum_{l_2} \frac{B_{urv_1} B_{urv_2}}{4\mu_0} \cos\left\{ \left[2(v_1 \pm v_2) \pm (l_1 \pm l_2)Z \right] \theta - \frac{2}{p}(v_1 \pm v_2)\omega_1 t \right\}$$

The above electromagnetic force components can be simplified and expressed as $(2k \pm iZ, 2kf_i/p)$, where $k=0,1,2,3,\dots, i=1,2,3,\dots$

Interior PMSMs have a significant difference in permeability amplitude between the d-axis and the q-axis of the salient pole rotor, and their permeability alternates with rotor position and synchronous speed, and the $2m^{\text{th}}$ permeability harmonic will be generated. The air gap magnetic density can be expressed as

$$b_{uri}(\theta, t) = \sum_{v=1,2,3,\dots} B_{urvi} \cos(2v\theta - \frac{2v}{p}\omega_1 t) \quad (6)$$

$$+ \sum_{v=1,2,3,\dots} \sum_{m=1,2,3,\dots} B_{urm} \cos[2(v \pm m)\theta - 2(\frac{v}{p} \pm m)\omega_1 t]$$

Correspondingly, the salient pole effect of the proposed interior PMSM will introduce more orders of air-gap magnetic density components and generates more orders and frequencies of electromagnetic force wave components compared to the surface-mounted PMSM.

IV. FINITE ELEMENT SIMULATION VERIFICATION

Taking the 8-pole 48-slot interior PMSM as an example, the waveforms and 2D Fourier decomposition (FFT2) results of the electromagnetic force under no load and rated load are shown in Fig. 3, Table I, Fig. 4 and Table II. The proposed rotor structure can transfer the 0^{th} -order and pole correlation order electromagnetic force wave components to other spatial orders, thus weakening the amplitude of 0^{th} -order and $2p$ -order electromagnetic force components, and effectively suppressing the 0^{th} -order and pole order electromagnetic vibration of the motor.

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