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Investigation and Analysis of Force Production Mechanism for Partitioned Stator Flux Reversal Permanent Magnet Linear Machine

Abstract- *In this paper, the force production mechanism in partitioned stator flux reversal permanent magnet (PS-FRPM) linear machine will be investigated. Since the PS-FRPM linear machine has both armature windings and the permanent magnet (PM) in one machine part and the other part is passive; thereby, the force production mechanism in conventional PM linear machine, is not valid for such a machine. In order to determine both magnetic and electrical loading frequency components, which result in production the electromagnetic force a spatial harmonic analysis is adapted. It has been found that the electromagnetic force in the PS-FRPM linear machine is produced by the interaction of the fundamental and its non-triple multiples harmonic orders of the stator winding magneto-motive force (MMF) with the air gap flux density, which is equal to the product of the PM (MMF) and the air gap permeance accounting for both the mover pole and the upper stator teeth. The analytical results are validated by finite element analysis (FEA), which are shown good agreement.*

Keywords *Flux reversal PM linear machines, Force production, Double salient permanent magnet machines*

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1.Introduction

Recently, new configuration of double salient permanent magnet (DSPM) machine has been introduced, such machine named as partitioned stator permanent magnet (PS-PM) machine, which is distinguished by having two active stators and one passive rotor [1], [2]. It has been stated that the PS-PM machine possesses the advantages of better inner space utilization and enhance electrical and magnetic loadings, consequently improved the machine torque capability [2]-[3]. The first configuration of PS-PM machine was designed in [2], the machine known as partitioned stator switched flux permanent magnet (PS-SFPM) machine. The machine structure and principle operating were explained. In addition, the optimal rotor poles number in terms of the highest average torque was determined. In order to evaluate the proposed machine, a comparison between the PS-SFPM machine and conventional SFPM machine was carried out. It was shown that higher torque capability can be achieved by the PS-SFPM machine. On the other hand, the influence of inner stator pole number as well as the winding configuration on the PS-SFPM machine was investigated in [4]. It was revealed that both double- and single-layer windings PS-SFPM machines in which both inner and outer stators have the same pole numbers exhibit higher torque than their counterparts in which the inner stator pole number is half of the outer stator pole number. Moreover, flux reversal permanent magnet (FRPM) machine with partitioned stator structure was developed in [3]. PS-FRPM machines having different rotor pole numbers were designed, optimized and compared. Compared to the conventional FRPM machine, the PS-FRPM machine has about more than 50% higher average torque. In order to reduce the PM volume and subsequently, reduce the machine cost, PS-FRPM machine with subsequence pole in which about 30% less PM usage was designed in [5]. It was stated that the developed machine has similar torque capability compared to the conventional PS-FRPM machine. Furthermore, PS-PM machines with different PM configurations named as PS- surface mounted PM, PS- interior I-shape PM, PS- interior spoke-shape PM and PS- interior V-shape PM machines were investigated in [6]. It was shown that the highest average torque is for PS- interior spoke-shape PM machine, while the best PM utilization is for interior I-shape PM machine.Generally, electrical machines can be designed as rotating and linear configurations. Owing to the advantages that can be offered by linear machines, they have been applied whenever

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direct drive applications are required. Linear machines have the advantages of high dynamic performance and enhanced reliability, due to the elimination of the conversion mechanism from rotary to linear motion, which should be used if the rotating machines are utilized for linear applications [7.[٨] [The history of linear machines can be dated back to more than a century ago, and is as old as the rotating counterparts. The first linear machine was introduced in 1845 by Charles Wheatstone .[٩]The operation principle of linear machines is similar to that of the rotating machines. However, their major differences include that the air gap of the linear machines is larger than that of the rotating machines, the linear machines having a start and an end, while the rotating machines do not.It is well known that PM linear machines possess the highest force and efficiency among other linear machine technologies, i.e. induction and SR linear machines [10] [11]. Therefore, they have been increasingly employed in various applications. However, the high manufacturing cost can be considered as one of the most crucial problems of the PM linear machines, particularly in long stroke applications in which a large amount of either permanent magnet or copper would be required [12]. Because of that the PM linear machines, which have both excitation sources in one part whilst the other part is passive, have become more favored in industrial applications and traction systems .[١٣] On the other hand, having both armature winding and PM in one machine part may present the limitations of thrust force capability and PM demagnetization withstand capability. Thus, in order to compromise such demerits, novel PM linear machine termed as PS-FRPM linear machine was proposed in [14]. The machine has been designed by adopting the concept of partitioned stator in which each stator part has one excited source while the mover is passive. Global optimization for maximum thrust force was carried out. The PS-FRPM linear machine was compared to the conventional FRPM linear machine [14]. It was concluded that the PS-FRPM linear has about 60% higher average thrust force. In this paper the force production mechanism for the PS-FRPM linear machine will be investigated and analysed. The rest of this paper is organized as follow: Section 2 includes a brief explanation of the machine structure and operating principle, while force production mechanism of the mentioned machine is analysed in Section 3. Moreover, a comparison between the analytical and Finite Element Analysis (FEA) results is presented in Section 4. Finally, Section 5 summarizes the conclusions.

1. Machine Configuration and Operating Principle

A cross-section of the PS-FRPM linear machine with 6/5 stator/mover pole number is shown in Figure 1. It can be clearly noted that the machine has one passive mover and two active stators. The mover is made of iron pieces, which are sandwiched between the two stators. On the other hand, the PMs and the armature windings, are located on separate stators. It is worth mentioning that the machine works under flux switched concept in which both the direction as well as the amplitude of the flux linkage are changed with the mover position. Further details of the machine structure and its operating principle can be found in [14].

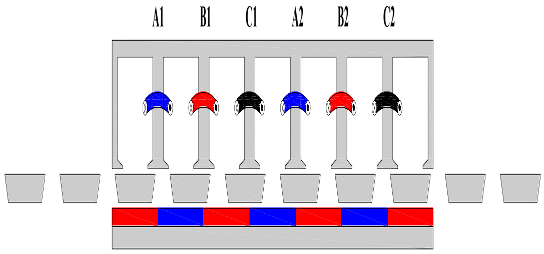


Figure 1: PS-FRPM linear machine cross-section.

2. Force Production Mechanism in PS-FRPM Linear Machine Analysis

Generally, in PM machines that have a negligible reluctance torque, the electromagnetic torque is directly proportional to the stator winding magneto motive force (MMF) and air gap flux density due to the PM [15]. Hence, in order to analyse the force production in the PS-FRPM linear machine, the winding MMF will be firstly calculated, and then the air gap flux density due to the stator permanent magnet and the air gap permeance will be determined by considering both stator teeth and mover poles. It should be noted that the analysis will be carried out for 6/5 slot/pole PS-FRPM linear machine, with concentrated windings. The MMF winding function calculation is carried out under the following assumptions:

- Saturation effect is not considered**.**
- The permanent magnet permeability is unity.

MMF of phase A, as illustrated in Figure 2, can be expressed by Fourier series [16].

$$N_a(\phi) = \sum_n N_n \cos(n\phi) \qquad (1)$$

where n is the harmonic order, N_n denotes the magnitude of the nth- order MMF harmonic and ϕ indicates the spatial angle. Similarly with proper phase shift the winding functions of both phases B and C can be obtained as follows:

$$N_b(\phi) = \sum_n N_n \cos(n\phi - n\theta_m) \quad (2)$$

$$N_c(\phi) = \sum_n N_n \cos(n\phi + n\theta_m) \quad (3)$$

where θ_m is the mechanical phase angle, which is equal to (π/3) for the analysed machine. The phase currents of the three phase set can be written as follows:

$$I_a = I\cos(\omega t)$$
$$I_b = I\cos\left(\omega t - \frac{2\pi}{3}\right) \quad (4)$$
$$I_c = I\cos\left(\omega t + \frac{2\pi}{3}\right)$$

where I is the current amplitude and ω represents the angular frequency. The total MMF distribution of three phase windings is

$$F_s = \sum_n (N_a I_a + N_b I_b + N_c I_c)$$

$$= \sum_n N_n \cos(n\phi) I\cos(\omega t) + \sum_n N_n \cos(n\phi - n\theta_m) I\cos\left(\omega t - \frac{2\pi}{3}\right) + \sum_n N_n \cos(n\phi + n\theta_m) I\cos\left(\omega t + \frac{2\pi}{3}\right)$$

$$= \sum_n \frac{N_n I}{2}[\cos(n\phi - \omega t) + \cos(n\phi + \omega t)] + \sum_n \frac{N_n I}{2}\left[\cos\left(n\phi - n\theta_m - \omega t + \frac{2\pi}{3}\right) + \cos\left(n\phi - n\theta_m + \omega t - \frac{2\pi}{3}\right)\right] + \sum_n \frac{N_n I}{2}\left[\cos\left(n\phi + n\theta_m - \omega t - \frac{2\pi}{3}\right) + \cos\left(n\phi + n\theta_m + \omega t + \frac{2\pi}{3}\right)\right]$$

$$= \sum_n \frac{N_n I}{2}[\cos(n\phi - \omega t) + \cos(n\phi + \omega t)] + \sum_n \frac{N_n I}{2}\left[\left\{\cos(n\phi - \omega t)\cos\left(n\theta_m - \frac{2\pi}{3}\right) + \sin(n\phi - \omega t)\sin\left(n\theta_m - \frac{2\pi}{3}\right)\right\} + \left\{\cos(n\phi + \omega t)\cos\left(n\theta_m + \frac{2\pi}{3}\right) + \sin(n\phi + \omega t)\sin\left(n\theta_m + \frac{2\pi}{3}\right)\right\}\right] + \sum_n \frac{N_n I}{2}\left[\left\{\cos(n\phi - \omega t)\cos\left(n\theta_m - \frac{2\pi}{3}\right) - \sin(n\phi - \omega t)\sin\left(n\theta_m - \frac{2\pi}{3}\right)\right\} + \left\{\cos(n\phi + \omega t)\cos\left(n\theta_m + \frac{2\pi}{3}\right) - \sin(n\phi + \omega t)\sin\left(n\theta_m + \frac{2\pi}{3}\right)\right\}\right]$$

$$= \sum_n \frac{N_n I}{2}[\cos(n\phi - \omega t)] + \sum_n \frac{N_n I}{2}\left[\cos(n\phi - \omega t)\cos\left(n\theta_m - \frac{2\pi}{3}\right)\right] + \sum_n \frac{N_n I}{2}\left[\cos(n\phi - \omega t)\cos\left(n\theta_m - \frac{2\pi}{3}\right)\right] + \sum_n \frac{N_n I}{2}[\cos(n\phi + \omega t)] + \sum_n \frac{N_n I}{2}\left[\cos(n\phi + \omega t)\cos\left(n\theta_m + \frac{2\pi}{3}\right)\right] + \sum_n \frac{N_n I}{2}\left[\cos(n\phi + \omega t)\cos\left(n\theta_m + \frac{2\pi}{3}\right)\right] \quad (5)$$

The forward and backward MMF equations can be expressed as:

$$F_f = \sum_n \frac{N_n I}{2}\cos(n\emptyset - \omega t)\left[1 + 2\cos\left(n\theta_m - \frac{2\pi}{3}\right)\right] \quad (6)$$

$$F_b = \sum_n \frac{N_n I}{2}\cos(n\emptyset + \omega t)\left[1 + 2\cos\left(n\theta_m + \frac{2\pi}{3}\right)\right] \quad (7)$$

The spatial harmonics of the stator winding MMF are illustrated in Figure 3. It can be observed that the dominated harmonics are the 2nd order and its non-triple multiples. It has been found that for a SFPM machine the fundamental spatial harmonic of the MMF stator winding is equal to the ratio of stator slot number to the phase number. Thus, the obtained results are in a good agreement with those observed in [15]. The MMF of the aforementioned machine and its spatial harmonic due to the PM are shown in Figure 4. Obviously, the primary harmonic is equal to half of the stator slot number (6/2=3). The air gap permeance and corresponding harmonic accounting for the mover pole are depicted in Figure 5. It can be clearly seen that, the main harmonic component is equal to the number of the mover pole (5^{th}).Flux density in the lower air gap, i.e. between the mover and stator one, which has the PMs, can be obtained by multiplying the magnet MMF and the air gap permeance considering the mover pole, Figure 6.

On the other hand, the open circuit flux density in the upper air gap located between the mover and stator two is equal to the product of the PM (MMF) and the air gap permeance accounting for both the mover pole and the upper stator teeth, Figure 7. By comparing Figure 4 and Figire 8, it can be clearly seen that only the 2nd and 8th harmonic orders have the same direction and frequency. Hence, they interact to produce non zero average thrust force. It can be concluded that like SFPM machines, the force in a PS-FRPM linear machine is generated by many field harmonics (2^{nd}, 3^{th} and 8^{th}) [15] [16].

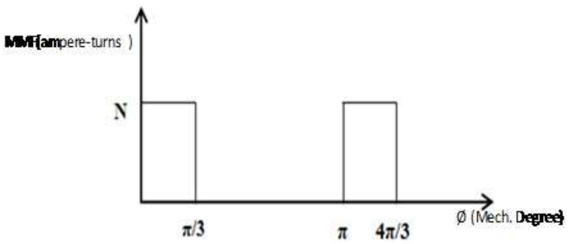


Figure 2:MMF of phase A for the 6/5 PS-FRPM linear machine.

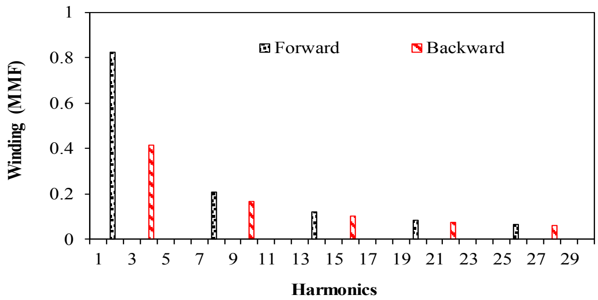
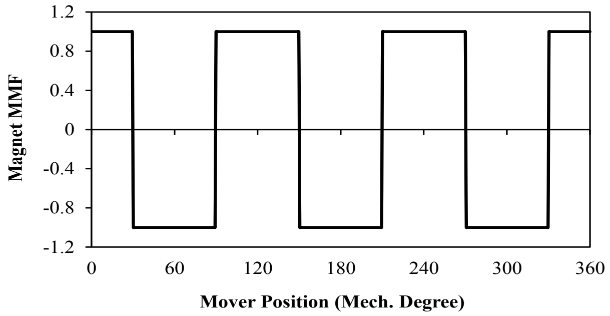
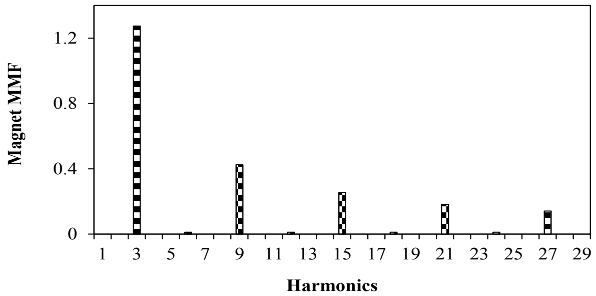


Figure 3: Spatial harmonic of the stator winding MMF for 6/5 PS-FRPM linear machine.

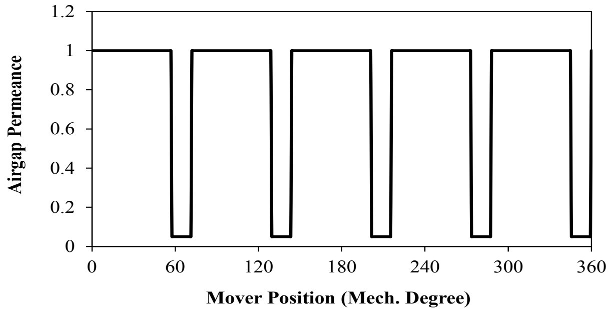


(a) Waveform

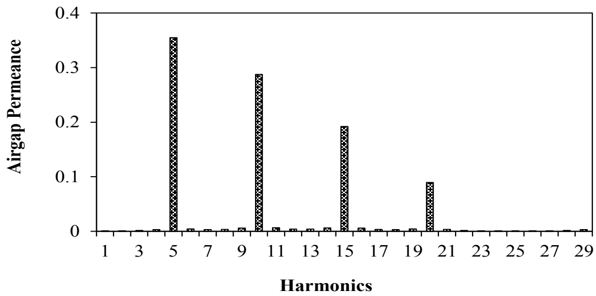


(b) Spectrum

Figure 4: Magnet MMF for 6/5 PS-FRPM linear machine.

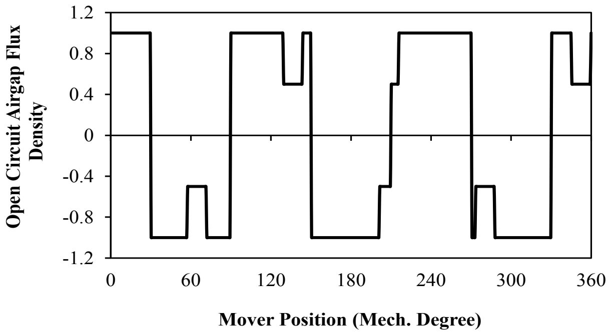


(a) Waveform

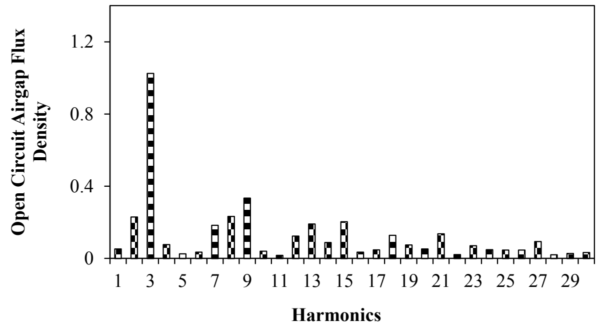


(b) Spectrum

Figure 5: Airgap permeance accounting the mover pole for 6/5 PS-FRPM linear machine.

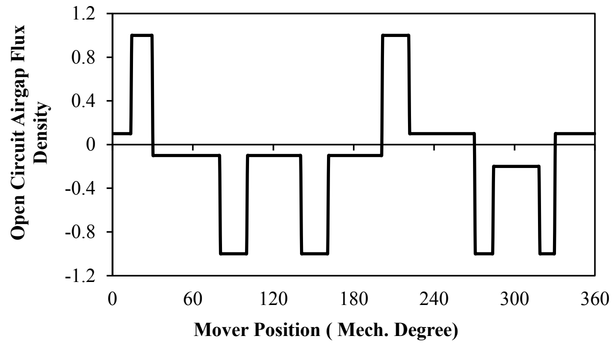


(a) Waveform

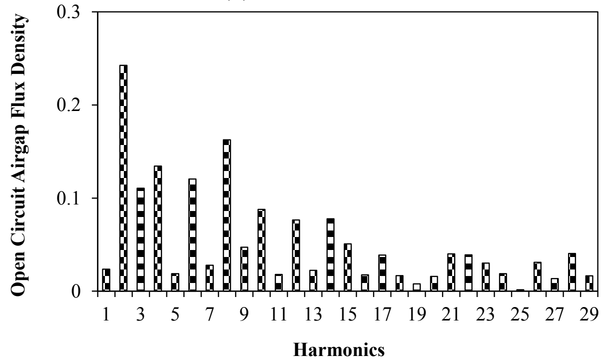


(b) Spectrum

Figure 6: Open circuit lower air gap flux density for 6/5 PS-FRPM linear machine.



(a) Waveform

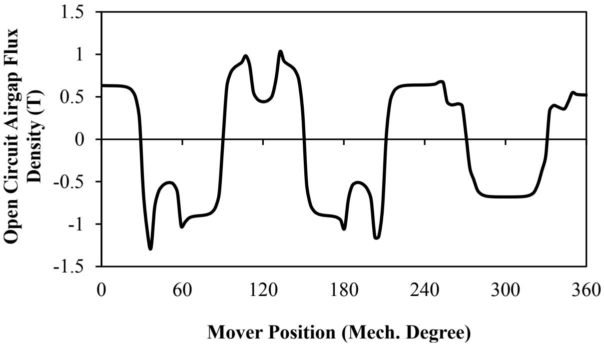


(b) Spectrum

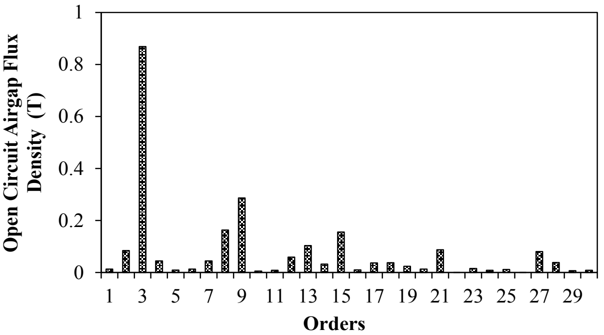
Figure 7: Open circuit upper air gap flux density for 6/5 PS-FRPM linear machine.

3. Finite Element Analysis Results

The open circuit flux densities and corresponding harmonics for both the lower and the upper air gaps, obtained from FEA simulation, are illustrated in Figure 8 and Figure 9, respectively. It should be mentioned that the purpose of the simple analytical model is to determine the harmonic orders that contribute to force production in the PS-FRPM but not to precisely calculate air gap flux density. Therefore, differences in shape between the predictable and the simulated air gap can be clearly seen. However, the FFT results for open-circuit airgap flux density harmonics in both air gaps are in a good agreement, which is the main objective of this analysis.

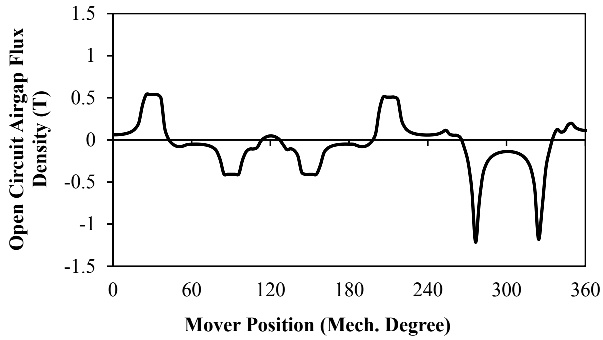


(a) Waveform



(b) Spectrum

Figure 8: FEA calculated lower air gap flux density.



(a) Waveform

(b) Spectrum

Figure 9: FEA calculated upper air gap flux density.

4. Conclusions

The principle of force production in 6/5 stator/mover pole number PS-FRPM linear machine has been analysed in this paper. In order to understand how the force is produced in the mentioned machine, spatial harmonic analysis has been utilized. It is shown that the interaction of the stator MMF (the fundamental and its non-triple multiples harmonic orders) with the air gap flux density results in production the electromagnetic force of the PS-FRPM linear machine. It should be noted that air gap flux density equals to the product of the PM (MMF) and the air gap permeance considering for both the mover pole and the upper stator teeth. Moreover, the fundamental harmonic of the stator MMF of the mentioned machine is equal to the ratio of the stator pole number to phase number. The analytical results match with the FEA results.

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