Influence of Split Teeth on the Performance of Linear Permanent Magnet Vernier Motor

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***Abstract*—In recent years, permanent magnet Vernier motors are popular research objects in electrical machine field. Linear permanent magnet Vernier motor (LPMVM) is a new type of special motor. It works according to the magnetic field modulation mechanism, which can use its own vernier effect to generate greater thrust at low speed. Based on its working principle, three motors are built up and compared in this paper by finite element analysis, while they have different split tooth structures, viz. a non-split-tooth topology, a two-split-teeth one, and a three-split-teeth one. The electromagnetic performances under no-load and on-load conditions are analyzed, focusing on the influence of different structures on thrust and power factor. Finally, it is concluded that the thrust ripple of the motor is weakened by the use of split-teeth, but at the same time, the average thrust of the motor is also reduced. Moreover, the increase of the number of split teeth will reduce the power factor of the motor.**

Keywords—permanent magnet, power factor, split-teeth, thrust, Vernier motor

I. INTRODUCTION

Permanent magnet Vernier machine (PMVM) has become one of the research hotspots over the last decade. Its structure is similar to conventional permanent magnet (PM) motors, but the working principle is different. In PMVM, the modulation poles are combined with the stator teeth. Through the modulation effect, the harmonic components of the armature magnetic field can be obtained, which can match and interact with the high pole pair number PM field. Without increasing the size of the motor or changing the number of slots, the goal of low speed and high torque density can be easily achieved. This kind of motor has good torque performance, simple structure, and small size [1]. In terms of the linear type, viz. linear PMVM (LPMVM), it has advantages in the fields of rail transit, cordless elevators, computer numerical control machine tools, etc. The main research directions of LPMVM are as follows:

(1) Proposing a new motor topology or a modular design of the motor to improve the power factor.

(2) Exploring suitable winding structure and slot/pole combination to suppress unwanted harmonics.

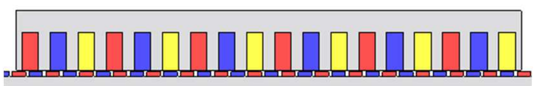
(3) Improving the existing control methods or apply new control strategies in order to achieve accurate control.

In [2] a back-electromotive force (back-EMF) equation for a Vernier motor is proposed, which was analytically derived using a classical magnetic permeance function. By using the equation, the errors between theoretical and experimental results can be narrowed. An 18-slot/26-pole PM Vernier synchronous motor with a coil pitch of two slots is proposed in [3]. By increasing the number of slots and adjusting the connection of the phase winding, the harmonics caused by the armature reaction are reduced without affecting the fundamental harmonic, and the power factor is improved as well, resulting in better force and flux weakening performance. The fractional slot concentrated winding (FSCW) PMVM with regular open-slot stator is quantitatively studied in [4]. It has been confirmed that PMVMs with two slot pitch windings have a higher power factor and lower end turns. It is demonstrated in [5] that double-sided (DS) PM motors have better torque capability than single-sided (SS) ones. However, research has also shown that not all DS motors with different rotor pole pairs have higher output torque capabilities than their corresponding SS motors. So, it is necessary to choose a reasonable slot/pole combination when designing DS motor topology. In [6], a method to find the optimal pole/slot combination for PMVMs with FSCW configuration is proposed, and its feasibility under various conditions is also verified. A PMVM with Halbach array magnets in stator slot opening is proposed in [7]. Half of the PMs on the rotor are transferred to the stator slot and changed to a Halbach array combination. Research has shown that the torque of the motor using this structure is half greater and its power factor is also improved.

The paper is organized as follows: Section II introduces the structures of three prototypes of LPMVMs, including one non-split tooth motor and two split-teeth motors. Section III focuses on the performances of the motors at no-load, rated load, and overload times, especially the changes in forces and power factors. Section IV summarizes the paper.

II. MOTOR TOPOLOGY

Three types of motors with different structures are built up, viz. a non-split-tooth topology, a two-split-teeth one, and a three-split-teeth one, as shown in Fig. 1. No matter the primary side adopts the non-split-tooth structure or split-teeth structure, the teeth play the role of magnetic field modulation. Besides, the secondary side adopts surface-mounted PMs. And the main motor parameters are shown in Table I.



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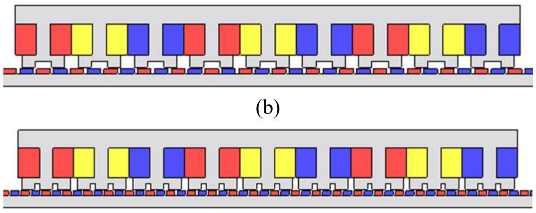


Fig. 1. Motor model. (a) motor A, $p_w/p_{PM}/Z_p$:3/15/18, (b) motor B, $p_w/p_{PM}/Z_p$:3/15/18, (c) motor C, $p_w/p_{PM}/Z_p$:3/24/27.

TABLE I. MOTOR PARAMETERS

Motor	A	B	C
$p_w/p_{PM}/Z_p$	3/15/18	3/15/18	3/24/27
Stack length (mm)	120		
Primary length (mm)	306		
Primary height (mm)	36		
Primary yoke height (mm)	13	11	11
Number of large teeth	18	9	9
Width of large teeth (mm)	7	8.4	8.4
Split-teeth height (mm)	/	7	7
Split-slot depth (mm)	/	3.5	3.5
Split-teeth width (mm)	/	8	8
Distance between split-teeth (mm)	/	10	3
Air-gap length (mm)	1		
Secondary length (mm)	504		
Secondary height (mm)	7		
Pole pitch (mm)	10.2	10.2	6.4
Pole-arc to pole pitch factor	0.8		
PM height (mm)	3		

In Fig. 1, p_{PM} is the pole pair number of PM, Z_p is the number of teeth on the primary side of the motor, and p_w is the pole pair number of armature winding, respectively. The number of poles and slots of the motor is determined according to the following formula [2]

$$p_{PM} = |Z_p \pm p_w| \tag{1}$$

It also points out that the addition and subtraction sign of (1) affects the magnitude of the back-EMF of the motor. To maximize the torque, the subtraction sign is usually taken. Therefore, the pole/slot combination of each motor complies with the subtraction form of (1).

To ensure the fairness in comparison, the three motors have the same primary lengths and secondary effective lengths. And the slot areas, slot filling factors, and number of turns in series per phase of three types of motors are also the same. In the following analysis, each motor has been already optimized.

III. MOTOR PERFORMANCE

A. No-load condition

When each motor are operated under no-load conditions at its own synchronous speed (v_s), viz.

$$v_s = 2\tau f \tag{2}$$

where τ is the PM pole pith and f is the power supply frequency (50Hz in this paper for all motors).

The back-EMFs of phase A are selected for observation, as shown in Fig. 2.

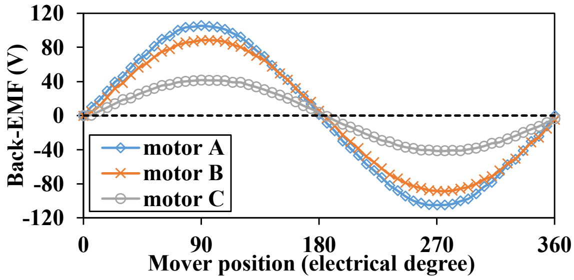


Fig. 2. Phase back-EMF of three motors under no-load condition at synchronous speeds.

Fig.2 shows that under the no-load condition, the motor without split teeth owns the maximum back-EMF. While the back-EMF of the motor with three split teeth is significantly lower than the other two motors. The difference of three LPMVMs in terms of back-EMF is owing to tooth-tip leakage, As shown in Fig. 3.

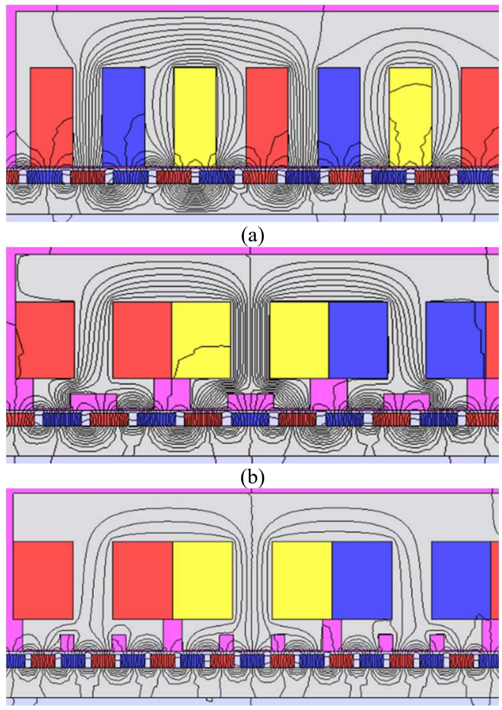


Fig. 3. Open circuit flux distribution for motors with phase A having the maximum back-EMF. (a) motor A, (b) motor B, (c) motor C.

Fig. 3 shows that for the motor with split teeth, the magnetic field lines passing through the yoke are greatly reduced when phase A has the maximal back-EMF. The major flux loops occur at tooth-tips, which cannot contribute to the main flux linkage. The magnetic flux leakage is exacerbated by split-teeth structure, especially the three-split-teeth structure, thus its main flux leakage is much smaller than that of the other two types of motors. The specific flux leakage will be explained in the next part.

For LPMVMs, there are force ripples under no-load condition due to PMs, as shown in Fig. 4.

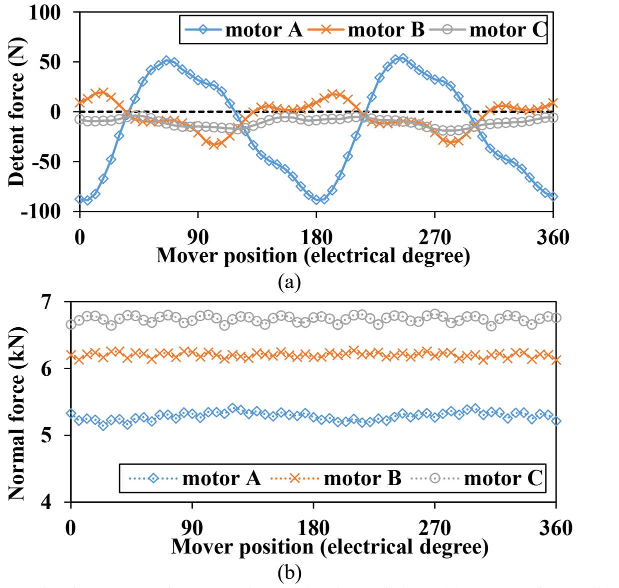
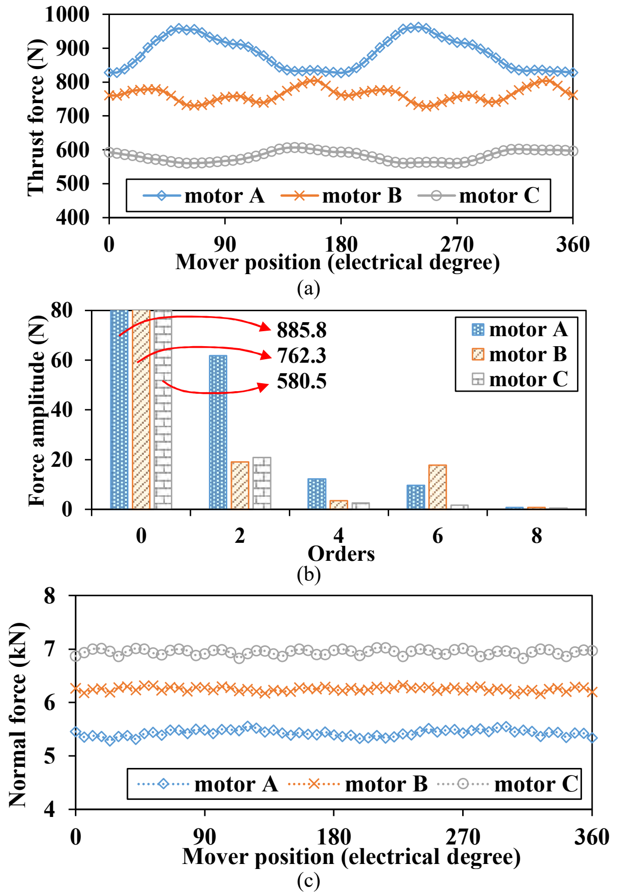


Fig. 4. The force waveforms under no-load condition. (a) Detent force. (b) Normal force.

Fig. 4(a) shows that the DF ripple is decreased when the split teeth structure is used and the more teeth are used, the lower ripple is obtained. The existence of PMs will lead to attractive normal force even if there is no current, as shown in Fig. 4(b). More split-teeth contribute to a larger value as well.

B. On-load condition

The same rated current is applied to the three motors running at synchronous speeds and the force performance are shown in Fig. 5.



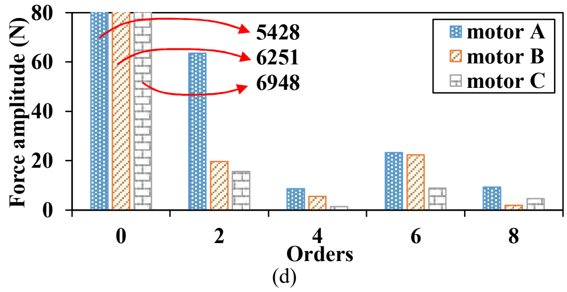


Fig. 5. The thrust force performance under on-load condition. (a) Waveforms of thrust force. (b) Harmonics of thrust force. (c) Waveforms of normal force. (d) Harmonics of normal force.

Fig. 5(a) shows that the non-split-tooth motor has the maximum force but also has the maximum force ripple rate. When split teeth are used, the increase of leakage flux as well as the reduction of main magnetic flux, as shown in Fig. 3, results in such phenomenon. Fig. 5(b) demonstrates that the force harmonics can be weakened by using split teeth in LPMVMs, especially the 2nd harmonic force. Thus, the thrust force is smoother for motors with more split-teeth. In terms of normal force, it can be seen from Fig. 5(c) that the waveforms are practically the same for both no-load and on-load situations. There is only a slight increase for the average value. Moreover, the adoption of split-tooth structure benefits to the force ripple reduction.

When the current increases, the average thrust force of these motors will change accordingly, as shown in Fig. 6.

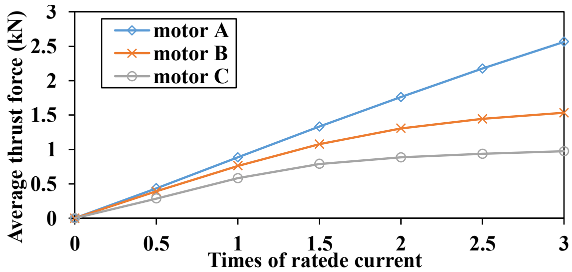


Fig. 6. Average thrust force-current characteristic.

As the current increases, the average thrust force difference between the motors with and without split-teeth quickly widens. The motor with a split-teeth structure is more likely to reach saturation, which limits its output thrust force.

C. Power factor

The power factor of LPMVMs with different split tooth structure is especially concerned. The power factor of three motors is low, which is the obvious disadvantage. Compared with the traditional PM motor, LPMVM owns more poles, which causes more leakage flux of the magnets. Meanwhile, the end effect of linear motor also contributes to a part of magnetic leakage. It is found that the power factor of LPMVM with split teeth is much lower because it has more teeth, which leads to more leakage inductance and lower power factor.

The way to quantify the magnetic flux leakage is shown in Fig. 7, where the no-load flux distribution with maximal phase A back-EMF time instant is adopted.

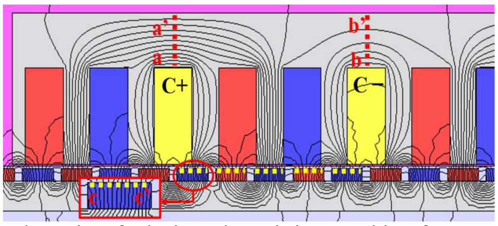


Fig. 7. Schematic of obtaing chatactistic quantities for power factor assessment.

The number of magnets under one coil pitch (N_{pmc}) is determined:

$$N_{pmc} = p_{PM}/p_w \quad (3)$$

For the prototype machine without split-teeth, there are five magnets under one coil pitch. The total flux linkage φ_{PM} generated by PMs can be obtained by adding the flux linkage extracted from the surface of these magnets (yellow dashed line in Fig. 7). The component φ_{EMF} that contributes to the back-EMF is extracted from the yoke (red dashed line in Fig. 7). The difference between these two is the total amount of magnetic flux leakage φ_{PM_lkg}. The magnetic flux utilization ratio which is used to evaluate PM leakage is defined by

$$\eta = \varphi_{EMF}/\varphi_{PM} \quad (4)$$

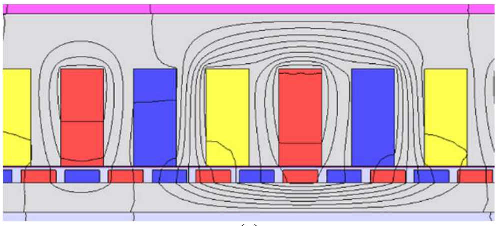
The results are shown in Table II.

TABLE II. POWER FACTORS AND MAGNETIC FLUX LINKAGE

Motor	A	B	C
Power factor	0.83	0.77	0.42
φ_{EMF} (mWb)	1.15	0.99	0.60
φ_{PM} (mWb)	4.31	4.48	4.81
φ_{PM_lkg} (mWb)	3.16	3.49	4.21
η	26.6%	22.2%	12.4%

Among the three motors, the PM flux linkage of the one without split teeth is the least, but it has the highest utilization ratio η and therefore the highest power factor. For the three-split teeth motor, there is a significant drop in the magnetic flux utilization ratio, as a large amount of magnetic leakage flux is generated in the tooth-tips. The magnetic flux leakage is mainly consisted of inter-pole flux leakage and tooth-tip flux leakage. It has been proven in [8] that the proportion of inter-pole flux leakage in magnetic leakage flux is small, and the inter-pole flux leakage is almost nonexistent when the pole/slot combination is low. The same applies to the motor in this paper, where the inter-pole flux leakage is small while the tooth-tip flux leakage is the main magnetic flux leakage.

When it comes to armature flux, it is necessary to consider stator slot leakage flux. Fig. 8 shows the distribution of armature magnetic flux linkage when only armature current is applied, at which point the A-phase current reaches its maximum value. It can be found that the slot flux leakage is almost negligible.



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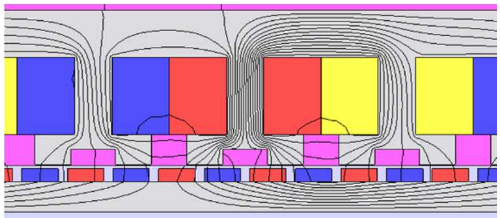

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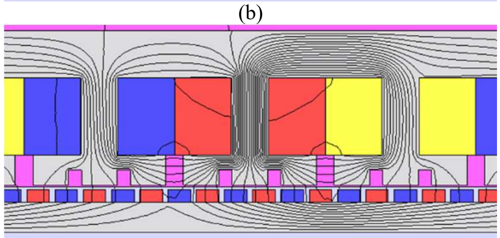

(c)

Fig. 8. Armature flux distribution for motors with phase A having the maximum current (without magnet excitation). (a) motor A, (b) motor B, (c) motor C.

In summary, when split teeth are applied to LPMVM, it will lead to a significant increase in magnetic flux leakage at the tooth-tips, thereby greatly reducing the power factor of the motor. The power factor of the motor also varies with the current, as shown in Fig. 9.

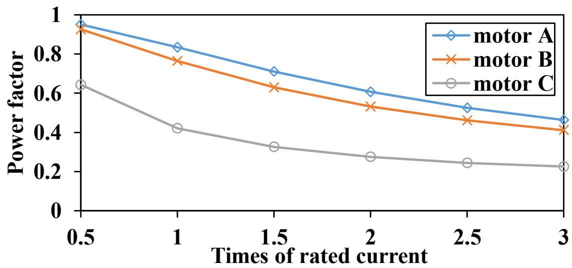

Fig. 9. Power factor-current charactiristic.

Fig. 9 shows that the power factor of the motor decreases as the current times increase. Considering that the power factor (PF) is related to ratio of armature flux linkage ψ_a to magnetic flux linkage ψ_{PM} as follows

$$\mathrm{PF} = \frac{1}{\sqrt{1 + (\psi_a/\psi_{PM})^2}} \quad (5)$$

The armature flux linkage increases with the increase of current, while the magnetic flux linkage remains unchanged, resulting in a continuous decrease in the power factor.

IV. CONCLUSION

In this paper, the characteristics of the LPMVM such as high thrust and low power factor can be seen. The influence of split tooth structure and the number of split teeth on the performance of LPMVM under similar conditions is analyzed and compared. It is concluded that the use of split teeth can weaken force ripple while sacrifice average force. The split tooth structure will reduce the power factor of the motor, and the increase of the number of split teeth will further reduce the power factor of the motor.

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