A Novel Doubly-Fed Flux Reversal Linear Machine With Armature Windings Wound on Both Stator and Mover Teeth

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ABSTRACT A novel doubly-fed flux reversal linear machine (DF-FRLM) is proposed in this paper, which has two sets of armature windings wound on stator and mover teeth, respectively. The proposed DF-FRLM can exhibit significantly higher thrust force than the conventional FRLM by fully utilizing the stator slot space. The configuration and operation principle of a 6/5 mover/stator-pole DF-FRLM are described. In order to obtain maximum thrust force, the major design parameters of both conventional FRLM and proposed DF-FRLM are optimized by 2D finite element (FE) method. The optimized DF-FRLM and FRLM are investigated and compared in terms of the electromagnetic performance. It is found that the average thrust force of the optimized DF-FRLM is 1.23 times that of the optimized FRLM. In addition, the optimized DF-FRLM can achieve 34.4% higher average thrust force compared to the conventional FRLM whose geometry parameters are the same as that of the optimized DF-FRLM. Furthermore, a periodic model of the DF-FRLM is used to analyze the influence of the longitudinal end effect on the machine electromagnetic performance. Finally, experimentation is carried out to verify the 2D FE simulation result.

INDEX TERMS End effect, flux reversal, linear machine, thrust force.

I. INTRODUCTION

Permanent magnet linear machines (PMLMs) have been widely used in various applications including industrial robots, domestic appliances, long distance transportation systems due to their high power density, high thrust force density, better precision, less maintenance, etc. [1]–[6]. As a new class of PMLMs, evolved from the stator-PM machines [7]–[10], linear primary-PM machines have attracted increasing attention, whose armature windings and PMs are located in the primary part (either mover or stator), and the secondary part is made of iron [11], [12].

Flux reversal linear machines (FRLMs) are one type of linear primary-PM machines, which were proposed and developed in [13]–[18]. The conventional FRLMs are doubly-salient structures, where two PMs with opposite polarities are mounted on each mover tooth surface and the polarities of two adjacent PMs of two adjacent mover teeth are the same or different. Although FRLMs inherit advantages of high efficiency as well as simple maintenance, and have been increasingly used in many applications such as petroleum exploitation, punching machine and logistics transportation [19], they still exhibit much pole flux leakage, which leads to the limitation of the thrust force. Much attention has been paid to improving the thrust force of FRLMs. The conventional FRLM was modified in [14], where middle salient tooth is introduced between two adjacent PMs and the polarities of PMs are identical. Thus, the width of mover teeth increases and the number of mover teeth is halved. The number of PMs is halved as well. The analysis shows that compared to the conventional FRLM, the proposed machine reduces flux leakage. As a result, the thrust density is improved even though the PM usage is halved. In addition, a consequent-pole FRLM was proposed in [15]. Three models with different PM arrangements and winding connections were compared in such paper. It was concluded that although the amount of PMs is halved, the consequent-pole FRLM can also enhance the thrust force compared to the conventional
FRLMs because of the reduction of the pole flux leakage. To further reduce the PM consumption and achieve higher thrust force, a novel consequent-pole FRLM with large mover slot opening was designed in [16]. In [17], a double-sided FRLM was introduced. The PMs are located at two sides of the mover and inserted into the middle of the mover teeth. Moreover, the PMs at the same side of the mover have the same polarity while the PMs at different sides of the mover have opposite polarity. Compared to the conventional single-sided FRLM, the double-sided FRLM can achieve higher thrust force density thanks to the reduction of the pole flux leakage.

The FRLMs mentioned above have both excitation sources in the primary side, which may lead to the limitation of electric and magnetic loadings. Therefore, a partitioned stator structure was proposed in [18], in which PMs and armature windings are separately placed in two stators. Thus, the proposed machine has bigger slot area and higher electric loading than the conventional FRLM, which contributes to the improvement of the thrust force. However, the manufacturing difficulties arise because of the relatively complexity of the proposed structure.

In this paper, in order to further improve the thrust force without increasing the difficulties of machine manufacturing significantly, another set of armature windings wound on stator teeth can be introduced to the existent structures of FRLMs. Based on the conventional FRLM structure, a novel doubly-fed (DF) FRLM (DF-FRLM) with two sets of armature windings wound on both stator and mover teeth is proposed. This paper is organized as follows. In section II, the configuration and operation principle of the novel DF-FRLM are introduced and compared with those of the conventional FRLM. In section III, the electromagnetic performances of the optimized conventional FRLM and DF-FRLM are analyzed and compared by the 2D finite element (FE) method. Section IV analyses the influence of the longitudinal end effect in the DF-FRLM. Finally, a prototype of DF-FRLM is manufactured and tested to verify the 2D FE simulation result.

II. MACHINE TOPOLOGY AND OPERATION PRINCIPLE
A. MACHINE CONFIGURATION
Fig. 1 (a) shows the topology of the conventional FRLM, in which the stator is three times the length of the mover. On this basis, another set of armature winding is placed in the stator slots and thus the proposed 6/5-pole DF-FRLM is obtained, which is shown in Fig. 1 (b). The DF-FRLM is fed with stator and mover armature current separately, which resembles the doubly-fed machine.

B. OPERATION PRINCIPLE
Removing the stator armature winding from the DF-FRLM, the residue part is similar to the conventional FRLM. Therefore, the operation principle of the mover armature winding is the same as that of the conventional FRLM. The open circuit flux distribution with different mover position are shown in Fig. 2.

As shown in Fig. 2 (b) and (d), positive maximum and negative maximum mover phase flux linkage are achieved when a stator tooth wound by the corresponding stator coil is aligned with a mover slot, while the phase flux linkage of stator armature winding is zero when the mover tooth is aligned with the stator tooth.
As the mover moves, the stator phase flux linkage varies, as presented in Fig. 5.

It should be noted that the fundamental frequency of stator flux linkage depends on mover slot number, while the mover flux linkage frequency is up to the stator pole number. Hence, the fundamental frequency of stator and mover flux linkage can be expressed as

\[ f_s = \frac{v}{\tau_{mpp}} \]  

(1)

\[ \tau_{mpp} = \frac{L}{(N_m/2)} \]  

(2)

and

\[ f_m = \frac{v}{\tau_{spp}} \]  

(3)

\[ \tau_{spp} = \frac{L}{N_s} \]  

(4)

where \( N_s \) denotes the number of stator poles, \( N_m \) is the number of mover slots, \( v \) is the linear speed and \( L \) is mover length.

The proper winding arrangements for both stator and mover armature windings are obtained by phasor diagram.
The electrical degree difference between two adjacent stator slots $\alpha_{es}$ can be given as
\begin{equation}
\alpha_{es} = \frac{N_m}{2} \frac{2\pi}{N_s}
\end{equation}
and the electrical degree difference between two adjacent mover slots $\alpha_{em}$ can be expressed by
\begin{equation}
\alpha_{em} = \frac{N_s}{N_m} \frac{2\pi}{2}
\end{equation}

Fig. 6 shows the back-EMF phasors of 3-phase mover armature windings and 5-phase stator armature windings. It should be noted that when the mover moves from left to right, the back-EMF of a stator coil leads its right adjacent coil by $\alpha_{es}$. However, for the mover armature windings, the stator moves from right to left and thus the back-EMF of a mover coil delays its right adjacent coil by $\alpha_{em}$.

### III. ELECTROMAGNETIC PERFORMANCE COMPARISON

By fixing the total machine height, the axial length in the z-direction, and the mover length, the conventional FRLM and the proposed DF-FRLM are both optimized to get maximum thrust force by FE method. During the optimization, the total armature winding copper loss of the mover and the stator is fixed at 40W in DF-FRLM, while the mover armature winding copper loss is fixed at 40W in FRLM. Their optimized parameter values are listed in TABLE 1. Besides, a FRLM having only mover armature windings whose geometry parameters are the same as that of the optimized DF-FRLM is also analyzed under the fixed 40W copper loss by FE method in this section, which is named as FRLM counterpart in this paper. The three machines are compared and investigated in terms of the electromagnetic performance in this section.

#### A. OPEN-CIRCUIT BACK-EMF

The phase back-EMFs of the stator and mover armature windings in DF-FRLM are shown in Fig. 7. The DF-FRLM exhibits sinusoidal mover phase back-EMF and the harmonics are relatively small. The 5th and the 7th mover back-EMF harmonics bring about the 6th thrust force ripple. The 3rd harmonic does not lead to thrust force ripple in the 3-phase mover armature windings. The stator phase back-EMF has large 3rd and 7th harmonics, but they do not generate thrust force ripple for the 5-phase stator armature windings.

#### B. COGGENG FORCE

The cogging forces of the optimized DF-FRLM and FRLM are shown in Fig. 8. Similar to the rotary machines, the PM linear machines have the open-circuit force, which is named as cogging force. In PM linear machines, not only the slot

| Parameter         | DF-FRLM | FRLM  |
|-------------------|---------|-------|
| Stator pole number | 5       | 5     |
| Mover slot number  | 6       | 6     |
| Number of stator phases | 5      | 0     |
| Number of mover phases | 3      | 3     |
| Stack length      | 50mm    | 50mm  |
| Stator pole pitch, $r_{st}$ | 38.4nm | 38.4nm |
| Mover pole pitch, $r_{mv}$ | 64nm   | 64nm  |
| Split ratio       | 0.42    | 0.28  |
| Stator tooth width, $w_{st}$ | 13mm   | 13mm  |
| Mover tooth width, $w_{mv}$ | 9mm    | 9mm   |
| Mechanical airgap, $g$ | 1mm    | 1mm   |
| PM width, $w_{pm}$ | 15mm   | 14mm  |
| PM thickness, $h_m$ | 3mm    | 2.5mm |
| Machine total height | 50mm   | 50mm  |
| Rated speed, $\nu$ | 0.96mps| 0.96mps |
effect but also the longitudinal end effect can lead to the cogging force. Therefore, they show different cogging force from the rotary machines [18]. The DF-FRLM and FRLM are essentially identical under the open-circuit condition. However, due to the different optimal geometry parameters, their cogging forces are different.

C. THRUST FORCE CAPABILITY

The thrust force waveforms of the optimized DF-FRLM and FRLM counterpart are shown in Fig. 9.

Apparently, the average thrust force of DF-FRLM is improved by about 34.4% compared to FRLM counterpart. Moreover, it is found that the mover thrust force waveform is higher than the stator thrust force. The average thrust force of stator is 65.7N. The average value of the mover thrust force is 1.2 times as big as that of the stator, which can reach 74.9% of FRLM counterpart. In other words, the DF-FRLM can produce at least 65.7N thrust force, in case one set of armature winding fails.

Fig. 10 shows that the average thrust force of the optimized DF-FRLM is about 1.23 times that of the optimized FRLM.

The thrust force characteristics of the three machines are concluded in TABLE 2. It shows that the optimized DF-FRLM exhibits the highest average thrust force, the highest efficiency and the lowest thrust force ripple.

IV. INVESTIGATION OF LONGITUDINAL END EFFECT IN DF-FRLM

A periodic model of the DF-FRLM with its optimized geometry parameters is designed, which is infinity long. Thus, longitudinal end effect does not exist. The periodic model of the DF-FRLM is shown in Fig. 11.

The electromagnetic performance of the practical and periodic model is investigated and compared by using the FE method.

The flux linkage and back EMF waveforms and their corresponding spectra for mover and stator windings are shown in Fig. 12 and Fig. 13, respectively. As can be seen, the periodic machine has symmetrical and balanced flux linkages and back-EMFs for stator and mover windings. By contrast, due to the longitudinal end effect, the flux linkages and back-EMFs of stator and mover windings are asymmetric and unbalanced in the practical machine.

Fig. 14 compares the cogging forces of the practical and the periodic models and the cogging force due to the longitudinal end effect. Apparently, the practical machine has higher peak–peak cogging force than the periodic one due to the longitudinal end effect. Moreover, it can be seen that the cogging force generated by the periodic model has the 6th harmonic order, which is similar to the corresponding rotary machine. It is only caused by slotting effect, rather than longitudinal
FIGURE 12. Open circuit flux linkage and back-EMFs of mover windings. (a) Flux linkage waveforms. (b) Flux linkage spectra. (c) Back-EMF waveforms. (d) Back-EMF spectra.

FIGURE 13. Open circuit flux linkage and back-EMFs of stator windings. (a) Flux linkage waveforms. (b) Flux linkage spectra. (c) Back-EMF waveforms. (d) Back-EMF spectra.
end effect. The cogging force of the practical model $F_{cog}$ is the sum of the periodic model cogging force $F_{slot}$ and the longitudinal end effect cogging force $F_{end\_effect}$ [18]. Thus, $F_{end\_effect}$ can be calculated by

$$F_{end\_effect} = F_{cog} - F_{slot} \quad (7)$$

As can be seen, the period of the cogging force component due to longitudinal end effect is the same as the electrical period, which is one stator pole pitch.

Fig. 15 illustrates the thrust force of the practical and periodic machines. Clearly, the periodic model shows higher thrust force while less thrust force ripple. Therefore, it can be seen that the thrust force ripple is mainly caused by the cogging force component due to longitudinal end effect.

V. EXPERIMENTAL VALIDATION
A. PROTOTYPE MACHINE
To further verify the correctness of the aforementioned 2D FE results, the optimized DF-FRLM is made, as shown in Fig. 16. “T”-shaped parts are added on the top of the primary and secondary steel sheets in order to fix the machine on the stainless steel frame.

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VI. CONCLUSION

A novel doubly-fed flux reversal permanent magnet linear machine is proposed in this paper, which has two sets of armature windings on stator and mover teeth, respectively. Main design parameters of DF-FRLM and conventional FRLM are optimized for maximum thrust force by 2D FE method. The electromagnetic performance of the optimized FRLM and DF-FRLM are investigated and compared. The results show that the average thrust force of the optimized DF-FRLM is about 1.23 times that of the optimized FRLM due to better utilization of the stator space. Moreover, the average thrust force of DF-FRLM has been improved by about 34.4%, compared to the FRLM whose parameters are the same as that of the optimized DF-FRLM. Finally, 2D FE simulation results are validated by experimental results.

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