Investigation of Permanent Magnet Linear Motor for Urban Mass Transit

Zhang Yujin, Zhang Ruihua, Du Yumei, Liu Yuhong & Jin Nengqiang
Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China
christina24a@126.com，*ruihuazh@mail.iee.ac.cn*，*ymdu@mail.iee.ac.cn*，*liuyh@mail.iee.ac.cn*，*jinnq@mail.iee.ac.cn*

ABSTRACT: In this paper, different structure types of permanent magnet linear motors are analyzed in detail, especially a new permanent magnet (PM) linear motor, in which both the magnets and armature windings are placed in the short mover, while the long stator consists of iron core only. Hence, this new PM linear motor can be called as primary permanent magnet linear motor, which exhibits the advantages of robust and simple mover, low cost, high efficiency, high power factor, and high thrust force density. Its topology structure and operation principle are introduced firstly. Then, the static characteristics are investigated, including back-EMF, phase inductance and thrust force. Finally, 2 methods are used to reduce the thrust ripple.

INTRODUCTION

Currently, the main types of traction motors used for urban rail transit can be classed by rotate motor and linear motor briefly. Obviously, direct linear drive motor has the benefits of higher dynamic performance, improved reliability, lower noise, and higher efficiency due to the avoidance of the energy conversion from rotary to linear motion. Linear induction motor (LIM) for the urban mass transit is short stator (primary), long rotator (secondary) arrangement. The primary including the iron core and windings is installed on the vehicle. The passive secondary is installed between the two rails on the guide way. The secondary is consisted of an induction board backed by a back iron. The linear induction motor is well used in urban mass transit such as low-speed maglev system and Linear motor vehicle system (with LIM propulsion and without magnetic levitation).

There is inevitably defect such as the low efficiency and power factor due to large air-gap of the LIM, permanent magnet linear motor has received wide attentions due to its merits of higher efficiency and power factor than those of the linear induction motor.

In this paper, different structure types of permanent magnet linear motors are analyzed in detail, especially a new permanent magnet (PM) linear motor for the urban mass transit , in which both the magnets and armature windings are placed in the short mover, while the long stator consists of iron core only. Its topology structure and operation principle are introduced firstly. Then, the static characteristics are investigated, including back-EMF, phase inductance and thrust force. Finally, finite element method (FEM) is used to verify the theoretical analysis results.

DIFFERENT STRUCTURE TYPES OF PERMANENT MAGNET LINEAR MOTORS

Currently, the main types of traction motors used for urban rail transit can be classed by rotate motor and linear motor briefly. Obviously, direct linear drive motor has the benefits of higher dynamic performance, improved reliability, lower noise, and higher efficiency due to the avoidance of the energy conversion from rotary to linear motion [1]. In this part, three different structure types of permanent magnet linear motors will be analyzed in detail.

Long Stator PM Linear Synchronous Motor

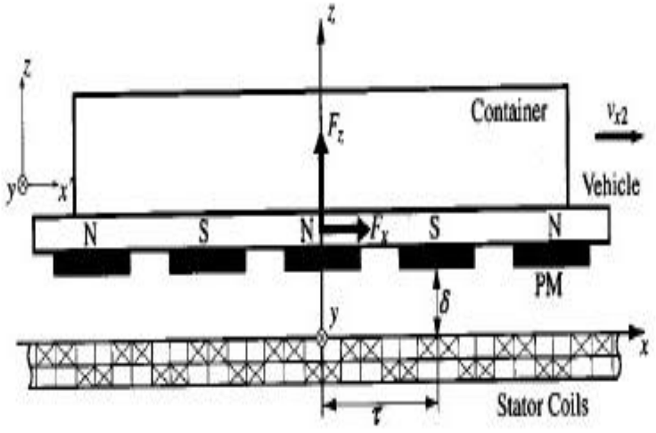
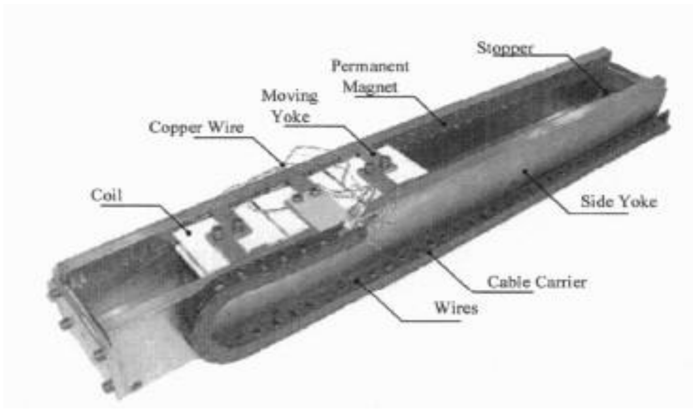


Figure 1. Principle structure

Figure 1 shows the longitudinal cross section of the long stator PM linear synchronous motor. The stator is set up horizontally on three-phase windings, and the translator consists of an array of PMs with alternative polarity fixed on a magnet yoke underneath. The stator coils are designed to be air-cored, so the motor operates in a repulsive mode.

In this type of the PM linear synchronous motor, a repulsive lift force F_z is produced simultaneously together with thrust force and, therefore, mass-reduced mode as well as Maglev mode are realized by controlling this repulsive force [2]. The purpose of using the lift force effectively for mass reduction is not only for reducing the friction loss and wear of the wheel and rail, but also for applying it to the transfer operation of heavier goods beyond the rated transport capability.

Double Side Interior Permanent Magnet Linear Synchronous Motor (DIPM-LSM)



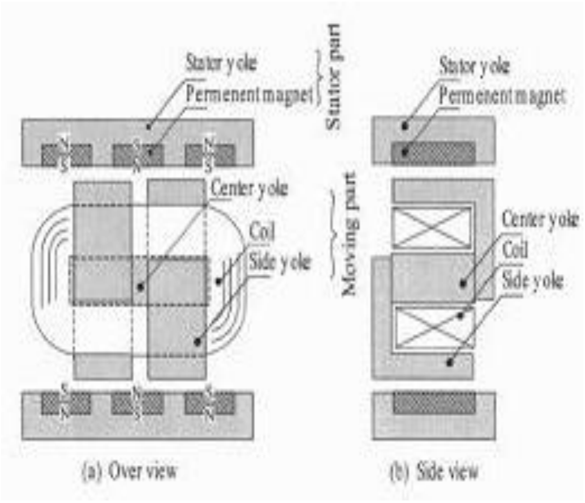
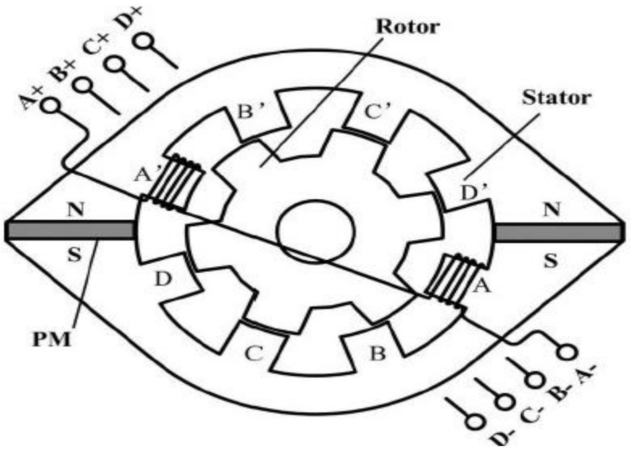


Figure 2. Basic structure of DIPM-LSM.

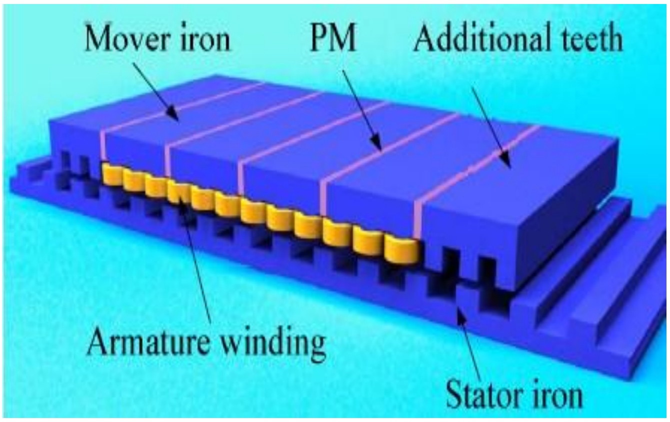
Figure 2 shows the basic structure of DIPM-LSM. This DIPM-LSM is designed in double sided of interior permanent magnet inside stator. The stator parts mainly composed of double side of stator yokes and permanent magnet. The permanent magnet was embedded inside the stator yoke. The moving parts are composed of moving coil and center yoke and side yoke. The side yoke is designed to be "L" shape to allow the flux flows from the center yoke to permanent magnet. The coil was wounded surrounding the center yoke [3]. This type of coil winding can give a large coil space which is expected to produce high electromotive force. There are three phase of coil have been set in moving parts where each coil represents one phase. The attractive and repel force was generated between permanent magnet and side yoke which force the moving part to move until reaching stabile position.

The New Primary Permanent Magnet Linear Motor

In recent years, based on the rotary motor(Figure 3a) [8], a new class of PM brushless motors with PMs in the stator, namely the doubly salient PM motor [9]-[10], has received wide attentions due to its merits of robust and simple mover, low cost, high efficiency and high thrust force density.



(a) Rotary motor



(b) Linear motor

Figure 3. The configuration of the double-salient PM motor

The new kind of motor is proposed as shown in Figure 3, in which both the PMs and the armature windings are set on short primary mover while the long secondary stator is only made of iron. Hence, this new PM linear motor can be called as primary permanent magnet linear motor. For the application of urban rail transit, the primary should be set at the steering device of the train and the iron stator be fixed between the two rails along the whole line. In order to balance the magnetic circuit of the end part for armature winding, the additional teeth are set at each end part of the primary mover. In addition, the concentrated armature windings are employed on the mover teeth except for the additional teeth.

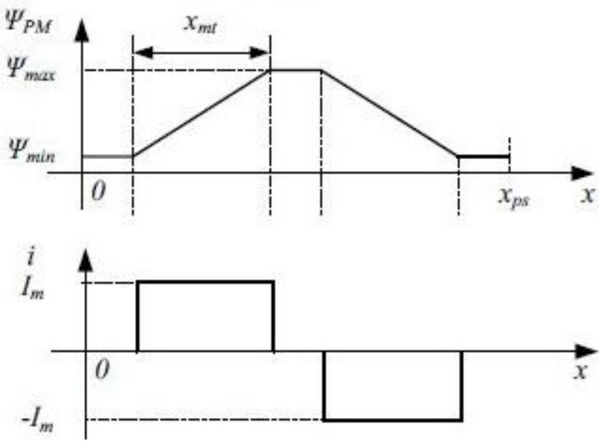


Figure 4. The operation principle of the double-salient PM motor

Assumption the end effect is negligible and the permeability of the core is infinite, a linear variation of PM flux linkage and thus a rectangular back-EMF are resulted in each mover windings at open load [4]. Hence, a theoretical constant thrust force can be achieved by applying a rectangular current in phase. The corresponding theoretical waveforms of PM flux Φ_m and phase current i are shown in Figure 4 Notice that the zero-current interval between the positive and negative currents is purposely provided to ensure successful current reversal.

STATIC PERFORMANCE

The electromagnetic performances of the primary PM magnet linear motor will be investigated in section [7].

Back-EMF

It is given by:

$$e = \frac{d\psi_m}{dt} = \frac{d\psi_m}{dx} \cdot \frac{dx}{dt} = \frac{d\psi_m}{x} \cdot v \qquad (1)$$

x is the mover part displacement, v is the mover speed, and ψ_m is the flux-linkage excited by PM only. Since the additional teeth balance the end part magnet circuit, the back-EMF waveforms are symmetrical.

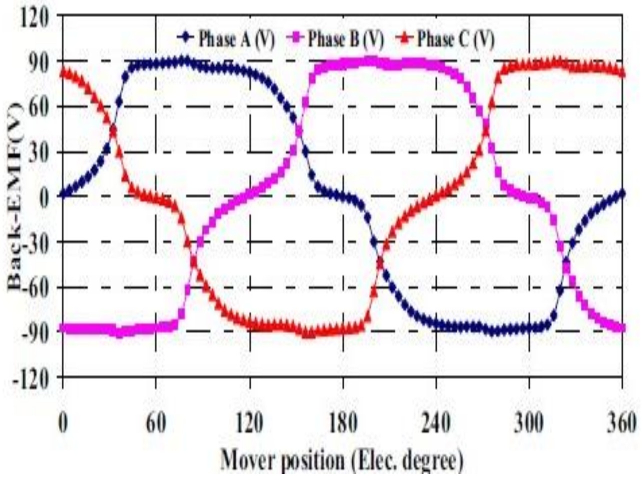


Figure 5. Back-EMF waveform

Inductance

It is given by:

$$L = \frac{\psi - \psi_{pm}}{i} \tag{2}$$

Where, ψ is the combined flux-linkage of phase-A produced by both PM and phase current. ψ_{pm} is the PM flux linkage provided by PM only, L is the inductance of one phase, i is the phase current. As is shown in Figure 6, Laa+4.69A and Laa-4.69A denote the strengthening and weakening action of the armature flux to the PM flux of the complementary structure, respectively.

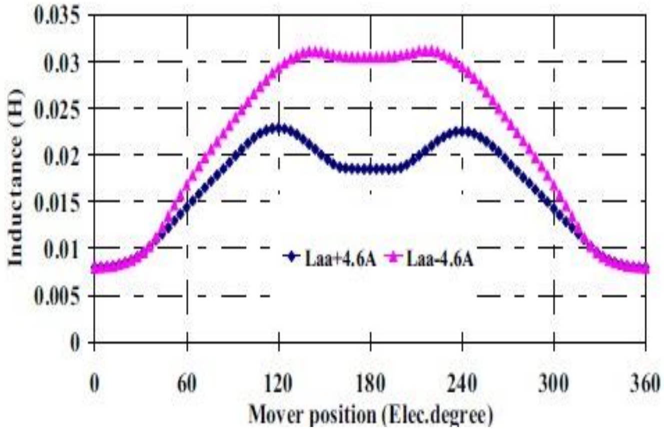


Figure 6. Inductance

Thrust Force

Figure 7 shows the rated static thrust force of the proposed motor. Apparently, the thrust force ripple is relatively high due to the doubly-salient structure.

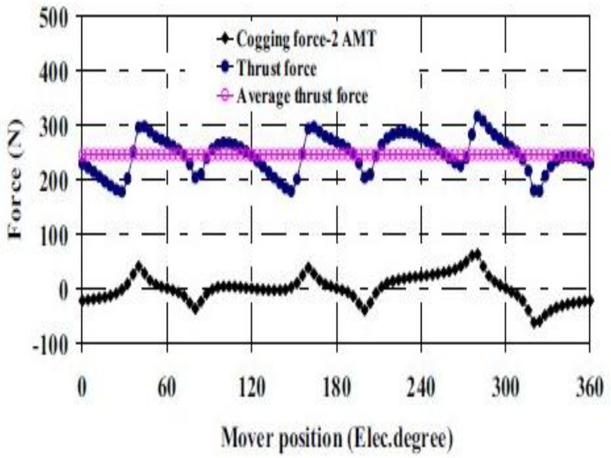


Figure 7. Rated static thrust force waveforms

METHODS TO REDUCE THE THRUST RIPPLE

From Figure 7 we can see that the thrust force ripple is relatively high due to the doubly-salient structure. Hence, two methods are proposed in to reduce the thrust ripple.

Stator Tooth Skewing

From Figure 3, it can be seen that the stator of the motor is simple, and there are no magnets or windings. Hence, in order to minimization the cogging torque, a skewing rotor teeth method was proposed in. As is shown in Figure 8, 2N is the segments number of the stator teeth along the teeth width axis, δ is the skewing displacement and k is temporary variable iteration [5]. Obviously, the skewed stator teeth method can improve the back-EMF waveform to be more sinusoidal and extremely reduce the cogging force.

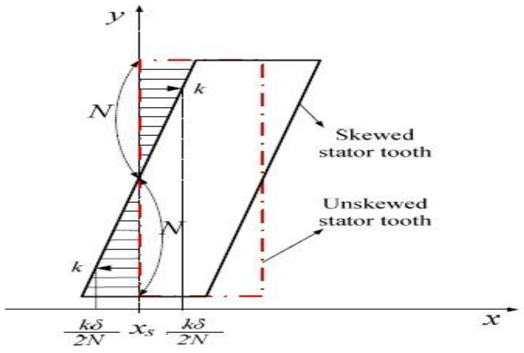
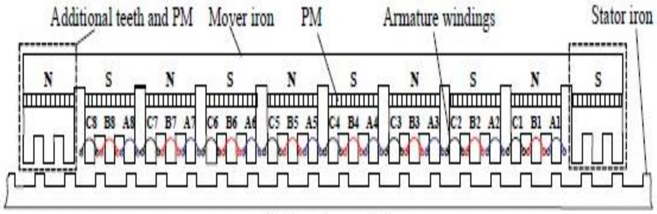


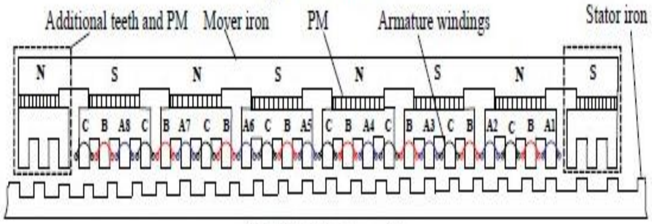
Figure 8. The stator teeth skewed model

Modified Model To Reduce The Thrust Ripple

In the case of linear structure as shown in Figure 9 (a), the motor suffers from high torque ripple. Hence, a modified model is proposed as shown in Figure 9 (b) [6].



(a) Basic model



(b) Modified model

Figure 9. Two proposed linear motor topologies

In order to achieve low force ripple, the phase number m, magnets number N_{PM} (including two additional magnets), mover pole number N_{mt} (not including the additional teeth), mover pole pitch τ_m, stator pole pitch τ_s should satisfy the below relationship:

(1) $N_{PM} = 2K \times m + 2$

(2) $N_{mt} = (N_{PM} - 2)(m + 1)$

(3) $\frac{\tau_m}{\tau_s} = \frac{m}{m \pm 0.5j}$

where j is an odd number and without common divisors with m. The proposed structure in Figure 9b adopts m=3, j=1, N_{mt}=24, N_{PM} =8, τ_m/τ_s=6/5. The basic model is shown in Figure 9a, where m=3, N_{mt} =24, N_{PM} =10, τ_m/τ_s=3/2. In order to reduce the end effect, three additional teeth and one piece of magnet are set at each end-part of the two motors.

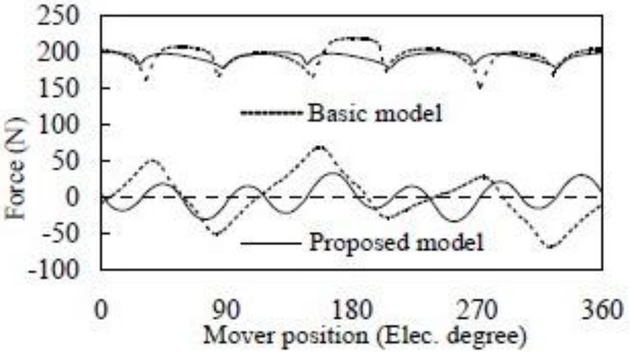


Figure 10. PM force and cogging force waveforms of two motors

Figure 10 shows the static thrust force excited by the traditional 120° conduction method and cogging force waveforms. Apparently, in the modified model, the cogging force and thrust ripple can be significantly reduced.

CONCLUSIONS

In this paper, 3 different structure types of permanent magnet linear motors are analyzed in detail, especially a new primary permanent magnet linear motor which incorporates the merits of doubly-salient PM motor and linear motor. It is suitable for the long stator applications, such as urban rail transit, resulting in reduction of system cost. Then, based on this structure, the electromagnetic characteristics are studied by FEM. Finally, the skewed stator teeth method and a modified model have been adopted in this motor to reduce the cogging force and thrust force ripple. The proposed motor offers a new scheme for the linear motor drive system of urban rail transit.

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