Electromagnetic Characteristics Analysis of Primary Permanent Magnet Linear Motors for Rail Transit (Postprint)

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Abstract

Linear induction motors employed in rail transit propulsion systems exhibit issues of low power factor and low efficiency. This paper proposes a novel primary permanent magnet linear motor featuring a short primary (mover side) and long secondary (stator side) configuration. The armature windings and permanent magnets are both mounted on the primary, while the secondary consists solely of a salient-pole reluctance structure. This type of motor not only retains the advantages of conventional linear induction motors, such as simple structure and non-adhesive direct drive, but also demonstrates superior performance in terms of power factor and efficiency. The paper first elaborates on the structural characteristics and operating mechanism of this motor, and derives its air-gap flux density equation and synchronous speed equation using the equivalent magnetic circuit method. Subsequently, a 12/8-pole primary permanent magnet linear motor is designed. With the assistance of finite element software, parametric modeling and magnetic field analysis are performed to reveal how the secondary pole arc coefficient affects magnetic field modulation capability. The air-gap magnetic field is then analyzed to obtain the winding back-EMF waveform and the Fourier decomposition diagram of the air-gap flux density. Finally, the static characteristics of the motor are investigated, revealing the impact of secondary structure on detent force and the effect of current magnitude on static electromagnetic thrust. The simulation results validate the rationality of the electromagnetic design scheme, offering valuable reference for research on linear drive motors in rail transit applications.

Full Text

Electromagnetic Characteristics Analysis of Primary Permanent Magnet Linear Motor for Rail Transit

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Abstract

Linear induction motors applied in rail transit drive systems suffer from low power factor and low efficiency. This paper proposes a novel primary permanent magnet linear motor (PPMLM) featuring a short primary (mover side) and long secondary (stator side) configuration. Both armature windings and permanent magnets are installed in the primary, while the secondary consists solely of salient pole reluctance structure. This motor not only retains the advantages of conventional linear induction motors such as simple structure and non-adhesive direct drive, but also exhibits excellent performance metrics including power factor and efficiency. The paper first details the motor's structural characteristics and operating mechanism, deriving the air-gap flux density equation and synchronous speed equation using equivalent magnetic circuit method. Subsequently, a 12/8-pole PPMLM is designed, and parametric modeling and magnetic field analysis are conducted using finite element software to investigate the relationship between secondary pole arc coefficient and magnetic field modulation capability. The air-gap magnetic field is then analyzed to obtain winding back-EMF waveforms and Fourier decomposition patterns of air-gap flux density. Finally, static characteristics are studied, including the influence of secondary structure on detent force and the effect of current magnitude on static electromagnetic thrust. Simulation results demonstrate the rationality of the electromagnetic design scheme, providing valuable reference for research on linear drive motors for rail transit.

Keywords: Primary permanent magnet linear motor, rail transit, pole-arc coefficient, finite element method

1 Introduction

Rail transit systems primarily employ two types of drive motors: rotary motors and linear motors. Compared with rotary motor drive systems, linear motor drive systems offer numerous advantages including simple structure, long service life, strong climbing capability, small wheel diameter, reduced tunnel cross-section, and greater freedom in route design [1]. The most common types are linear induction motors and linear permanent magnet synchronous motors. Linear induction motor-driven rail transit systems have been implemented, but suffer from low efficiency and low power factor [2]. Linear permanent magnet synchronous motors offer high efficiency, high power density, compact size, and excellent performance. However, in conventional linear permanent magnet synchronous motors, the armature windings and permanent magnets are placed in the primary and secondary respectively, requiring permanent magnets to be laid along the track, which results in high manufacturing and maintenance costs and limits their application in long-distance scenarios such as urban rail transit [3].

Flux-switching permanent magnet motors proposed in literature [4-6] represent a novel motor type with advantages such as large induced electromotive force and high power density, but they exhibit significant detent force that leads to large thrust ripple. Professor T. A. Lipo et al. proposed a doubly salient permanent magnet motor based on switched reluctance motors [7]. As this motor operates with unipolar permanent magnet flux linkage, its power density is slightly lower than that of flux-switching permanent magnet motors. Vernier permanent magnet motors are a recently developed novel motor type [8-11], with permanent magnets placed at the primary tooth tips, several pairs of permanent magnets per tooth, a salient pole secondary structure, and windings that can use either distributed or concentrated winding configurations. This motor can generate large thrust at low speeds through its inherent vernier effect, but suffers from large inter-pole leakage flux.

This paper proposes a novel primary permanent magnet linear motor (PPMLM) that not only retains the advantages of conventional linear induction motors such as simple structure and non-adhesive direct drive, but also demonstrates excellent performance indices including power factor and efficiency [12-13]. Since both permanent magnets and windings are located in the primary (mover side), the secondary (stator side) laid along the track is made only of ordinary ferromagnetic material, significantly reducing manufacturing costs and essentially eliminating maintenance requirements. Consequently, this motor shows promising application prospects in the rail transit domain.

2.1 Primary Structure

The proposed 12/8-pole PPMLM structure is shown in [Figure 1: see original paper]. The primary (mover) core is laminated from ordinary silicon steel sheets, with three-phase armature windings embedded and permanent magnets placed in the primary. The secondary employs a conventional salient pole structure. The armature winding pole pair number is q, and the permanent magnet pole pair number is p_{PM}, with the two magnetic fields having different pole pair numbers. The primary core adopts a semi-closed slot design. During operation, the primary armature magnetic field and permanent magnet magnetic field achieve electromechanical energy conversion through magnetic coupling via the secondary reluctance. The salient features of this structure are: permanent magnets are placed in the primary, the secondary uses a conventional salient pole structure, reducing costs, improving operational reliability, and enhancing performance.

2.2 Secondary Structure

The motor secondary employs a salient pole reluctance structure. The number of salient poles corresponding to the primary is N_r, which satisfies a specific relationship with the pole pair numbers of permanent magnets and windings. For the studied 12/8-pole PPMLM, the permanent magnet pole number on primary teeth is 12, and the armature winding is designed for 8 poles, resulting in 0.5 slots per pole per phase. To reduce winding end length, concentrated windings can be employed as shown in [Figure 4: see original paper].

The relationship is given by:

$$N_r = p_{PM} + q$$

where p_{PM} and q are the pole pair numbers of permanent magnets and armature windings, respectively.

[Figure 2: see original paper] shows the motor secondary structure diagram. To facilitate investigation of how structural parameter variations affect motor performance, two parameters are defined. The pole arc coefficient α is defined as the ratio of salient pole portion length to length per pole, expressed as λ_1/λ_2. The salient pole gradient is defined as β_1/β_2. The secondary structure used in this paper has neither windings nor permanent magnets, making it simple, reliable, and particularly suitable for long-distance rail transit applications.

When the motor operates, the relative air-gap permeance with respect to secondary coordinates can be expressed as:

$$\lambda(x,t) = \lambda_0 + \sum_{k=1}^{\infty} \lambda_k \cos\left[kN_r \frac{2\pi}{L}(x - v_t t)\right]$$

where v_t is the motor operating speed.

3 Operating Principle

During steady-state operation of PPMLM, the armature windings create a traveling wave magnetic field in the air gap that follows a sinusoidal distribution along the linear direction. The permanent magnets produce a stationary constant magnetic field. These two magnetic fields are modulated through the secondary to achieve indirect coupling, forming electromagnetic thrust on the mover. The coupling principle is illustrated in [Figure 3: see original paper].

The magnetomotive force produced by permanent magnets on primary tooth surfaces in the air gap can be expressed as a Fourier series:

$$F_{PM}(x) = \sum_{n=1,3,5\ldots}^{\infty} \frac{4}{\pi n} \frac{B_r h_{PM}}{\mu_0} \sin\left(\frac{n\pi}{2}\right) \cos\left(\frac{n p_{PM} \pi x}{L}\right)$$

where B_r is permanent magnet remanence; h_{PM} is permanent magnet thickness; p_{PM} is permanent magnet pole pair number; and μ_0 is vacuum permeability.

Neglecting higher-order harmonics, the magnetomotive force produced by permanent magnets in the air gap can be approximated as:

$$F_{PM}(x) \approx F_{PM1} \cos\left(\frac{p_{PM}\pi x}{L}\right)$$

Therefore, during no-load operation, the air-gap flux density can be approximated as:

$$B_g(x,t) \approx F_{PM1}\lambda_0 \cos\left(\frac{p_{PM}\pi x}{L}\right)+\frac{1}{2}F_{PM1}\lambda_1 \cos\left[\frac{(N_r - p_{PM})\pi x}{L}+\frac{N_r \pi v_t t}{L}\right]+\frac{1}{2}F_{PM1}\lambda_1 \cos\left[\frac{(N_r + p_{PM})\pi x}{L} - \right.$$

In the above expression, the first term represents the air-gap flux density component directly produced by permanent magnets. Since the permanent magnets mounted on primary tooth surfaces are stationary relative to the armature windings, this component cannot induce electromotive force in the armature windings. The second and third terms represent air-gap flux density components generated through modulation of permanent magnet flux by secondary salient pole reluctance. The second term has shorter wavelength and slower operating speed, while the third term features longer wavelength and faster operating speed. According to induction electromotive force principles, the induced EMF amplitude is proportional to the rate of change of effective air-gap flux. Therefore, selecting the third term as the effective harmonic component of PPMLM is beneficial for increasing induced electromotive force and thus improving thrust density.

From the analysis, the effective harmonic flux pole pair number p_{flux} and effective harmonic operating speed v_{flux} are respectively:

$$p_{flux} = |N_r - p_{PM}|, \quad v_{flux} = \frac{N_r}{N_r - p_{PM}} v_t$$

As shown in the equation, the PPMLM's permanent magnet pole pair number p_{PM} and effective harmonic flux pole pair number p_{flux} are different because this effective harmonic flux component is modulated by the secondary salient pole reluctance structure. The armature winding pole pair number can be designed according to this effective harmonic flux pole pair number, i.e., the armature winding pole pair number q equals the effective harmonic flux pole pair number p_{flux}. For the studied 12/8-pole prototype, the permanent magnet pole pair number is 6, the armature winding pole pair number is 4, and the secondary salient pole number under the corresponding primary length is 10.

3.1 Air-Gap Flux Density Analysis

To simplify the derivation, this paper makes several necessary assumptions: primary slotting effects are neglected, leakage flux is ignored; the secondary reluctance is assumed to have ideal characteristics, i.e., the air-gap permeance per unit area at secondary tooth tips is constant while the air-gap permeance between secondary teeth is zero; the relative permeability of permanent magnets is assumed to be 1. When primary and secondary are stationary, the air-gap permeance function for an ideal reluctance secondary can be expressed as:

$$\lambda(x) = \lambda_0 + \sum_{i=1}^{\infty} \lambda_i \cos\left(\frac{iN_r\pi x}{L_a} + x_0\right)$$

where λ_0 is the average air-gap permeance; λ_i is the i-th order permeance harmonic amplitude; N_r is the secondary salient pole number; L_a is the primary length; and x_0 is the initial primary position.

The first-order permeance harmonic has the largest magnitude, with higher-order harmonics typically neglected. Thus, the no-load air-gap permeance can be approximated as:

$$\lambda(x) \approx \lambda_0 + \lambda_1 \cos\left(\frac{N_r\pi x}{L_a} + x_0\right)$$

3.2 Operating Speed Analysis

Linear motors evolved from rotary motors. The traveling wave magnetic field's moving speed equals the linear speed of a rotary magnetic field on the stator inner surface, referred to as the linear motor synchronous speed v_s.

In rotary motors [14], the synchronous speed is n_r, with:

$$n_r = \frac{60f}{p}$$

where f is the frequency of AC current in armature windings.

The PPMLM synchronous speed can be expressed as:

$$v_s = \frac{\pi D n_r}{60N_r} = \frac{2fL}{N_r}$$

where D is the rotary motor stator inner circumference diameter; N_r is the rotary motor synchronous number. When PPMLM operates as a motor, after starting with the armature windings connected to a frequency converter, the motor operating speed can be controlled by regulating the armature winding frequency.

3.3 Winding Connection Method

For the studied 12/8-pole PPMLM, the permanent magnet pole number on primary teeth is 12, and the armature winding is designed for 8 poles, resulting in 0.5 slots per pole per phase. To reduce winding end length, concentrated windings can be employed as shown in [Figure 4: see original paper].

4 Analysis of Motor Magnetic Coupling Capability

Theoretically, there is no direct coupling between PPMLM armature windings and permanent magnets. Electromechanical energy conversion is achieved through their magnetic coupling via the secondary, which acts as a pole number converter. The strength of secondary coupling significantly impacts motor performance, making determination of secondary structural parameters particularly important. This section analyzes the influence of pole arc coefficient on motor coupling capability.

4.1 Influence of Salient Pole Arc Coefficient on Flux Linkage

The salient pole arc coefficient is one of the main secondary structural parameters, determining the air-gap size between salient poles and thereby affecting secondary coupling capability. To analyze motor performance under different pole arc coefficients, parametric models with pole arc coefficients ranging from 0.1 to 0.9 in increments of 0.05 were established under identical structural dimensions and operating conditions. Finite element analysis was conducted for different pole arc coefficients. With permanent magnet excitation alone, the variation in A-phase winding flux linkage amplitude was analyzed as shown in [Figure 5: see original paper] to investigate motor coupling capability.

[Figure 5: see original paper] shows that as the pole arc coefficient increases, the A-phase flux linkage amplitude first increases then decreases. The A-phase flux linkage is relatively large when the pole arc coefficient is between 0.3 and 0.6.

4.2 Influence of Salient Pole Arc Coefficient on Effective Harmonic Content

Fourier decomposition of air-gap flux density yields the percentage of 8-pole effective harmonics relative to the fundamental, as shown in [Figure 6: see original paper]. The figure indicates that as the pole arc coefficient increases, the percentage of effective harmonics relative to the fundamental first increases then gradually decreases. This follows the same pattern as the A-phase flux linkage amplitude variation, demonstrating that the winding back-EMF waveform is primarily generated by the 8-pole effective harmonic magnetic field. Although smaller pole arc coefficients yield larger effective secondary magnetic field component content when the coefficient is between 0.3 and 0.6, they also increase secondary magnetic circuit saturation. Based on empirical pole arc coefficient selection, the secondary pole arc coefficient used in this paper is chosen as 0.45.

5.1 No-Load Back EMF

No-load back EMF is an important indicator of motor performance, reflecting the rationality of winding turn coordination and the motor's load-carrying capacity. [Figure 7: see original paper] shows the three-phase winding no-load back-EMF waveform, which contains minimal harmonic content.

5.2 Air-Gap Flux Density Decomposition

Based on finite element method, the PPMLM magnetic field and air-gap flux density are analyzed to obtain the vertical air-gap flux density waveform. Using Fourier transformation, the 8th-order effective harmonic flux density sinusoidal waveform is decomposed, as shown in [Figure 8: see original paper]. Using the 8th harmonic magnetic field as the effective air-gap magnetic field for motor operation and designing the armature winding according to its pole pair number can yield larger induced electromotive force and thrust density.

5.3 Detent Force

Detent force is the collective term for end force and cogging force, with magnitude and direction independent of motor operating conditions. It is an important performance indicator for permanent magnet motors, affecting starting performance and causing thrust ripple [15-16]. To investigate the influence of salient pole height and gradient on motor detent force, parametric modeling was performed with salient pole height varying from 5 mm to 20 mm in 1 mm steps, and salient pole gradient varying from 0 to 0.6 in 0.1 steps. [Figure 9: see original paper] shows the motor detent force variation with salient pole height and gradient, calculated using the virtual work method in Ansoft finite element simulation software. Considering the modulation effect of salient poles on the magnetic field, the final selected salient pole height is 10 mm with a gradient of 0.4, yielding a detent force of 40.2 N.

Static electromagnetic thrust refers to the force varying with position when the secondary is stationary and DC current is applied to the primary windings. The static force-displacement characteristic is the most fundamental PPMLM characteristic and the basis for dynamic characteristic analysis. To meet thrust requirements for rail transit drive systems, the concept of “unit motor” can be introduced based on linear motor structural characteristics. By changing the number of these “units” and arranging them in the length or width direction, motor output thrust can be adjusted, with each unit considered independent and non-interfering. [Figure 10: see original paper] shows the motor static thrust under different DC currents. As the applied current increases, the thrust exhibits an approximately linear growth trend, indicating the iron core is not yet saturated. When the current exceeds 9 A, thrust increase gradually plateaus, indicating the iron core is approaching saturation. Simulation results show the motor utilization is highest at 9 A, producing an average thrust of approximately 496 N.

6 Conclusion

This paper proposes and designs a novel primary permanent magnet linear motor, analyzes its electromagnetic characteristics, derives the motor’s air-gap flux density and synchronous speed equations, and investigates static characteristics including no-load induced electromotive force, detent force, and thrust. The research demonstrates that based on salient pole magnetic field modulation effects, the motor generates harmonic magnetic fields in the air gap with long wavelength and high operating speed, resulting in large no-load induced electromotive force and electromagnetic thrust density, making it particularly suitable for rail transit applications.

References

[1] Hellinger R, Mnich P. Linear motor-powered transportation: history, present status, and future outlook[J]. Proceedings of the IEEE, 2009, 97(11): 1894-1905.

[2] Han Yongchun. Study on the relationship between air gap and train energy consumption of linear motor[J]. Railway Rolling Stock, 2015, 35(6): 69-72.

[3] Fan Y, Li G G, Lü G. Linear motors and their application in urban rail transit systems[J]. Urban Rapid Rail Transit, 2006, 19: 1-6.

[4] Cao R, Cheng M, Mi C, et al. Modeling of a complementary and modular linear flux-switching permanent magnet motor for urban rail transit applications[J]. IEEE Transactions on Energy Conversion, 2012, 27(2): 489-497.

[5] Min W, Chen J T, Zhu Z Q, et al. Optimization and comparison of novel e-core and c-core linear switched flux PM machines[J]. IEEE Transactions on Magnetics, 2011, 47(8): 2134-2141.

[6] Cheng M, Hua W, Zhang J, et al. Overview of stator-permanent magnet brushless machines[J]. IEEE Transactions on Industrial Electronics, 2011, 58(11): 5087-5101.

[7] Cheng Ming, Zhou E. Model split winding doubly salient permanent magnet motor analysis and control[J]. Chinese Science (Series E), 2001, 31(3): 228-237.

[8] Du Y, Chau K T, Cheng M, et al. Design and analysis of linear stator permanent magnet vernier machines[J]. IEEE Transactions on Magnetics, 2011, 47(10): 4219-4222.

[9] Hua W, Cheng M, Zhu Z Q, et al. Analysis and optimization of back EMF waveform of a flux-switching permanent magnet machine[J]. IEEE Transactions on Energy Conversion, 2008, 23(3): 727-733.

[10] Nakata Y, Ishiguro H, Kitani K, et al. Development and control of a novel cylindrical IPM linear vernier motor for compliant robot actuation[J]. Industrial Electronics Society, 2013, 45(11): 2744-2749.

[11] Du Wei, Cheng Ming, Zou Guotang. Design and static characteristics analysis of primary permanent magnet vernier linear motor[J]. Electrotechnical Society, 2012, 27(11): 22-30.

[12] Liu Wenqing. Research on linear vernier permanent magnet motor drive system[D]. Zhenjiang: Jiangsu University, 2015.

[13] Zhang Fengge, Jia Guanglong, Zheng Yang, et al. Simulation and experimental study of brushless electric excitation synchronous motor[J]. Journal of Electrotechnical Society, 2015, 30(14): 100-107.

[14] Du Weimin. Electromagnetic design and magnetic resistance force research of permanent magnet linear motor[D]. Jiaozuo: Henan Polytechnic University, 2009.

[15] Wang C F, Shen J X. A method to segregate detent force components in permanent-magnet flux-switching linear machines[J]. IEEE Transactions on Magnetics, 2012, 48(5): 1948-1955.

Note: Figure translations are in progress. See original paper for figures.