Characteristics and Optimization of a PMLSM for HTS Magnetic Suspension Propulsion System


Abstract—Permanent magnet (PM) linear synchronous motors (PMLSMs) can be integrated with a high temperature superconducting (HTS) magnetic suspension system to be used in such as electromagnetic aircraft launcher and maglev transportation which have a levitated object moving on a long linear track. This paper presents the design and electromagnetic characteristic analysis of a long-primary single-sided PMLSM for a HTS bulk-PM guideway repulsion magnetic suspension propulsion system. Based on the characteristics and performance analysis of the PMLSM, a new type of HTS suspension propulsion system driven by a double-sided PMLSM with an optimal PM structure is then proposed. The running characteristics of the linear propulsion systems are studied through finite element analysis (FEA) with comprehensive performance results obtained for practical development.

Keywords—High temperature superconductor (HTS), Permanent magnet linear synchronous motor (PMLSM), Electromagnetic simulation, HTS bulk, HTS magnetic suspension.

1. Introduction

Permanent magnet linear synchronous motor (PMLSM) technology has a rapid development in recent years, which results PMLSM increasingly used as actuators in industrial drive applications, such as computer controlled machining tools, X-Y driving devices, robots, semiconductor manufacturing equipment, transportation and suspension propulsion system. When a PMLSM is applied into the magnetic suspension propulsion system like maglev, HTS bulk-PM guideway repulsion type suspension system can be integrated due to stable levitation force and guidance force—simultaneously generated between PMs and HTS bulks [1-3]. The main advantages of HTS magnetic suspension system is the strong levitating force with passive and self-stabilizing feature, leading to the simplification of the sophisticated control system for regulating the length of air gap, which is necessary for other types of levitation transportation systems.

In this work, a HTS magnetic suspension propulsion system having a long-primary single-sided moving-magnetic type PMLSM for driving has been developed, which has lightweight of secondary mover and able to realize higher force density and acceleration capability in shorter time. The HTS magnetic suspension system consists of HTS bulks put in cryogenic vessels on the mover and PM guideways installed on both sides of PMLSM stator. The electromagnetic characteristics and performance of the PMLSM are studied by numerical analysis and finite element analysis (FEA) methods. Based on the results, an optimal HTS suspension propulsion system driven by a double-sided PMLSM is proposed with its performance characteristic analysis.

2. Model of HTS Magnetic Suspension Propulsion System

The structure model of the HTS magnetic suspension propulsion system composed of a PMLSM and HTS bulks-PM guideway repulsion suspension sub-structure is shown in Fig. 1. The primary stator of the PMLSM is consisted of three-phase copper windings and an iron core, while the secondary is made up of PMs and a piece of back iron. Table 1 lists the major parameters of the PMLSM.

The HTS magnetic suspension systems are fitted on both sides of the PMLSM, and the PM-guideways are composed of PMs and magnetic iron (Fe) ribs assembled as shown in Fig. 2. The magnetization directions of left-side and right-side PMs are along the vertical direction, and the middle PMs are installed with opposite magnetization direction. The iron core is put in the middle of PMs to concentrate magnetic field for generating stronger magnetic field on the upper surface of PM-guideways and weaker magnetic field on the lower surface.

The HTS bulks-PM guideway repulsion suspension system can realize self-levitation and self-guidance, so that the PMLSM can run without any sliding friction force and any assistant guidance control system.

Fig. 1. Model of HTS suspension propulsion system driven by a single-sided PMLSM.
The transverse section and longitudinal section of the PMLSM are shown in Fig. 3. The length of PMs $l_s$ is equal to the pole pitch $\tau$ with no gap between them. Neglecting the magnetic resistance of primary iron-core and secondary back-iron, the magnetic flux linkage of one coil generated by one pole-pair of PMs can be obtained approximately as

$$\psi_{PM} = \frac{\mathcal{F}}{R_m} = \frac{H \cdot h_s}{\mu \mu_0 l_s w_s + g/\mu_0 (l_s + l_f)/2 (w_s + w_l)/2}$$

where $\mathcal{F}$ is the magnetomotive force of magnetic circuit, $R_m$ is the magnetic reluctance of PM, $R_a$ is the magnetic reluctance of air-gap, $\mu_s$ is the relative permeability of PM, $H_s$ is the magnetic field intensity of PM, $\mu_0$ is the permeability of vacuum; $l_s$, $w_s$, and $h_s$ are the length, width and height of PM respectively; $l_f$, $w_l$, the length and width of stator-tooth respectively. When the parameters are substituted in (1), the $\psi_{PM}$ can be calculated out with the value of 0.4 Wb.

When the secondary rotor moves, an electromotive force (EMF) is induced in the stator windings. By differentiating the PM flux of phase winding against time, the back EMF is determined with an rms value as

$$E_n = \frac{1}{\sqrt{2}} \frac{\pi}{\tau} N_i k_N \psi_{sc} = k_E v_i$$

where $k_E = \frac{1}{\sqrt{2}} \frac{\pi}{\tau} N_i k_N \psi_{sc}$ is the back EMF constant, $\tau$ is the pole pitch, $N_i$ the number of turns of winding, and $k_N$ the winding factor.

Neglecting the magnetic reluctance of stator core, the magnetic reluctance of the closed circuit in which the magnetic flux flows generated by one coil can be calculated as

$$R_m = \frac{y_i}{2 \mu_0 A_s}$$

where $A_s$ is the area of stator teeth, $A_c = 1500 \text{ mm}^2$. So that the inductance $L$ of one coil can be calculated by

$$L = \frac{N_i \phi f}{i} = \frac{N_i^2}{R_m}$$

where $N_i = 200$, $L = 5 \text{ mH}$. There are 12 coils for one-phase, so the one-phase coil inductance is $L_1 = 60 \text{ mH}$.

3. Numerical Analysis

3.1 PM Flux Linkage and Back EMF

The transverse section and longitudinal section of the PMLSM are shown in Fig. 3. The length of PMs $l_s$ is equal to the pole pitch $\tau$ with no gap between them. Neglecting the magnetic resistance of primary iron-core and secondary back-iron, the magnetic flux linkage of one coil generated by one pole-pair of PMs can be obtained approximately as

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![Fig. 3. Model of PMLSM. (a) Transverse section; (b) Longitudinal section.](image)

3.2 Thrust and Normal Forces

In 2D plane magnetic field analysis, the thrust force $F_{em}$ and normal force $F_n$ have been expressed as [4]

$$F_{em} = \int_S \frac{1}{\mu_0} \left( B_y^2 - B_z^2 \right) n_s + 2n_s B_z B_y \text{ d}S$$

$$F_n = \int_S \frac{1}{\mu_0} \left( B_y^2 - B_z^2 \right) n_s + 2n_s B_z B_y \text{ d}S$$

where $S$ is the integrative path surrounding the moving part of the motor in the air-gap, $B_y$ and $B_z$ are the components along tangential and normal direction, respectively; $n_s$ is the tangential vector per unit and $n_t$ are normal vector per unit.

For the long-primary PMLSM, the stator copper loss cannot be neglected. The PMLSM has the characteristics of $X_A = X_b = X_l = 2\pi f L_1$ [5], therefore the electromagnetic power can be derived as follows
The electromagnetic thrust force is

\[
P_{\text{em}} = \frac{3E_0}{R_1^2 + X_1} \left[ U \left( X_1 \sin \theta + R_1 \cos \theta \right) - E_0 R_1 \right]
\]

(7)

The levitation force and guidance force are generated to levitate and guide the mover. When the materials and dimensions of HTS bulk-PM are properly chosen, an appropriate levitation force and guidance force can be generated to levitate and guide the mover.

The levitation force and guidance force are the product of an external magnetic field and a shielding current flowing in a HTS bulk, and can be calculated by the following equations

\[
F_{\text{Lev}} = \int_{h/2}^{TH} \int_{\delta/2}^{W/2} \int_{L/2}^{L/2} \frac{J_\delta \times B_\delta \mathrm{d}x \mathrm{d}y \mathrm{d}z}{2} \quad \text{and} \quad F_{\text{Gui}} = \int_{h/2}^{TH} \frac{J_\delta \times B_\delta \mathrm{d}x \mathrm{d}y \mathrm{d}z}{2}
\]

(10)

(11)

where \( F_{\text{Lev}} \) is the levitation force, \( F_{\text{Gui}} \) the guidance force, \( J_\delta \) the critical current density, \( B_\delta \) the field along the transverse direction, \( B_\delta \) the field along the vertical direction; \( W, L \) and TH are the width, length and thickness of the HTS bulk, respectively; and \( \delta \) the depth of field penetration. Here, it is assumed that induced shielding currents flowing in the bulk body are equal to the critical currents. The \( \delta \) used as integral range is given by the following relation [7]

\[
\delta = \frac{B_\delta - B_{\text{nc}}}{\lambda \mu_0 J_\delta}
\]

(12)

where \( B_{\text{nc}} \) is the trapped magnetic field, \( \lambda \) the Nagaoka coefficient determined by the configuration of a sample. The Fig. 4 shows the interaction between a HTS bulk and the PM-guideway, and the Fig. 5 and Fig. 6 are the distributions of \( B_x \) and \( B_z \) for different heights \( h \) from upper surface of PM-guideway, respectively.

The levitation force versus the distance between a HTS bulk and the PM-guideway can be described with an exponential function as follows [8]

\[
\begin{align*}
F = & \begin{cases} 
F_{\text{lev},1} \exp(-\alpha z) - F_{\text{att},1} \exp(-\beta z) & \text{moveowards} \\
F_{\text{lev},2} \exp(-\alpha z) - F_{\text{att},2} \exp(-\beta z) & \text{moveaway}
\end{cases}
\end{align*}
\]

(13)

where \( F_{\text{lev},1} \) and \( F_{\text{att},1} \) are the levitation force and attractive force when the HTS bulk is moved towards the PM-guideway, respectively; \( F_{\text{lev},2} \) and \( F_{\text{att},2} \) are the levitation force and attractive force when the HTS bulk is moved away from the PM-guideway, respectively; \( \alpha_1, \alpha_2, \beta_1 \) and \( \beta_2 \) are constants, which are closely related to the superconductor and the distribution of magnetic field; \( z \) the distance between the HTS bulk and PM-guideway. Fig. 7 shows the levitation force characteristics versus the distance of HTS bulk to the PM-guideway.
5. Performance Analysis

5.1 FE Model

According to the geometric parameters of PMLSM, a 2D FE model is built, which is sufficient for the theoretical analysis with relatively low computational complexity. The FE model is shown in Fig. 8 with the materials in model are numbered as: ① PM North (with the magnetization direction along the negative y-axis direction); ② PM South (with the magnetization direction along the x-axis direction); ③ PM back iron; ④ Band; ⑤ Stator iron core; and ⑥ Copper stranded coils.

The magnetic vector potentials obey the periodical boundary conditions on the y-direction boundary lines of the primary stator and band. The time-stepping transient analysis is applied to resolve. The analysis results of the no-load, start-up, detent force, thrust force and normal force characteristics of the PMLSM are detailed as follows.

![1-PM North, 2-PM South, 3-Back iron, 4-Band, 5-Iron core, 6-Coils.](image)

**Fig. 8.** FE model of the PMLSM.

5.2 No-Load Analysis

In 2D transient simulation at no-load without any excitations, the back electromagnetic force (EMF) and PM flux linkage can be calculated. Set the secondary rotor move with a constant speed as \( v = 2f \tau = 450 \text{ mm/s}, \) where \( f = 5 \text{ Hz}, \ \tau = 45 \text{ mm}. \) The time step of simulation is 1 s, and the time step is 0.01 s.

After simulating, the three-phase induced current and back EMF is obtained as shown in Fig. 9 and Fig. 10, respectively. As can be seen from the figures, the amplitude of induced current is \( I_m = 0.82 \text{ A}, \) and the back EMF is \( E_0 = 12 \text{ V}. \) Fig. 11 shows the three-phase flux linkage characteristics with the same amplitude of \( \psi_{pm} = 0.4 \text{ Wb} \) but are shifted by 120° electrical to each other.

By comparing the phases of the flux linkage, induced voltage and induced current, it is found that the three-phase induced currents have 120 electrical degrees delay after those of the induced back EMF, and which are also 120 electrical degrees delay to the flux linkages.

![Induced voltage (V)](image)

**Fig. 9.** Three-phases current characteristics.

![Flux linkage (Wb)](image)

**Fig. 10.** Three-phases induced back EMF.

![Three-phases flux linkage characteristics.](image)

**Fig. 11.** Three-phases flux linkage characteristics.

5.3 Detent Force Analysis

The slotted PMLSM has a detent force \( F_d \) due to the interaction of the secondary PMs with the primary slotted core, and the detent force includes the cogging force and end force. For the long-primary moving-magnetic type PMLSM, the end force can be neglected. The detent force is generally undesired effect that contributes to the force ripple and vibration of motor. So it is necessary to realize the detent force characteristic and minimize it.

The detent force can be approximately obtained by measuring the force while setting the secondary mover move at a very low constant velocity at no-load. In the simulation, a constant velocity of 4.5 mm/s is applied with the result is shown in Fig. 12. From the results, it is found that the pole arc coefficients \( a_i \) have important influence on the detent force. As can be seen from the waveforms, the detent force wave shows a periodic fluctuation with the period length equal to 30mm, which is equal to the tooth pitch \( y_t. \) The amplitudes of detent force vary with the \( a_i. \) When \( a_i = 1, \) the amplitude is about \( \pm 28 \text{ N} \) as shown in Fig. 12(a), and Fig. 12(b) shows that the plus-minus amplitudes change to 5.6 N and -8.5 N when \( a_i = 0.75, \) respectively.

The average amplitude of detent force \( F_{d,avg} \) versus different \( a_i \) is calculated as shown in Fig. 13. It is concluded that it has a maximum amplitude of detent force at \( a_i = 1 \) when the length of PM equal to the pole pitch \( \tau. \) When the \( a_i \) is selected between 0.75-0.875, it will have a relative small detent force.

Similarly, the normal force \( F_d \) also has the period characteristic like detent force as the results shown in Fig. 14 with the maximum fluctuation amplitudes of 43 N and 22.1 N for \( a_i = 1 \) and \( a_i = 0.75, \) respectively. It is can be thought that the tangential component of the fluctuation value of normal force lead to the detent force, and the detent force can be eliminated when the non-salient pole is adopted.
5.4 Start-Up Characteristics

In load analysis, the three-phase voltages are excited as

\[ U_a = \sqrt{2}U \sin(2\pi ft + \theta_0) \]  

\[ U_b = \sqrt{2}U \sin(2\pi ft + \theta_0 - 2\pi / 3) \]

where \( U \) is the amplitude of phase voltage, \( \theta_0 \) the initial phase angle. The main dynamic simulation parameters with the values based on the actual prototype and calculation are listed in Table 2.

Fig. 15 shows the start-up thrust force characteristics at no-load with the initial position of the axis of phase A coinciding with the d-axis. As can be seen from Fig. 15(a), a great thrust pulsation is generated at the initial stage with the maximum amplitude of 367 N, and tends to steady state 0.6 s later with a force ripple of ±30 N as shown in Fig. 15(b), which is approximately equal to the amplitude of detent force as shown in Fig. 12(a), which verifies that the force ripple is mainly caused by the detent force.

The start-up speed and position characteristics are shown in Fig. 16(a) and Fig. 16(c). The velocity pulsation is caused by the thrust pulsation, and he maximum overshoot is 205%. After 0.6 s, the motor reaches a steady state in a mean running velocity of 0.45 m/s with the velocity ripple about ±0.04 m/s as shown in Fig. 16(b), and the mean velocity is equal to the synchronous velocity of 2f. Under this speed, the displacement is 682.7 mm after 1.5 s.

Initial position \( x_0 \) has important influence on the start-up performance. Fig. 17 shows the start-up characteristic of PMLSM for different positions with the value of \( 0, \tau/2, 3\tau/4, 3\tau/2, \) and \( 7\tau/4 \). As can be seen from Fig. 17, when \( x_0 = \tau/2 \), it has the smallest thrust pulsation, but when \( x_0 = 3\tau/4 \) and \( 3\tau/2 \), a shift in the reverse direction is generated instantaneously, which degrades the start-up performance.

Fig. 18 and Fig. 19 show the influence of load force and load weight on the start-up of PMLSM at different initial positions, respectively. As can be seen from the figures, the motor can start normally when the load force \( |F_L| \leq 140 \) N at \( x_0 = 0 \), and the maximum load force can reach 300N at \( x_0 = \tau/2 \) shown in Fig. 18(b), which is 2.1 times that of the former. Fig. 19(b) shows that the maximum load weight mass = 60 kg at \( x_0 = 0 \), and it reaches a value of 145 kg at \( x_0 = \tau/2 \), which is 2.4 times that of the former.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Quantities</th>
<th>Parameters</th>
<th>Quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>8.5 kg</td>
<td>Voltage</td>
<td>106 V</td>
</tr>
<tr>
<td>Load force</td>
<td>0 N</td>
<td>Phase resistance</td>
<td>13.5 ( \Omega )</td>
</tr>
<tr>
<td>Initial velocity</td>
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<td>Inductance</td>
<td>60 mH</td>
</tr>
<tr>
<td>Damping</td>
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<td>Time stop</td>
<td>1 s</td>
</tr>
<tr>
<td>Frequency</td>
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<td>Time step</td>
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</tr>
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</table>

Table 2. Major Parameters of Dynamic Simulation
5.5 Thrust and Normal Forces Characteristics

The $F_{em} = f(\theta)$ is an important characteristic for the PMLSM. Fig. 20 shows the locked-rotor thrust force characteristic for $f = 5$ Hz, and it is just the force-angle characteristic. As can be seen from it, when $\theta = 54^\circ$, the maximum locked-rotor thrust force is 399 N, and it is equal to the maximum thrust force $F_{em,\text{max}}$. The $F_{em,\text{max}}$ decreases with the frequency of exciting voltage with the result shown in Fig. 21.

The magnetic flux density $B$ of PM and exciting current have direct effects on thrust force and normal force. Fig. 22 shows the $F_{em,\text{max}}$ and average normal force $F_{n,\text{avg}}$ versus $B$. As can be seen from the figure, the $F_{em,\text{max}}$ and $F_{n,\text{avg}}$ increase nearly linearly with $B$. The ratio of $F_{n,\text{avg}}/F_{em,\text{max}}$ is between 1.59-5.96 when the $B = 0.3-1.2$ T. Similarly, the
F_{em\_max} and F_{n\_avg} increase with the exciting current nearly linearly as shown in Fig. 23, and the ratio of $F_{n\_avg}/F_{em\_max}$ is between 6.89~1.76 when the exciting current $I = 3.2$~46.2 V. It is concluded that improving the exciting current has a better effect to increase the thrust force with lower $F_{n\_avg}/F_{em\_max}$.

The shape and size of PM have non-ignorable influences on $F_{em}$. Fig. 24 shows the $F_{em\_max}$ vs. thickness of PM for different exciting voltage, and it can be seen that the $F_{em\_max}$ will tend to saturate with the thickness of PM increasing to 20 mm for different exciting voltages.

The pole arc coefficient $a_i$ also has important effects on $F_{em}$, and it has an optimal value to realize an optimal thrust force. As can be seen from Fig. 25, the $F_{em\_max}$ increases with $a_i$ until the value equal to 0.75, then the thrust force will decrease with the $a_i = 1$ where the $F_{em\_max}$ is smaller than that at $a_i = 0.75$. The curve of $F_{em\_max}/F_d$ versus the $a_i$ shows that it reaches a peak value at $a_i = 0.75$. It is concluded that it will reach an optimal thrust force with lower force ripple generated by detent force when $a_i = 0.75$.

The influence of the number of secondary PM poles $N_{PM}$ on the $F_{em}$ is calculated as shown in Fig. 26. As can be seen from it, the thrust force increase linearly with the number of poles when $N_{PM} < 7$. When $N_{PM} \geq 7$, the thrust force will reach saturation with the mean $F_{em\_max} = 450$ N.

Based on the analysis above, it can be seen that the normal force between the primary stator and PM-secondary is great, and it is about 1.6~6.9 times the thrust force, which counteracts the levitation force generated by HTS bulk-PM guideway suspension sub-system and leads to decrease the load capacity. In this work, an optimization design is carried out with a new HTS suspension propulsion system is proposed, which is driven by a long-primary double-sided PMLSM with a novel integrated model as shown in Fig. 27.

6. Optimal Design
In the double-sided design, the normal attraction forces produced by the motor can be mostly cancelled, and the thrust force will be double as the single-sided one. The HTS suspension unit is installed underneath the secondary mover, which only needs to support the weight of mover and load. In order to confirm the performance of the propulsion system, the primary stator used in the previous single-sided one is adopted in the double-sided model. The optimal dimensions of the PMs are listed in Table 3 with the running parameters and performance features.

Fig. 28 shows the start-up thrust force characteristics at no load. Fig. 29 shows the thrust force $F_{em}$ versus the electrical angle $\theta$. As can be seen from it, the maximum thrust force $F_{em_{\text{max}}}$ are approximately 2 kN at $\theta = 54^\circ$. From the $F_{em_{\text{max}}}$ vs. load force characteristics shown in Fig. 30, the maximum start-up thrust force at $x_0 = \tau/2$ can be achieved as about 1050 N, which is 3.5 times that of the single-one, and the maximum start-up force in place can reach 1.3 kN.

Fig. 31 shows the characteristic of $F_{em}$ vs. load weights. It is shown that the maximum load weight is 560 kg, which is 3.8 times that of the single-sided one. Without the influence of normal force, the secondary mover with the load can be levitated by HTS magnetic suspension system easily.

### Table 3. Optimal parameters of double-sided PMLSM

<table>
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<tr>
<th>Item</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PM</strong></td>
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<td>PM length (mm)</td>
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<tr>
<td>Pole arc coefficient</td>
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<td>PM height $h_s$ (mm)</td>
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<td>PM trapping field $B$ (T)</td>
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<td>Maximum load mass (kg)</td>
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<tr>
<td>Maximum thrust force (N)</td>
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<tr>
<td>Maximum start-up thrust force (N)</td>
<td>1300</td>
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### 7. Conclusions

A prototype of HTS magnetic suspension propulsion system derived by a single-sided PMLSM is developed. The characteristics and performance analysis of the PMLSM show that it has an optimal pole arc coefficient to obtain a minimum detent force which minimizes the force ripple. The initial position has influences on start-up performance, and the maximum start-up load capacity has difference at different position. It also has an optimal thickness and poles of PM for different exciting voltage to obtain a saturation thrust force. In order to eliminate the influence of normal force, a new HTS suspension propulsion system driven by a double-sided PMLSM with an optimal secondary is proposed, and the performance characteristic analysis of which shows that it has comprehensive performance for the practical application.
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References