Electromagnetic Performance Calculation of HTS Linear Induction Motor for Rail Systems

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Abstract. According to a high temperature superconducting (HTS) linear induction motor (LIM) designed for rail systems, the influence of electromagnetic parameters and mechanical structure parameters on the electromagnetic horizontal thrust, vertical force of HTS LIM and the maximum vertical magnetic field of HTS windings are analyzed. Through the research on the vertical field of HTS windings, the development regularity of the HTS LIM maximum input current with different stator frequency and different thickness value of the secondary conductive plate is obtained. The theoretical results are of great significance to analyze the stability of HTS LIM. Finally, based on theory analysis, HTS LIM test platform was built and the experiment was carried out with load. The experimental results show that the theoretical analysis is correct and reasonable.

1. Introduction
In recent years, with the urgent needs of the novel motors, as well as the progress of linear motor and HTS technology, the research of HTS LIM has become a hot spot. Compared with the traditional rotary induction motor, linear induction motor has the advantages of low noise, strong gradeability, non adhesion drive and small passing curve radius [1]. However, the traditional linear induction motor also has lots of defects, such as low power factor and efficiency, unbalanced primary current, distorted end magnetic field [2], which greatly restrict its development.

The combination of HTS technology and the traditional liner motor with HTS materials will produce more superior operating performance than the general motor. In addition, HTS LIM not only has a higher power density and reliability, but also effectively decreases the size of the motor, saving the raw materials of manufacturing motor, reducing the noise generated by motor operation [3-5]. Therefore, the research on LIM HTS has important theoretical significance and commercial value.

In this paper, a mathematical model is established for the HTS LIM that is applied in rail systems, which is based on the electromagnetic parameters and mechanical structural
parameters. Then the electromagnetic horizontal thrust, vertical force and the maximum vertical magnetic field of HTS windings are analyzed to verify the theory through the experimental test platform.

2. HTS LIM physical model

2.1. Electromagnetic theory of HTS LIM

According to force characteristic analysis of HTS LIM, the horizontal thrust and vertical force formula of HTS LIM can be obtained in one cycle by the FEM method [6-7]:

\[ F_x = \frac{1}{T_e} \int_{t_1}^{t_2} L_{ef} \sum_{i=1}^{n} B_{yi} J_{zi} S_i dt \]

(1)

\[ F_y = F_{y1} + F_{y2} \]

(2)

\[ F_{y1} = \frac{1}{T_e} \int_{t_1}^{t_2} L_{ef} \sum_{i=1}^{n} B_{yi} J_{zi} S_i dt \]

(3)

\[ F_{y2} = \frac{\partial W_m}{\partial g_e} = \frac{1}{T_e} \int_{t_1}^{t_2} \frac{\partial }{\partial g_e} \frac{L_{ef}}{2\mu_0} \sum_{i=1}^{n} B_{yi}^2 S_i dt \]

(4)

In the formula, \( F_x \) is the HTS LIM horizontal thrust, \( F_y \) is the HTS LIM vertical force, in which, \( F_{y1} \) is the repulsive force as a result of the interaction between the primary magnetic field and the secondary eddy current and \( F_{y2} \) is the attractive force produced between the primary magnetic field and the secondary ferromagnetic material. \( B_{xi} \) and \( B_{yi} \) are the magnetic flux density components of the \( x \) and \( y \) directions within the grid subdivision of the FEM, \( J_{zi} \) is the eddy current density in the secondary grid cell, \( S_i \) is the area of the grid cell \( i \), \( T_e \) is a period of time, \( L_{ef} \) is the effective length of the primary core, \( W_m \) is the magnetic field energy, \( g_e \) is the electromagnetic air gap length, \( \mu_0 \) is the vacuum permeability, \( n \) is the total number of mesh generation in the calculation region.

| Items                | Value     | Items                | Value     |
|----------------------|-----------|----------------------|-----------|
| Rated power, (kW)   | 3.5       | Number of HTS coils  | 12        |
| Rated current, (A)  | 20        | Mechanical gap, \( \delta \) (mm) | 12        |
| Rated frequency, \( f \) (Hz) | 10        | Width of motor, \( D \)(mm) | 250       |
| Rated speed, (m/s)  | 3.5       | Number of primary slots, \( N_p \) | 26        |
| Rated thrust, (N)   | 1000      | Height of reaction plate, \( h_c \) (mm) | 3         |
| HTS material        | Bi-2223/Ag | Height of back iron, \( h_b \) (mm) | 8         |

2.2. Main parameters of HTS LIM

![Figure 1. Model of HTS LIM](image1)

![Figure 2. Prototype of HTS coil](image2)
In this paper, the main structural parameters of the HTS LIM designed, as shown in Table 1, of which the rated power is 3.5kW and the rated frequency is 10Hz. The designed motor model adopts the structure with unilateral type, short primary and compound secondary made of aluminum and iron, of which the coils are made of Bi-2223/Ag HTS tapes instead of the traditional copper wires as shown in Fig.1.

**Table 2. Typical Specifications of HTS coil**

| Items                  | Value          | Items                    | Value          |
|------------------------|----------------|--------------------------|----------------|
| Critical current of tapes(A) | 97 (Self field, 77K) | Width of tapes (mm) | 4.3 |
| Thickness of tapes (mm)            | 0.24                      | Turns of coil            | 240           |
| Length of tapes (m)                  | 254                       | Resistance (77K) (Ω)     | 1.2E-5        |
| Inductance (mH)                        | 29                        | Insulation resistance (MΩ) | 1000          |

The typical specifications of the HTS coils are shown in Table 2. The HTS coil is the compound of HTS tapes and epoxy resin. Because the HTS coil is limited by the curvature radius of tapes and can’t be twisted [8], HTS winding is only designed for the double pancake type structure, of which the upper pancake coil and the lower pancake coil are separated by corona resistant polyimide films. The prototype of superconductive winding, which is wound with 240 turns of superconducting tapes, is as shown in Fig.2. Due to the special nature of HTS materials and the particularity on environmental requirements of HTS LIM, HTS windings cooling system must be made with non magnetic stainless steel materials.

3. Research on electromagnetic performance of HTS LIM

3.1. Effect of stator current on electromagnetic characteristics of HTS LIM

HTS LIM can effectively improve the load capacity with HTS windings instead of the traditional copper windings as result of strong current flow ability of superconducting tapes. To study the influence of current size on the electromagnetic characteristics of HTS LIM, the frequency of the power supply is kept constant for 10Hz to observe the variances of the electromagnetic force, vertical force and the maximum vertical field of superconducting windings with the change of the current size.

Fig. 3 indicates the relationship curves of the motor’s electromagnetic thrust and vertical force with the primary current respectively. Visible from the graph, with the increase of the current from 4A to 40A, the electromagnetic thrust of HTS LIM increases from 50N to 4697N, and vertical force increases from 44N to 4807N.

![Graph showing the relationship between current and thrust/vertical force](image)

(a) Transient curve of the thrust force  (b) Transient curve of the vertical force

**Figure 3. Relationship of the force with different exciting current**
Fig. 4 shows the 3D transient waveform of HTS winding subjected to maximum vertical field with the change of the excitation current. It can be seen from the figure that the vertical field shows a linear increasing trend as the current is gradually increasing. When the current is increased from 4A to 40A, the maximum vertical field of the superconducting winding is increased from 0.032T to 0.311T.

![3D transient waveform](image)

**Figure 4.** 3D transient $B_{\perp \text{max}}$ vs current.

The maximum vertical field curve of HTS winding under different excitation current is compared with that of HTS strip with the critical current in 77K low temperature environment. The comparison curves are shown in Fig. 5. The intersection of the two curves in Fig. 5 is the maximum current that can be applied to the motor designed, which the maximum current is 24A, and the maximum vertical field of the superconducting coil is 0.195T. Therefore, setting the maximum current peak value to 20A is sufficient to ensure safe and stable operation of the HTS LIM.

3.2. *Effect of excitation frequency on electromagnetic characteristics of HTS LIM*

Figure 6 shows the transient waveforms of the electromagnetic force and the vertical force by changing frequency. The figure shows, with the increase of frequency, the electromagnetic thrust increases first and then decreases, and the vertical force always trends to reduce. The lower the frequency is, the more slowly the stability of the electromagnetic force and the vertical force is at the start time of HTS LIM. When the frequency is increased from 2Hz to 18Hz, the maximum value of the electromagnetic force is 1433N at 6Hz. But the vertical force is reduced from 25.2kN to 371N.
In order to study the effect of frequency on the current capacity of superconducting motor, the frequency of the power supply is chosen for 4Hz to 14Hz to analyze the variation of the maximum vertical field size of the superconducting windings with different current conditions. Fig.7 shows the change curve of the maximum vertical field of the superconducting windings with the maximum input current of HTS LIM at different frequencies, in which the solid line represents the surface vertical field with critical current of Bi-2223/Ag superconducting tapes in 77K low temperature environment. According to the intersection point of the curve in Fig.7, the maximum current curve of the HTS LIM can be obtained with different frequencies, as shown in Fig. 8. It can be seen from Fig. 7 and Fig. 8 that the maximum vertical field of the superconducting winding is increasing with the decrease of the frequency of the power supply under a certain voltage. When the power frequency is increased from 4Hz to 14Hz, the maximum input current of HTS LIM is increased from 22.82A to 24.52A, and the change is not very obvious.

**Figure 6.** Transient curve of the thrust and vertical force with different frequency

**Figure 7.** Maximum current vs different frequency

**Figure 8.** Maximum current vs different frequency

3.3. Effect of thickness of the secondary conductive plate on electromagnetic properties

The secondary plate of HTS LIM is a compound structure made of aluminum and iron. Fig.9 shows the horizontal thrust and the vertical force change curve of the motor with different aluminum thickness. It can be known from the graph that the electromagnetic force increases at first and then decreases with the increase of the thickness of the secondary aluminum plate.
but the vertical force continually reduces at the start time of the motor. When the aluminum thickness size is between 2-3mm, the electromagnetic force reaches the maximum value of about 1290N; then the electromagnetic thrust decreases with the increase of the thickness of the aluminum plate, and the electromagnetic force is reduced to 900N when the thickness size increases to 6mm. However, the vertical force of HTS LIM is always shown as attractive between primary and secondary when the thickness size of the aluminum plate is increased from 1mm to 6mm, and its value is gradually reduced from 3188N to 0; when the thickness of the aluminum plate is larger than 6mm, the vertical force is almost 0—that is to say roughly equal attraction and repulsion. If the thickness of aluminum plate is increased continually, the vertical motors will behave as a repulsive force.

![Graph A](image1)

(a) The curve of the electromagnetic force

![Graph B](image2)

(b) The curve of the vertical force

**Figure 9.** The curve of $F_x$ and $F_y$ vs $s$ with different aluminum thickness

In practical applications, due to the different expansion coefficient of aluminum and steel materials and the attraction of primary and secondary in the vertical direction when the motor is working (about 4 ~ 6 times of the thrust), the aluminum plate is easy to break off affecting the motor's normal operation. Therefore, the aluminum plate thickness value of 2mm, 3mm, 4mm, 5mm, 6mm is respective chosen to research the current capacity of HTS LIM. Fig. 10 shows the variation curve of the maximum vertical field of the superconducting winding with different aluminum thickness value, in which the solid line represents the surface vertical field with the critical current of the Bi-2223/Ag superconducting tapes in 77K low temperature environment. According to the intersection point of curve in Fig. 10, the maximum current curve of motor can be obtained with different aluminum thickness value, as shown in Fig.11.

![Graph C](image3)

**Figure 10.** $B_{\perp \text{max}}$ vs maximum current with aluminum thickness

![Graph D](image4)

**Figure 11.** Maximum current vs aluminum thickness value
Fig. 10 and Fig. 11 show that the maximum input current of HTS LIM is increased from 23.33A to 24.97A when the thickness value of the aluminum plate is increased from 2mm to 6mm. This is because the increase of thickness of the secondary aluminum plate results in a gradual increase of the eddy current induced by the secondary conductive plate and weakening air-gap flux density, which will enlarge the repulsion and reduce the vertical force between the primary and secondary. Similarly, the weakening of the air-gap flux density will also decrease the maximum vertical field of HTS winding and increase the input current HTS LIM.

4. Test
In order to verify the correctness and feasibility of the theoretical calculation, the load test is carried out on the experimental platform which has been built, and the load is a linear motor with a copper winding. Fig. 12 shows the experimental platform and control devices. Two sets of completely independent inverter control system are respectively connected with the power line of HTS LIM and the prototype with a copper winding, and the signal line of speed sensor and pull pressure sensor is tied together with the motor power line to move through the pulley with the movement of the car. According to the test platform built, HTS LIM' own friction is measured as 70N.

Due to the limit of railway track length, HTS LIM cannot reach the rated speed 3.5m/s (rated frequency is 10Hz), so the operating power frequency is selected as 4Hz. The horizontal thrust waveform diagram of HTS LIM with load by the test was obtained, as shown in Fig. 13. The thrust measured by the sensor 493N plus its own friction 70N, the total thrust of the motor is 563N. Under the same conditions, the simulation thrust waveforms obtained by FEM are shown in Fig. 14. The simulation result shows that the thrust of the motor is 499N, which is 0.886 times of the result measured by test. From the above analysis, it can be known that the motor performance requirements can be satisfied.
5. Conclusion
In this paper, the effects of electromagnetic parameters and main structural parameters on the electromagnetic force, vertical force and the maximum vertical field of HTS windings are analyzed. Through the research of the vertical field of HTS winding, the rule of the maximum input current of HTS LIM with the stator frequency and the thickness value of the secondary conductive plate is obtained, which is of great significance to the analysis of the stability of HTS LIM. In addition, the load test is carried out on an experimental platform, which has been built with the load that is a linear motor with a copper winding, to compare the test results with the FEM results with the same operation conditions. The comparison shows the reliability of the FEM in the design process of the motor.

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