Influence of variable slip frequency control strategy on tractive performance

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Abstract: In order to improve the current situation of poor traction ability of medium-low speed maglev train, a variable slip frequency control (VSFC) strategy is proposed based on the constant slip frequency control (CSFC) of linear induction motor (LIM). The control frequency of the starting stage of the vehicle is selected low on the premise of no obvious influence on the levitation performance. After reaching the maximum power point, the traction of the motor is always the maximum that can be exerted under the corresponding speed. Firstly, the mathematical model of linear induction motor is established, and the analytical expressions of traction and normal force are listed; Then the influence of slip frequency on vehicle tractive performance is analyzed by traction calculation, the VSFC strategy is proposed and its advantages are analyzed. The results show that the VSFC strategy can fully suppress the influence of normal force on levitation stability at low speed, and can give full play to the tractive performance of the motor in the whole process.

1. Introduction

The LIM has the advantages of simple structure, good heat dissipation conditions and strong climbing ability, so it is used as the traction equipment of medium-low speed maglev train. The medium-low speed maglev train simultaneously adopts electromagnet to achieve suction levitation. The LIM and the levitation electromagnet are respectively installed in the middle and lower part of the levitation module. The motor produces normal force while generating traction, and the existence of the normal force will affect the levitation stability of the vehicle. Therefore, the LIM not only determines the tractive performance of the vehicle but also affects its levitation performance. In order to improve the tractive performance of the motor and effectively control the magnitude of normal force, a lot of researches have been done by domestic and foreign scholars.

On the design and optimization aspect, Bazghaleh et al. [3] developed several different multi-objective functions, which will be used to improve efficiency, power factor, end effect intensity, and motor weight. Employing the derived equations and considering all phenomena involved in the single-sided LIM, Shiri et al. [4] presented a simple design procedure and analyzed the effect of different design variables on the performance of the motor. In the aspect of Analytical computing, Faiz et al. [5] introduced a new idea to account for the longitudinal end effect factor. Meanwhile, other electromagnetic effects, such as transverse edge effects and skin effect, are taken into account. Pai R M et al. [6] developed a per-phase equivalent circuit of the LIM with sheet secondary. In the aspect of
controlling, accounting for the end effect, a field orientation control scheme is developed by Kang et al. [7]. With the proposed control scheme, the flux-attenuation problem due to the end effect is shown to be resolved in the high-speed range. A decoupled-control method of levitation and propulsion for the single-sided LIM maglev-vehicle was proposed by Yoshida et al. [8].

Various researchers have done a lot of in-depth research on the structural optimization, theoretical calculation and control methods of the LIM, and put forward many meaningful conclusions for the design and control of the LIM, but there is a lack of research on the combination with practical engineering and other systems. The current application status is that the maximum running speed of medium-low speed maglev vehicle is no more than 100km/h. In order to improve the tractive performance of maglev vehicle and improve its market competitiveness, this paper studies the influence of slip frequency on the operation performance of maglev vehicle based on the relevant data of the LIM for the new-generation medium-low speed maglev test vehicle, and proposes a better slip frequency control strategy to provide selection basis for engineering application.

2. LIM for medium-low speed maglev

The running mechanism of the medium-low speed maglev vehicle is levitation frame, each levitation frame includes two levitation modules, one of which is equipped with a LIM and a levitation electromagnet, as shown in figure 1. The LIM installed on the vehicle moving with the vehicle is the primary; The secondary of the motor is the track, including the back of the F rail and a layer of about 4mm aluminum plate, as shown in figure 2. The LIM and the levitation electromagnet are installed in the same levitation module, which will inevitably affect each other when they work. In particular, when the motor generates traction, it will generate normal force, which can be represented as suction or repulsion. In the form of suction, the burden of levitation system is increased. As the repulsive force, it can act as a part of levitation force. The magnitude and direction of the force can be controlled by slip frequency.

3. Analytical calculations of traction and normal force

The LIM series equivalent circuit considering the two dynamic side effects is shown in figure 3. $Z_1$ is the primary resistance plus leakage resistance, $Z_{0e}$ is the secondary equivalent resistance and excitation reactance, $Z_{te} = k_w Z_{we}$ is the impedance caused by the second type transverse end effect, and $Z_{le} = k_e Z_{we}$ is the impedance caused by the second type longitudinal end effect.
The magnetic vector potential can be calculated [9] as follows:

\[ \nabla^2 A - \mu_0 \frac{\partial^2 A}{\partial t^2} + \mu_0 \rho (\nabla \times (\nabla \times A)) = -\mu_0 j_i \]  

(1)

The air gap flux density expressions in the x and y directions are as follows:

\[ B_x = (k_1 \cosh \alpha y + k_2 \sinh \alpha y) e^{-j\omega x} \]  
\[ B_y = j(k_1 \sinh \alpha y + k_2 \cosh \alpha y) e^{-j\omega x} \]  

(2)

Where \( k_1 = \frac{\mu J_1}{\alpha \cosh \alpha \delta - j \frac{\omega}{\omega_0} \sinh \alpha \delta} \)  
\( k_2 = -\frac{j\omega J_1}{\alpha \cosh \alpha \delta - j \frac{\omega}{\omega_0} \sinh \alpha \delta} \)  
\( \alpha = \frac{\pi}{\tau}, \gamma = k_1 \frac{P}{d} \).

The expression of traction is:

\[ F_t = \frac{1}{2} B_t J_s S \]  

(3)

The normal force of the motor is:

\[ F_n = F_{\alpha} + F_{\gamma} = \frac{1}{2\mu_0} B_t^2 S - \frac{1}{2} B_t J_s S \]  

(4)

At present, the LIM is usually controlled by constant slip frequency, that is, the speed of travelling magnetic field is always faster than the running speed of the vehicle. \( f \) is the slip frequency and \( \tau \) is the motor pole pitch. Table 1 shows the LIM parameters of the new-generation maglev vehicle. Based on the parameters, the variations of the traction and normal force with velocity and slip frequency are analyzed and calculated. Under CSFC, the motor generally includes two stages in the full speed range, the first stage is the constant force region and the second is the constant power region. The primary current in the constant force region remains unchanged, and the supply frequency and voltage increase with the speed, at this stage, the traction of the motor changes little. The constant power region refers to the stage after the motor reaches the maximum power value, in which the motor voltage remains unchanged, the current decreases as the speed increases, the supply frequency increases as the speed increases, and the traction attenuation of the motor is relatively fast, as shown in figure 4a.

![Figure 3. Equivalent circuit of the LIM](image)

Figure 3. Equivalent circuit of the LIM

The theoretical calculation value of the traction

![Figure 4a. Theoretical calculation value of the traction](image)

(a) The theoretical calculation value of the traction

The theoretical calculation value of the normal force

![Figure 4b. Theoretical calculation value of the normal force](image)

(b) The theoretical calculation value of the normal force

Figure 4. The force characteristics of the LIM with different slip frequencies
Table 1. LIM parameters

| NAME                              | SIZE   | NAME                              | SIZE   |
|-----------------------------------|--------|-----------------------------------|--------|
| The length of the motor/mm        | 2850   | The motor capacity/kVA            | 248    |
| The width of the motor/mm         | 220    | Rated phase voltage/V             | 212    |
| Pole number                       | 12     | Rated phase current/A             | 390    |
| Pole pitch/mm                     | 220    | Air gap/mm                        | 11     |
| Phase number                      | 3      | Slip frequency/Hz                 | 8      |
| Number of slots per pole per phase| 3      | Single phase effective series turns| 144    |
| Resistivity of secondary plate    | 2.83x10^-8 | Secondary thickness               | 4/mm   |

The frequency setting of the CSFC is generally between 6-20Hz. The LIM normal suction in the starting stage is large when the slip frequency selection is too small, the traction is insufficient when the selection is too big, and the vehicle accelerates slowly. Other parameters remain unchanged in the analytical calculation of the traction and normal force, such as motor structure and air gap size; only the slip frequency is changed, and the change of traction and normal force in the process from 0 to 160km/h at different slip frequency is compared. The calculation results are shown in figure. 4. It can be seen that: 1) the smaller the slip frequency is, the greater the traction is when the motor starts, and the greater the normal force is; 2) with the improvement of slip frequency, the speed of the motor to reach the constant power point will increase; 3) the lower the slip frequency is, the faster the traction attenuation at high speed; 4) the larger the slip frequency is, the smaller the change ranges of the traction and the normal force are. 5) when the slip frequency is 10Hz, the normal force at the start stage of the motor is close to 0.

4. Resistance calculation

The basic resistance of the medium-low speed maglev vehicle only takes into account air resistance, electromagnetic resistance and flow resistance. The calculation formula of resistance [10] refers to the parameters of Japan’s HSST train, and the formula is modified by multiplying the correlation coefficient before the constant. The calculation formula is as follows:

\[ W_a = (k_1 \cdot 1.652 + k_2 \cdot 0.572N) v^2 \]  \hspace{1cm} (5)

\[ W_m = \begin{cases} 
  k_3 \cdot 3.354 M v & \text{if } v < 5.6m/s(20km/h) \\
  (k_4 \cdot 18.22 + k_5 \cdot 0.074 v) M & \text{if } v \geq 5.6m/s(20km/h)
\end{cases} \]  \hspace{1cm} (6)

\[ W_c = k_6 \cdot 41.67 \]  \hspace{1cm} (7)

Among the above categories: \( W_a \) represents air resistance, \( W_m \) represents electromagnetic resistance, and \( W_c \) represents flow resistance, unit N; \( N \) denotes the number of vehicles, and this paper takes 1 for single vehicle. \( M \) stands for train weight, unit t; \( v \) denotes the running speed of the train in a still wind state, unit m/s; \( k_1 \) to \( k_6 \) is the correction coefficient, \( k_1=1, k_2=1.9, k_3=1.5, k_4=1.5, k_5=1.8, k_6=2 \).

The total resistance calculation formula of the engineering vehicle is: 
\[ W = W_a + W_m + W_c \]  \hspace{1cm} (7)

5. Ttractive performance
In the traction calculation in this section, three levitation frame maglev vehicles are adopted, that is, one vehicle includes three levitation frames and six LIMs. The full load vehicle weight is 18t, the velocity range is calculated to be 0-160km/h, and the maximum speed running resistance is calculated to be about 6.4kN. The range of slip frequency used for medium-low speed maglev vehicle is 8-14hz. The acceleration distances and average accelerations of each speed range by different CSFC are calculated. The variation of tractive performance by different CSFC is compared and analyzed. The calculation results are shown in figure 5.

It can be seen from figure 5, when low slip frequency is used, the average acceleration at low speed is larger and the acceleration distance is shorter; the acceleration distance and average acceleration of different slip frequency have little difference between 0 and 120km/h speed intervals. At the speed range of 0-160km/h, the average acceleration controlled by the low slip frequency is significantly reduced, while the acceleration is more stable under the higher slip frequency. Therefore, the slip frequency is relatively small, and the traction capacity of the vehicle is relatively strong in the initial stage, but it decays quickly after reaching the constant power point.

6. VSFC strategy

The design speed of the motor analyzed is 160km/h, so the selected range of traction calculation and control strategy is 0-160km/h. The detailed variable slip control strategy is shown in figure 6. When the speed is less than 90km/h, the constant slip frequency control of 9Hz is selected. Under the air gap of 11mm, the normal force of the LIM is about 250N and the traction is about 4200N, as shown in figure 7 and 8, the influence of normal force caused by the starting slip frequency on levitation stability can be ignored. At the speed range of 90-130km/h, the slip frequency increases linearly to 18Hz. At the range of this region, the maximum output power of the motor remains unchanged and the real constant power area is maintained. At this time, the traction curve of the motor with the speed goes through the constant power transition at each slip frequency. When the speed is greater than 130km/h, the slip frequency remains unchanged at 18Hz, at which time the motor can exert the maximum output force that can be achieved in the speed section.
Figure 6. VSFC strategy

Figure 7. The traction by the VSFC strategy

Figure 8. The normal force by the VSFC strategy

Table 2. Tractive performance under VSFC

| Speed Range (km/h) | 0-40km/h | 0-80km/h | 0-120km/h | 0-160km/h |
|-------------------|----------|----------|-----------|-----------|
| Accelerating distance (m) | 38.08/36.56 | 177.61/171.02 | 457.58/486.23 | 1175.78/1294.84 |
| average acceleration (m/s²) | 1.27/1.32 | 1.24/1.29 | 1.15/1.09 | 0.90/0.79 |

In Table 2, the left side data is the tractive performance by the VSFC strategy, and the right side data is the optimal value of the corresponding speed section by the CSFC of 8-14 Hz. It can be seen that when the speed is below 80km/h, the data of constant slip frequency control is better, because the data at this time is the result by 8Hz, but the normal force of the CSFC is 2 times that of the VSFC strategy. At high speed ranges of 0-120km/h and 0-160km/h, the average accelerations and acceleration distances by the VSFC strategy are better than the maximum by the CSFC. Therefore, the VSFC strategy has obvious advantages considering comprehensively the tractive performance and the normal force suppression.

**7. Conclusion**

1) Although the lower slip frequency makes the vehicle starting acceleration larger, the normal force is also larger, which brings a burden to the levitation system. The traction attenuation in the constant power zone is faster, which makes the vehicle difficult to drive at a higher speed. The higher slip frequency makes the starting normal force as the repulsive force, which can reduce the burden of the levitation system, but accelerates slowly at the low speed range and the acceleration time is longer.
2) The constant slip frequency control cannot give full play to the tractive performance of the LIM. In this paper, the VSFC strategy is proposed, the constant force region controls the normal force to a small size; after the maximum power point, the traction of the motor is always the maximum value the LIM can exerts at the corresponding speed. The VSFC strategy can effectively control the starting normal force and improve the tractive performance of the maglev vehicle.

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