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DESIGN OF SINGLE-SIDED LINEAR INDUCTION MOTOR FOR LOW-SPEED MAGLEV VEHICLE IN 160 km/h AND VARIABLE SLIP FREQUENCY CONTROL

Background: The mid-low speed Maglev train adopts the single-sided linear induction motors (SLIMs) as drive part, of which design and control method has become research hotspot when the velocity is elevated from 120 km/h to 160 km/h.

Aim: For SLIMs applied in 160 km/h low-speed maglev train, the design scheme is introduced and then a novel variable slip frequency control method is proposed.

Methods: This control method adopts low slip frequency at start-up to produce large starting traction force and high slip frequency during high velocity area to obtain great power. The influence to the normal force is also investigated.

Results: With this method, the weight of the system can be effectively reduced and the lightweight design of SLIM is realized.

Conclusion: The novel variable slip frequency control method meets the requirement of both high starting acceleration and enough residual acceleration for 160 km/h mid-low speed maglev train.

Keywords: Mid-low speed maglev train; linear induction motor; slip frequency; traction force; normal force

INTRODUCTION

The Changsha medium-low speed maglev line is the first commercial operation line in China and the longest one in the world. Its designed velocity is 120 km/h, and the running velocity is 100 km/h. During its two-year long commercial operation since May 6th, 2016, the longest mileage has reached 400,000 km and the punctuality rate has reached 99.8 %, which has set a good exemplary role. After the successful operation of the Changsha maglev line, the intercity transportation with higher speed class (160 km/h) by adopting the maglev train is put on the agenda. This paper presents the design of SLIMs for mid–low speed maglev train with velocity 160 km/h and optimizes the force performance from the aspect of control method.

1. BASIC PARAMETERS OF MAGLEV TRAINS IN CHANGSHA LINE

The mid-low maglev train in Changsha line consists of three coaches. Each coach covers five suspension frames, one converter and ten SLIMs. The

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basic parameters of the train and the converter are listed in Table 1. Ten SLIMs are equally divided into two groups, which are connected in parallel. To five SLIMs in one group, the phase windings connected in series are transposed to reduce the end effect, as shown in Fig. 1. As it can be seen, three phase windings are Y connected.

Table 1. Basic parameters

Item	Parameters	Value
Vehicle	Voltage of power network /V	DC1000~1800
	Track gauge /mm	1860
	Running velocity/ km/h	100
	Design velocity / km/h	120
	Coach number	3
	Vehicle mass（AW2）/t	30
	Starting acceleration /m/s^2	1.0
	Average acceleration/m/s^2	0.4
	Residual acceleration/m/s^2	0.1
	Number of suspension frame	5
Converter	Input voltage /V	DC1000~1800
	Rated line voltage/ V	1100
	Rated maximum current /A	2×340
	Rated Continuous current /A	2×240

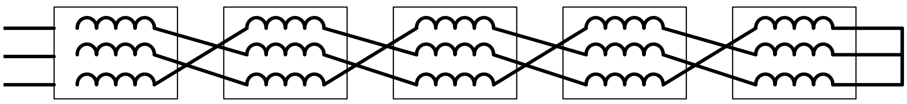

Fig. 1. The winding connection of five SLIMs in one group

2. DESIGN ANALYSIS OF SLIMS FOR 160KM/H MAGLEV TRAIN

2.1 Traction force requirement

The 160 km/h maglev train also adopts three coaches. Its resistance force can be calculated by adopting the resistance formula of the Changsha maglev line, which includes three components as follows.

1) Magnetic resistance force

The magnetic reluctance force D_m can be calculated by piecewise formula as follows:

$$D_m = \begin{cases} 3.354Wv & v < 5.6\text{m/s} \\ (18.22 + 0.074v)W & v > 5.6\text{m/s} \end{cases}, \quad (1)$$

where W is the vehicle mass (t), and v is the running velocity (m/s).

2) Relay resistance force

The relay resistance force D_c is almost constant, which value is 41.67 N.

3) Aerodynamic resistance force

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The aerodynamic resistance force D_a mainly depends on the velocity and coach number.

$$D_a = \left(1.652 + 0.572N\right)v^2 , \qquad (2)$$

where N is the coach number.

The total resistance force D is the sum of three former components. The traction force F is obtained through the total resistance force and acceleration.

$$F = D_m + D_c + D_a + Wa = D + Wa , \qquad (3)$$

where a is the acceleration.

When the running velocity is increased from 120 km/h to 160 km/h and the minimum residual acceleration is maintained at 0.1 m/s^2, the power increases by 66.7 %, as shown in Table 2.

Table 2. Power requirement of the 160 km/h maglev train

Design velocity	120 km/h	160 km/h
Vehicle mass / t	30	32
Total resistance force / kN	5.65	8.76
Traction force/per motor / kg	50	62.5
Vehicle power / kW	490	816.7

2.2 Basic parameters of traction system

As the vehicle power increases, the number of converters or the capacity of single IGBT needs to be increased. Obviously, it is more economical to increase the IGBT capacity. The maximum current of available IGBT with matching voltage level is 2×450 A. Therefore, the power can increase by 32 % in comparison with the Changsha lines with IGBT of 2×340 A maximum current.

Since the IGBT capacity does not increase by 66.7 %, it means the starting traction force should be reduced or the volume should be improved to reduce the starting current. According to the consultation with the OEM, the length of SLIM can be increased from 1,820 mm to 2,020 mm. In addition, the starting traction force is reduced since the starting acceleration is changed from 1.0 m/s^2 to 0.8 m/s^2, which meets the start acceleration of the general intercity vehicle.

2.3 Vehicle configuration

The number of modules per train and the selection between available mode (five-string double-parallel) and new mode (two-string five-parallel mode) need to be determined. The most economical and reliable method is to keep the original vehicle structure.

2.4 Design requirements

Based on the foundation of the Changsha maglev line, the main design requirements of the 160 km/h maglev train are listed in Table 3.

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Table 3. Power requirement of the 160km/h maglev train

Vehicle mass (AW2) / t	32
Mechanical air gap of SLIMs / mm	12
Length of the SLIM / mm	2020
Converter input current / A	2×450
Maximum vehicle velocity / (km/h)	160
Average starting acceleration(0~70 km/h) / (m/s^2)	≥0.8
Average acceleration (0-160 km/h) / (m/s^2)	≥ 0.4
Residual acceleration (160 km/h) / (m/s^2)	≥0.1

3. THE DESIGN OF SLIMS

3.1 Basic parameters

Based on the former analysis, the SLIMs, JX170, applied in the 160 km/h maglev train is designed, shown in Fig. 2. The train has the original five-module structure and SLIMs per coach with five strings two parallel connection mode. The motor basic parameters comparison with SLIM of the Changsha maglev line, JX130, are listed in Table 4.

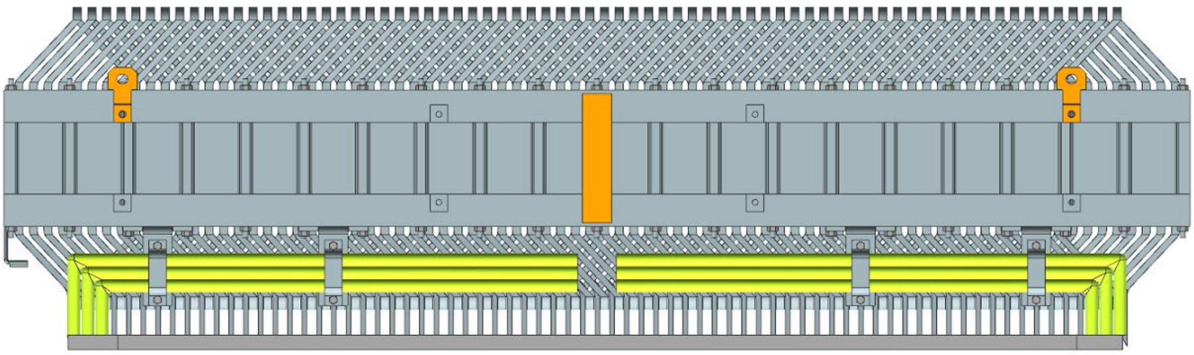

Fig. 2. JX170 SLIM

Table 4. Basic parameters comparison of two SLIMs

SLIM type	**JX130**	**JX170**
Rated voltage/V	220	
Pole number	8	
Thickness of the aluminum plate/mm	4	
Width of F-shaped rail/mm	220	
Starting current/A	340	450
Rated current/A	240	360
Starting force/N	3,234	2,764
Primary mass/kg	200	215
Pole pitch/mm	202.5	225
Primary length/mm	1,820	2,020
Air gap/mm	13	12

3.2 Control settings

The control method of the SLIMs for magnetic levitation trains is different from that of the induction traction motor for subways. First, for simple

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control, the SLIMs for magnetic levitation trains generally use constant current and constant slip frequency control method. Second, SLIMs must consider the effect of the normal force. Therefore, the suitable slip frequency f_2 is important parameter for SLIMs.

With the equivalent circuit of an induction motor, the influence of slip frequency on SLIMs performance can be analyzed.

Normally, constant current control method is used during start-up. Their relationship is shown as follow. Apparently, the traction force is inversely proportional to the slip frequency, f_2.

$$F_x = \frac{mR_2^{'}(I_2^{'})^2}{2\pi f_1 s} = \frac{mR_2^{'}(I_2^{'})^2}{2\pi f_2}, \quad (4)$$

when the starting acceleration of the train reaches 0.8 m/s^2, the traction force per SLIM is 2567 N. Under this condition, the maximum slip frequency f_2 should be 15.7 Hz. If adopting the control method of constant slip frequency, the traction force at maximum velocity is 710N per SLIM and the residual acceleration of the train at 160 km/h is 0.13 m/s^2.

At high velocity, the SLIM already adopts full voltage. The SLIM torque-slip curve is similar with induction-machine. As can be seen from Fig. 3, during the motor region, the higher the f_2, the higher the slip, and the larger the traction force is.

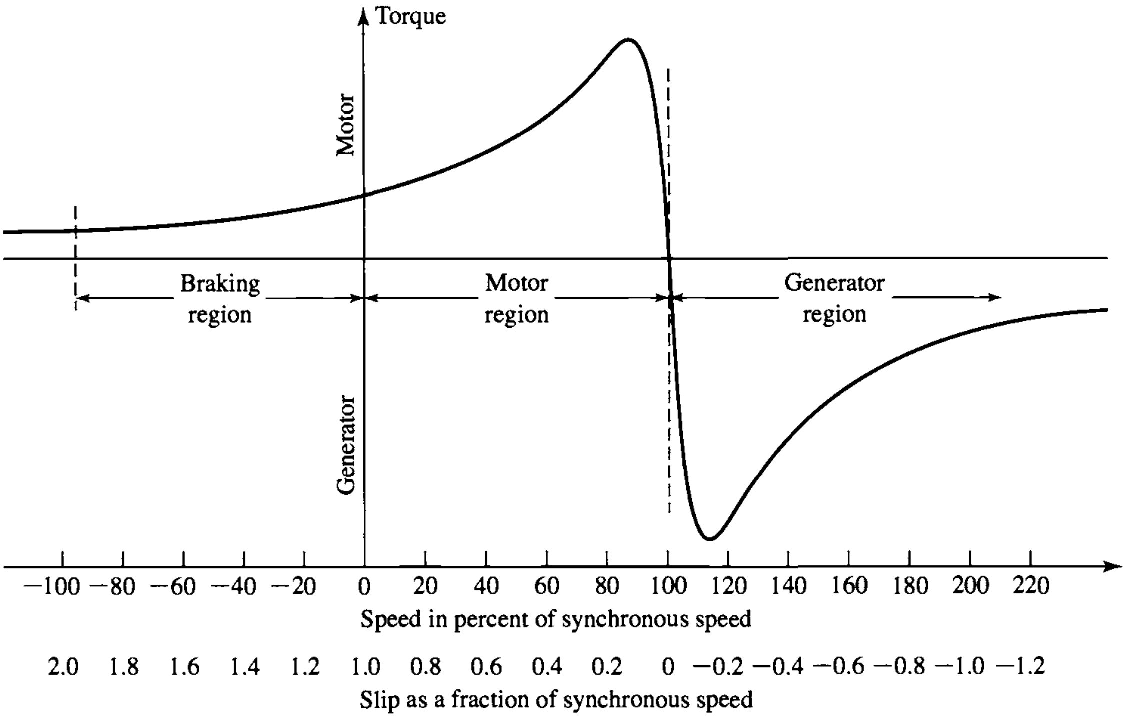

Fig. 3. Induction-machine torque-slip curve during whole operation area

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When the required remaining acceleration is 0.1 m/s^2, the traction force per SLIM is 612 N. To this required traction force, the minimum slip frequency f2 is 13.7 Hz. If keeping this slip frequency as constant value, the starting traction force can be increased up to 2,764 kg.

In order to verify the former traction force at start-up and maximum velocity, the 3D model of JX170 is erected by 3D FEM. For slip frequency 13.7 Hz, the calculated thrust force at start-up is 2,720 N. For slip frequency 15.7 Hz, the calculated thrust force at maximum velocity is 753 N. Compared with the predicted results of equivalent circuit method, the errors are 44 N and 43 N under two conditions respectively. Apparently, the results of equivalent circuit method are reasonable.

Therefore, the slip frequency should between 13.7 to 15.7 Hz. The traction characteristics are shown in Fig. 4 with the slip frequency values of 13.7 Hz and 15.7 Hz, respectively. And the normal force is considered acceptable.

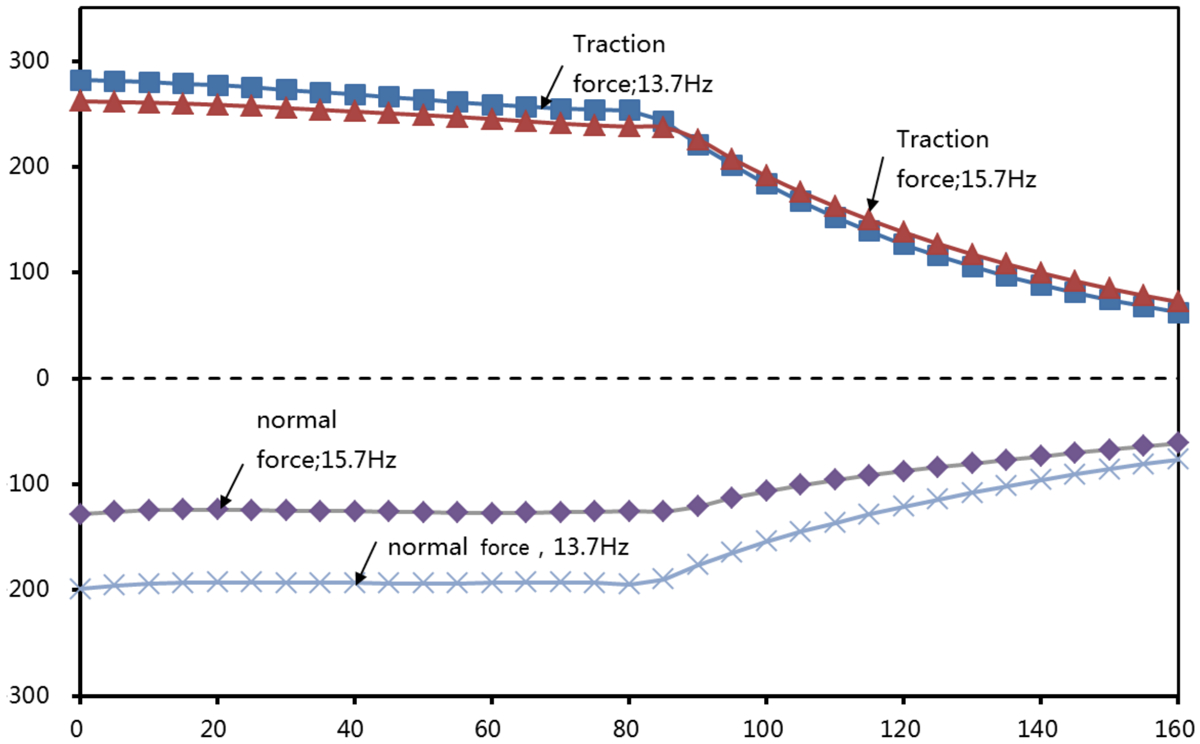

Fig.4. The traction characteristics with the constant current slip frequency 13.7 Hz and 15.7 Hz

4. VARIABLE SLIP FREQUENCY CONTROL METHOD

From former analysis, it can be deduced that the SLIM performance of high velocity or low velocity is inevitably sacrificed when a constant current and constant slip control method is applied. However, this can be avoided if variable

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slip control method is adopted in SLIMs. Since they start with a lower starting frequency to produce larger starting traction force, and operate with higher slip frequency to obtain larger power at high velocity area, the capacity can be fully utilized.

To JX170 SLIMs, at the low velocity, the slip frequency 13.7 Hz is adopted to increase the starting traction force. At high velocity, the slip frequency is increased to 17.2 Hz, which increases the traction force. The traction characteristics are shown in Fig. 5. This method considers the starting acceleration and the residual acceleration of high velocity, which increases the starting capability and reduces the starting distance.

When the variable slip frequency control method is used, the traction characteristics of the train can only be within the envelope to meet a certain overload capacity. Moreover, it should not be far away from the envelope to make full use of motor capability as shown Fig. 5

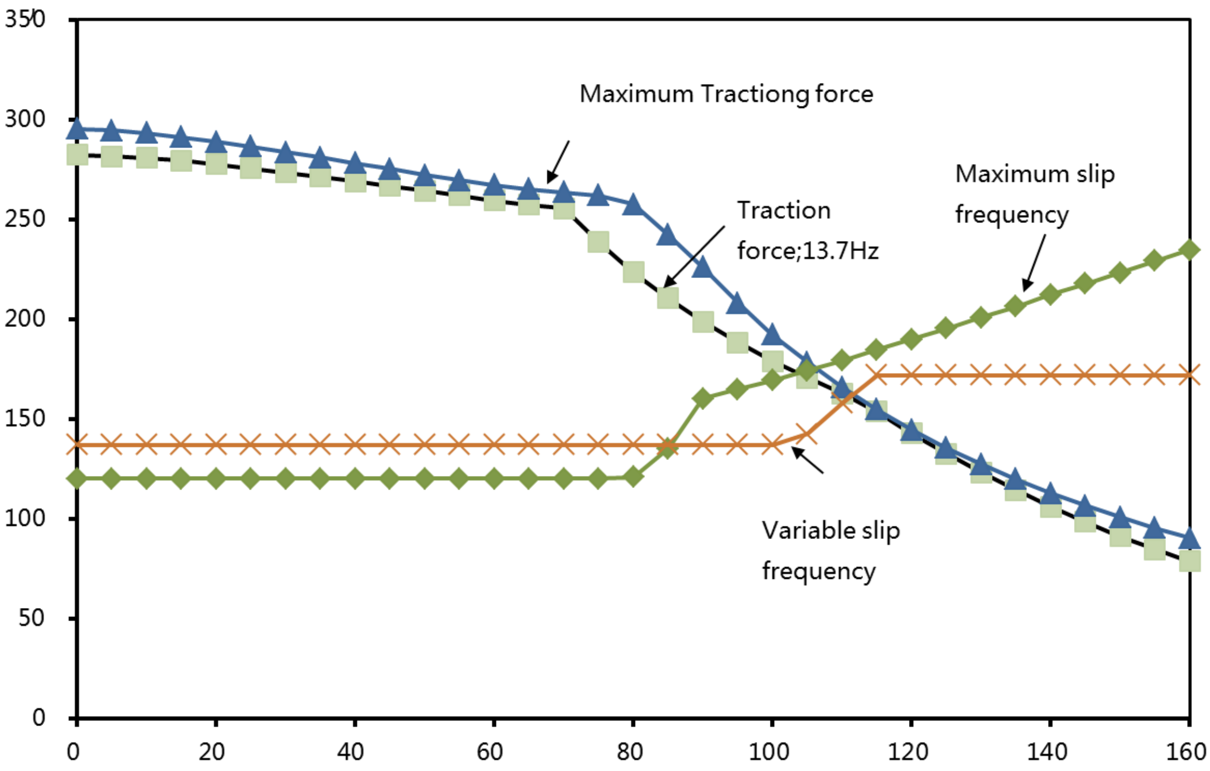

Fig. 5. Maximum traction force curve

With slip frequency change from 13.7 Hz to 17.2 Hz, the residual acceleration is increased by 70 % compared with the constant slip frequency control method, and then the acceleration time is reduced by 17 % and the acceleration distance is reduced by 22 %, as shown in Table 5.

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Table 5. Starting performance of variable slip frequency control method

Control method	Constant slip frequency	Variable slip frequency	Change rate
Start-up frequency /Hz	13.70	13.7	
Start acceleration/(m/s^2)	0.86	0.86	
End-up slip frequency /Hz	13.7	17.2	
Residual acceleration/(m/s^2)	0.10	0.17	+ 70 %
Average acceleration/(m/s^2)	0.40	0.48	+ 20 %
Acceleration time /s	110.6	91.7	– 17 %
Acceleration distance/m	3,369	2,613	– 22 %

5. CONCLUSION

This paper presents the design of SLIMs for mid–low speed maglev train with velocity 160 km/h, which meets the performance requirement of the 160 km/h mid-low speed maglev train. It has the characteristics of derivative design and economical reliability.

It also proposes a variable slip frequency control method for the SLIM. With a lower slip frequency at start-up, the SLIM has a larger starting traction force. At high velocity, a higher slip frequency is used, and a larger motor power is realized. The train acceleration performance is optimized without additional space, mass and cost. This proposed control method can also be applied to other maglev trains driven by SLIMs.

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