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Characteristic Analysis of Permanent Magnet Linear Synchronous Motor for Rope-less Hoist System

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Keywords: permanent magnet linear synchronous motor (PMLSM), rope-less hoist system, finite element method (FEM), characteristic analysis

Abstract. Permanent magnet linear synchronous motors (PMLSMs) is the best driving motor for rope-less hoist system because of the advantages of simple structure, small volume, high force, unlimited hoisting height and speed. In this paper, the finite element method (FEM) is adopted to design a PMLSM with 16-pole 15-slot as a unit for rope-less hoist system. Through the FEM analysis, the EMF constant K_e and the force constant K_f of unit motor were got. Then a direct driving elevator prototype drove by the proposed PMLSM was built. Experimental results show the stable operation performance of the experimental device, having good prospects for the development and application.

Introduction

Linear motor with the advantages of simple structure, low noise, high precision, easy maintenance etc., has been widely used, gradually into people's daily life. With the high-rise building higher and higher, mining more and more deep, it needs higher requirement for hoist system to save energy and space, enhance capacity, improve safety and performance. The traditional wire rope hoist system will encounter insurmountable problems, such as hoisting height constraint, operating speed constraint, larger space occupied, lower force-energy index, and so on. So, it urgently needs to develop a new hoist model instead of the traditional model. The rope-less hoist system driven by linear motor is the best choice, which is proven as the hot research topic to solve the hoisting problems for the high-rise buildings and ultra-deep mine [1, 2].

Permanent magnet linear synchronous motor (PMLSM) combining the advantages of permanent magnet motor and linear motor, is generally acknowledged as one of the best driving sources for rope-less hoist system. PMLSM rope-less hoist system shows a novel hoist mode without rope, balance weight, intermediate drive, restriction of the hoisting height and speed. With the advantages, such as simple structure, small volume, high-efficiency, high hoisting capacity, easy to realize the multi-car, PMLSM rope-less hoist system can be widely used in high-rise buildings and the mine hoist [3~5].

It is an important technical problem for PMLSM rope-less hoist system to design the derived PMLSM with large force and good performance. In this paper, the FEM is used to design a PMLSM with 16-pole 15-slot as a unit to drive the rope-less hoist system. The waveforms of the EMF and the force with different power angle of unit motor were got through the FEM analysis, then the EMF constant K_e and the force constant K_f were calculated. In order to the experimental research, a rope-less hoist system prototype drove by the proposed PMLSM was built. Experimental results showed the safe and stable operation performance of the experimental device, with good prospects for the development and application of PMLSM rope-less hoist system.

Structure of 16-pole 15-slot unit motor

The driving motor is designed, 16-pole 15-slots as a unit, shown in Fig. 1.

In addition to minimizing the length of the winding end, improve the air gap flux density, inhibit the thrust force fluctuations, fractional-slot concentrated winding is used in the design of the driving motor, which improves the stability of the whole system. As Fig.1shown, precondition the thrust force to be ensured, this type of unit motor minimizes the axial length in order to reduce the normal force of the PMLSM. This type of structure can effectively suppress the impact of the inherent normal force of PMLSM. The winding arrangement is shown in Fig. 2.

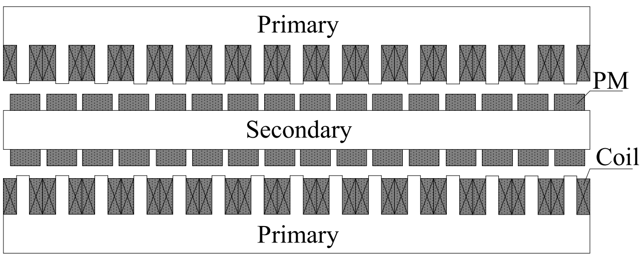

Fig. 1 16p15s PMLSM physical structure model

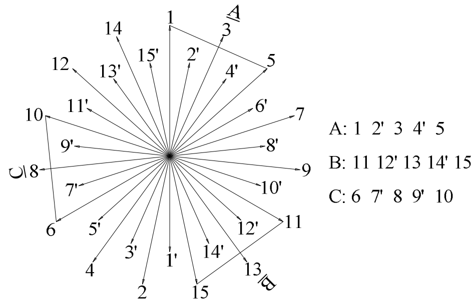

Fig. 2 Winding arrangement of 16p15s PMSM

As Fig. 1 shown, the 16p15s PMLSM physical structure model of a unit motor is double side structures. The hoisting capability of whole rope-less hoist system can be enhance by increasing the number of the unit motors. For whole system, the sub-station power supply is used, not only saving, but also reduces the power capacity requirements.

As Fig.2 shwon, the electrical angle of the adjacent two teeth is 16×360/15=384deg. The vector diagram of electromotive force (EMF) generated by the primary winding. As Fig. 2 shown, the EMF vectors of the 15 stator coils are named consecutively from 1 to 15, and 1′ represents the reverse vector of 1, then numbering successively. The 15 EMF vectors are divided into symmetric three groups, and then per phase in series, the three phase winding will be got. This type of winding configuration has high winding factor and low loss, and can also reduce the cogging force.

Finite element method analysis

FEM model

The finite element method (FEM) is adopted to build the model of 16-pole 15-slot unit motor. This type of PMLSM has two salient features. The one is that the slot pitch is close to the pole pitch. The other is that the fractional-slot concentrated winding is adopted in the stator design. This unit motor with 16-pole 15slots has lower cogging force and high thrust force density.

Analysis results of FEM

The relative movement of the primary and secondary can be processed by a moving edge boundary, i.e., a moving line in the air-gap. In order to improve the solving precision, the method of self-adaptive time stepping is adopted to adjust the space length of FEM. After moving for a time stepping, the size of the mesh between the primary and secondary isn't changed, but only the grids in the moving region, which will be meshed again for each time stepping, is changed. The layering research and the adaptive method are adopted to choose the proper time-stepping in the area where the magnetic density changes heavily.

Based on the FEM model with double side structure, the FEM analysis is done. While the correlative solving results of single FEM model can be converted through the solving results of double side structure FEM model.

The magnetic flux distribution and air-gap induction spatial distribution are the precondition to check FEM model and accurate calculation.

Fig. 3 and Fig. 4 show the two-dimensional magnetic field lines distribution of armature reaction magnetic field and the resultant magnetic field of 16p15s unit PMLSM respectively, when the A-phase current reaches maximum and the currents of B-phase and C-phase are the half of the A-phase current.

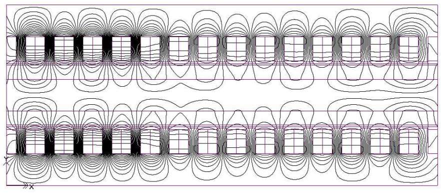

Fig. 4 Armature reaction magnetic field

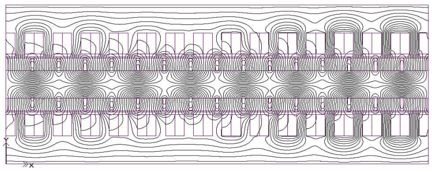

Fig. 5 The resultant magnetic field

As Fig. 3 hown, the armature reaction magnetic field is dense at the A-phase winding, corresponding air-gap induction higher. The air-gap induction is well-proportioned at the A-phase and B-phase winding, because the corresponding armature reaction magnetic field is even.

In the Fig. 4 the resultant magnetic field has a little asymmetry, because the armature reaction magnetic field is smaller than the PM excitation magnetic field.

Because of the even symmetry boundary condition in the primary, the two-dimensional magnetic field lines distribution of armature reaction magnetic field and the resultant magnetic field, shown in Fig. 3 and Fig. 4 are consecutive at the end of the FEM model.

The EMF is an important parameter for the analyses and calculation of the motor performance. For the 16-pole 15-slot unit PMLSM with double side structure, when the air-gap is 2.6mm, the EMF waveform is got at the speed 0.5m/s, shown in Fig. 5.

Based on the analysis of the FEM model with double side structure, the characteristic waveform of the thrust force with different power angle is got, shown in Fig. 6.

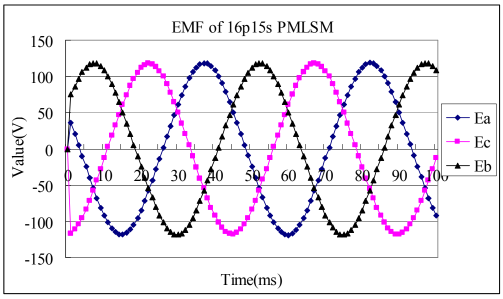

Fig. 5 Waveform of EMF

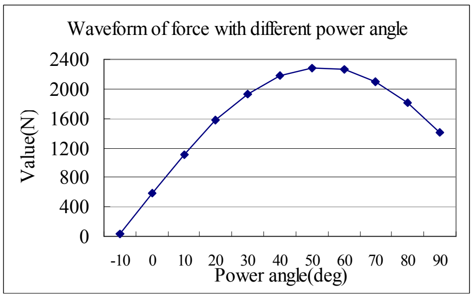

Fig. 6 Waveform of force with different power angle

As Fig. 5 shown, the EMF waveforms of A-phase, B-phase and C-phase are very sinusoidal, with 120^0 phase mutual deviation. The amplitudes of E_a, E_b and E_c are accordant. Then the EMF constant K_e can be got through the following equation.

$$K_e = \frac{E_a}{v} = \frac{80.7}{0.5} = 161.4 \text{ Vp-nrms/m/s} \tag{1}$$

In general, because primary resistance of permanent magnet motor r_s is much smaller than the synchronous reactance X_t, the impact of primary resistance can be negligible. So, the power angles 0^0 and 90^0 correspond to $0Nm$ and the maximum thrust force. However, the $0Nm$ and the maximum thrust force aren't at the power angle 0^0 and 90^0 respectively in the Fig. 6, which maybe due to the low simulation operating frequency of the unit motor.

When the frequency is low, the voltage drops in the primary resistance increases significantly, and the unit motor has the characteristic of the small reactance and large resistance, which results that the power angle is negative when the thrust force is zero. Furthermore, the interval of the positive thrust force becomes narrower.

In Fig. 6, considering 1.25~1.5 time of overload, the best operating force of the double-side structure unit driving motor with 16-pole 15-slot, namely the rated force, is 1700N, and the corresponding current is 3.6A. So, the force constant K_f of 16-pole 15-slots unit motor can be calculated through the following equation.

$$K_f = \frac{F_N}{I_N} = \frac{1700}{3.6} = 472.2 \text{ N/Arms} \tag{2}$$

Experiment

Experimental Platform

In order to verify the feasibility of the nonel rope-less hoist system, elevator prototype, named direct driving high-speed elevator drove by the proposed PMLSM with double-U type structure was built, shown in Fig. 7.

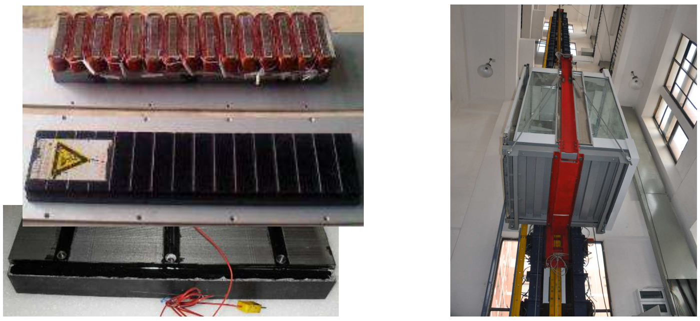

Fig. 7 A unit driving motor and elevator prototype

It should be noted that this elevator prototype uses double-U type PMLSM as the driving source, arranged on both side of the shaft. This type of double-U type driving scheme has the simplest principle, which can inhibits the effect of the normal force of PMLSM to the operation of the rope-less hoist system. The primary of the prototype is the stator; while the secondary of the prototype is the mover, composed of 10 secondary of the 16-pole 15-slot unit motor.

General Testing of Single Side Structure Unit motor

For 16-pole 15-slot unit motor with double side structure, the insulation, pressure, resistance, inductance testing are done, shown in Table 1.

Table 1 Results of general testing

Items [units]	Value
Insulation resistance [GΩ]	2
Pressure-resisting values [V]	1500
Leakage current [mA]	1.5
Resistance of A phase R_a [Ω]	13.50
Resistance of B phase R_b [Ω]	13.42
Resistance of C phase R_c [Ω]	13.36
Inductance of A phase L_{aa} [mH]	114.48
Inductance of B phase L_{bb} [mH]	113.08
Inductance of C phase L_{cc} [mH]	114.04

EMF testing results

The mover of the elevator prototype is drayed by electric field vector hoist at the speed almost 0.06m/s, the measured results of the EMF is shown in Fig. 8.

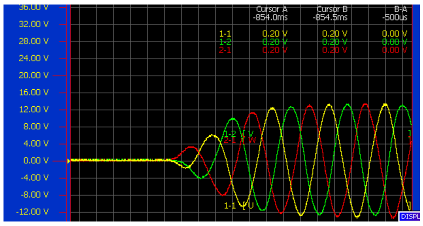

Fig. 8 The measured results of the EMF

Load Experiment

The thrust force, current, the force constant K_f were got at the different load, shown in Table 2. It is noted that the experimental results are eventually converted to unit PMLSM.

Table 2 Load experiment results of 16-pole 15-slot unit PMLSM

Thrust force (N)		1068	1110	1378	1426	1694
Current (A)		2.26	2.38	2.91	3.04	3.58
K_f (N/Arms)	Testing results	472.6	466.4	473.6	469.0	473.2
	FEM	472.2				

Conclusion

In this paper, FEM was used to design and analyze a 16-pole 15-slot unit PMLSM for the rope-less hoist system. The EMF constant K_e and the force constant K_f were got. And then a rope-less hoist system prototype drove by the proposed PMLSM was built. The experiment results showed the good operation performance, and verify the feasibility of the role-less elevator by the proposed PMLSM.

Acknowledgements

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