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Research on the Operation Control for Rope-less hoist system Driven by Permanent Magnet Linear Synchronous Motor

ZHANG Hongwei [1], WANG Xinhuan[1], YU Fashan[1]

1. School of Electrical Engineering & Automation, Henan Polytechnic University, Jiaozuo, Henan Province,454000, China
E-mail: zhanghw@hpu.edu.cn

Abstract: The rope-less hoist system driven by Permanent Magnet Linear Synchronous Motor (PMLSM) is a revolutionary new technology for high-rise buildings, but also requiring new technology for propulsion, safety and control. Based on the analyzing of rope-less elevator driven by PMLSM, the article proposes the operation control system, designs the power supply system and safety control system. Linear motor drives load directly without any mechanical transfer 1inks. On the basis of theory of direct torque control in asynchronous motor, principle of Direct Thrust Force Control (DTFC) for PMLSM is analyzed in this paper. Simulations with SIMULINK of MATLAB have been given to demonstrate validity of the control system. The obtained results are expected to be usable for extra-rise buildings.

Key Words: Rope-less elevator, Permanent Magnet Linear Synchronous Motor, Operation control, Power supply, Safety protection system, Direct thrust force control

1 Introduction

Many skyscrapers have been built so far in the world, where the high-speed elevators have been developed in order to meet the demand. The typical elevators employ the rope-hoisted method. With the continuous increase in building height, the rope weight may exceed the limit of the strength of the rope itself if the rope length becomes lager than 1,000m. Besides, more than one car cannot be operated in one shaft in the case of the rope elevator method. Therefore rope-less elevators are required to realize a high-rise skyscraper elevator system with sufficient transport capacity. In the nineties of 20th century, the concept of vertical transportation system driven by linear synchronous motor was proposed and began theoretical and experimental research. It mainly used in skyscraper elevators and mine hoisting systems [1, 2, 3]. PMLSM has the characteristics of larger thrust, high efficiency, high power factor and energy conservation, is the ideal driving source for rope-less hoist system. It drives the elevator car directly without wire rope and breaks the limitations of rope-hoisted method.

Supported by the National Natural Science Foundation of China, Innovative Talent's Fund of Henan Province, and Innovation Scientists and Technicians Troop Construction Projects of Henan Province, etc. we have been carrying out search work in the modeling, driver, safe operation control of PMLSM, and constructed a rope-less elevator system driven by PMLSM [4-9]. In the paper, we described the structure and features of rope-less elevator. The operational control system for rope-less elevator is proposed. Finally we introduced the direct thrust force control strategy.

2 Description of Rope-less Elevator Driven by PMLSM

Fig.1 shows the configuration of the rope-less elevator experimental apparatus. It has been driven by a double sided PMLSM.

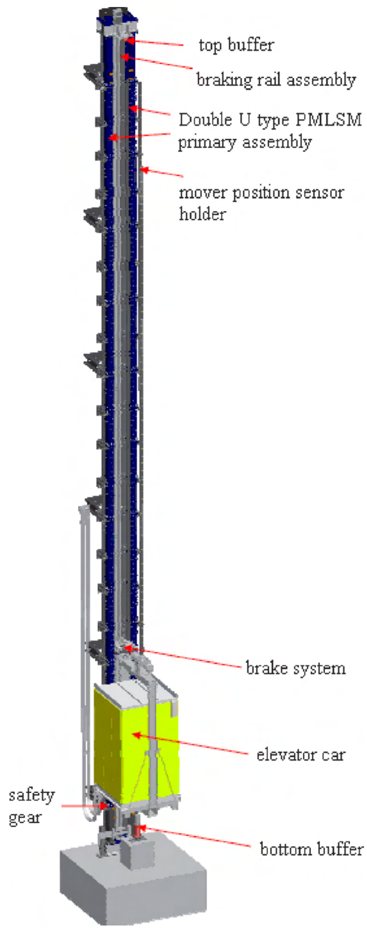

Fig.1: Rope-less elevator driven by PMLSM

A permanent magnet type secondary has been mounted to the elevator car. The guide rail has been equipped with primary, which faced to the secondary. The cage has been supported with a set of wheels so as to move up and down and to keep the air gap between the primary and secondary member. The attracting force adsorbs the mover on the track, which can make the elevator car stable. The specification of the rope-less elevator is shown in Table 1.

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Table 1: Specification of Rope-less Elevator

Name	Value
Driving mode	Double U-type PMLSM
Rated power	35 [kW]
Rated current	4 [A] (single motor)
Rated current	8[A] (Double U type motor)
Mass of rated load	3000[kg]
Movable height	18 [m]
Rated velocity	1 [m/s]

For long stator configuration, the length of the stator sector to be energized has a direct effect on the number of converters and on the resulting efficiency. The optimum is a traffic performances and an economical trade-off, requesting simulations of the full system. Long stators will be constructed by placing unit armatures in rows along the guide way. Driving power is only supplied to the armatures facing permanent magnets and the other armature windings are shorted circuit. In case of interruption in the power supply, the elevator car will go down at slow speed by energy consumption braking.

In the first two generation rope-less elevator experiment apparatuses, the form of motor winding selects integer-slot winding which has the problems that thrust fluctuation is large and end part of the stator coil is long. In the new rope-less elevator we use concentrated fractional-slot winding which can reduce slot effects of PMSLM. Moreover, slot thrust fluctuation curve can be fit out. The new PMLSM selects 16-pole 15-slot as one unit. Four units assemble one double U type motor. The rope-less elevator is driven by two PMLSM with double side structures. The design scheme of double side structures is shown in Fig2.

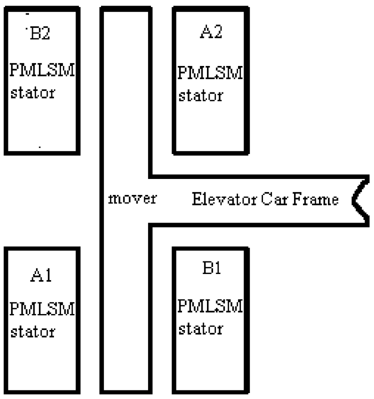


Fig.2: Distribution map of double U-type motor stators

Stators wiring diagram of double U-shape motor is shown in Fig.3. Wiring uses star method. A1 and B1 are assembled in series connection; A2 and B2 are assembled in series connection, and then assembled parallel.

3 Design of Operation Control System

The rope-less elevator operation control system is consists of a traction system, the guidance system, elevator car systems, door systems, electric drive systems (thrust and speed control system), stators power supply system, signal detection system, electrical control system and safety control system. The scheme of rope-less elevator operation control system driven by PMLMS is shown in Fig.4.

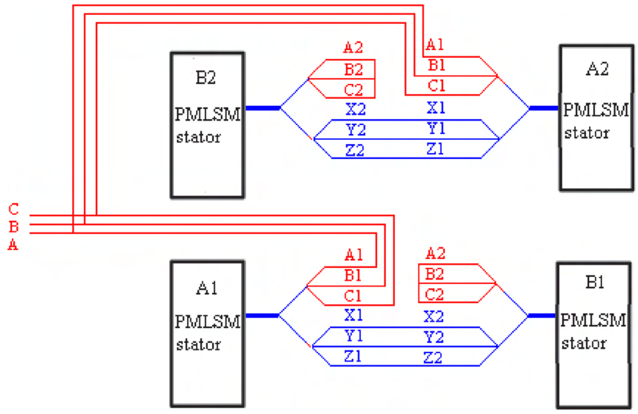


Fig.3: Stators wiring diagram of double U-shape motor

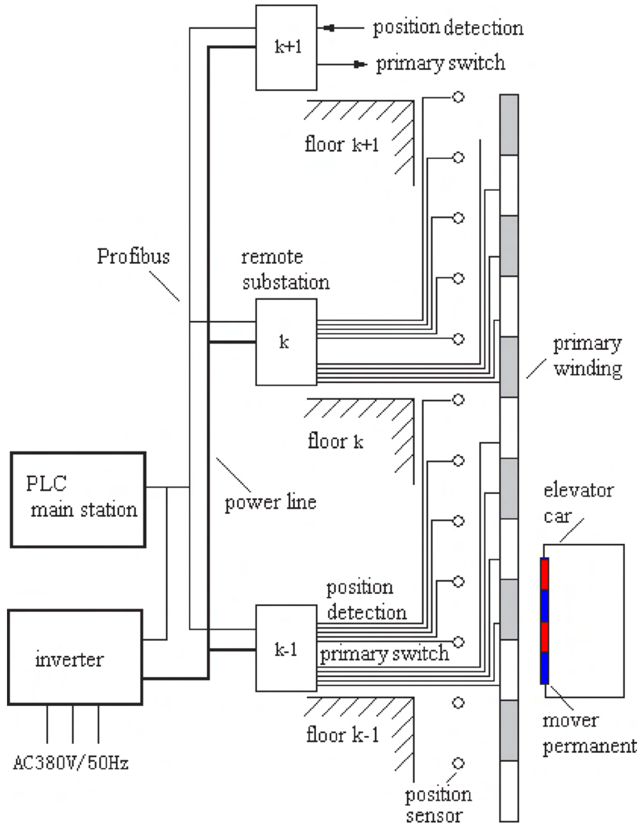


Fig.4: Scheme of rope-less elevator operation control system

The electrical control system selects SIEMENS S7-300 PLC as control station. PLC is responsible for data acquisition and control output. The safety protection system is designed to make sure the rope-less system operating safely under any turbulence.

3.1 Power Supply System

Driving power is only supplied to the armatures facing permanent magnets and the other armature windings are shorted circuit. In order to realize the power supply and energy consumption braking, we select a special AC contactor which has three normal open main contacts and three normal main close contacts. Every unit stator is powered by an AC contactor [8, 9]. The general scheme of power and energy consumption braking system is shown in Fig. 5. The contactors are controlled by remote I/O module ET200M. Under normal drive condition, PLC controlled the contactors to power the stators facing permanent magnets according to the position signal of mover. In case of interruption in the power supply, the armature windings will be short circuited by contactor and cutting off inverter. The cage will go down at slow speed by energy consumption braking.

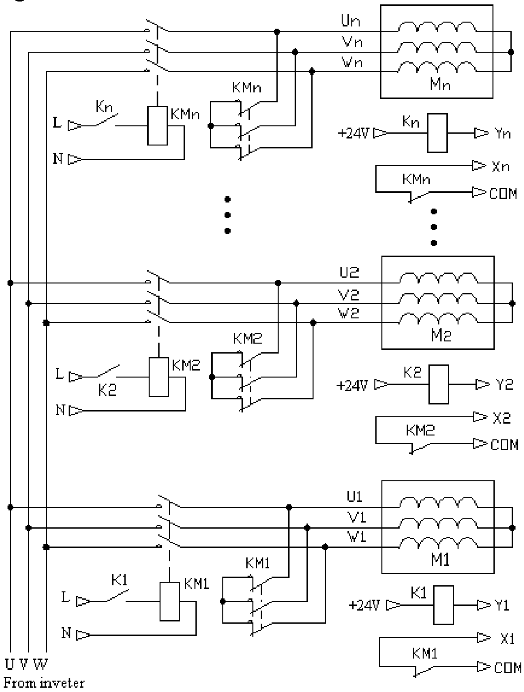


Fig.5: Power and energy consumption braking system scheme

3.2 Safety Control System

According to the features of PMLSM rope-less elevator, quadruple protections are designed: energy consumption brake, hydraulic fail-safe brakes, safe gear and bottom buffer. This greatly improves the safety performance of the rope-less elevator [8, 10]. Hydraulic fail-safe brakes have the specifications of spring braking and hydraulic release. In the normal parking state, the system starts hydraulic fail-safe brakes at service floors. Elevators can be positively held during stop and prevent the elevator drop down. However, in case of loss of motor power, over speed, over travel or any other emergency situation, the disc brake will generate positive braking pressure and arrest the fall of the elevator car. The hydraulic fail-safe brakes are therefore vital for the safe and reliable operation of a rope-less elevator. The hydraulic diagram of fail-safe brakes is shown in Fig. 6.

The hydraulic power unit contains an electrical motor, hydraulic pump, pressure relief valve, solenoid valve and other apparatus required to control the hydraulic brake units. To ensure high safety and reliability, the hydraulic control unit has two parallel valve systems for pressure control. There are three hydraulic connections in the hydraulic station, one to pressurize the brake units and two for the controlled return oil from the brake units. The two separate and independent oil return branches ensure reliable operation of the brake system in case of a fault in one of the branches.

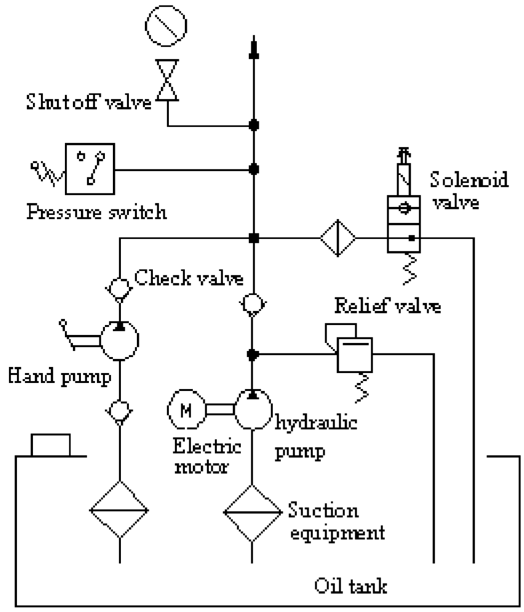


Fig.6: Hydraulic diagram of fail-safe disc brakes

The control system of disc brake is shown in Fig.7. The hydraulic pump is driven by electrical motor which is control by PLC. In order to ensure the safe operation of the hydraulic system, oil pressure relay and thermal relay are connected to the control circuit. An analog hydraulic pressure transducer and brake release indicator switch are connected to the PLC, which continuously monitors the hydraulic oil pressure and brakes running status to ensure the proper operation of the disc brake system.

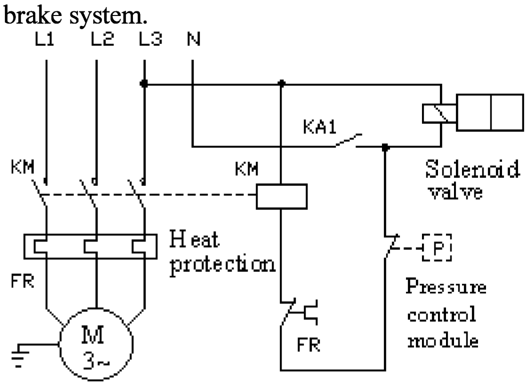


Fig.7: Control system diagram of hydraulic disc brake

4 Direct thrust force control

Linear motor drives load directly without any mechanical transfer 1inks as well as itself structure preponderance. Since M. Depenbrock proposed direct self-control and I. Takahashi proposed direct torque control (DTC) for induction machine in the middle of 1980's[11], Many Papers in recent years have been published about direct torque control of rotating machines either induction motor or synchronous motor[12-17]. Direct thrust force control (DTFC) is known to provide fast and robust response for PMLSM. The DTFC provides robust and fast thrust response without such coordinate transformation, PWM pulse generation and current regulators. Moreover, DTFC minimizes the use of motor parameters [18-20].

4.1 Basic mathematics models of PMLSM

When do theoretical analysis, the principle of coordinate transformation is usually used to transform the motor model, so as to simplify the analysis and calculation. As long as the mover of linear motor is taken as the stator of rotating motor, then d-axis and q-axis theory is common way to analyze linear motor. We use d-q rotating coordinate, fixed on the rotor axis to analyze PMLSM steady and dynamic performances, it is proved to be more convenient than other coordinates.

In d-q coordinate system, the voltage equations and flux-linkage equations are expressed as follows [18-20]:

$$\begin{cases} u_d = R_s i_d + p\psi_d - \omega\psi_q \\ u_q = R_s i_q + p\psi_q + \omega\psi_d \\ \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \tag{1}$$

Where, u_d, u_q: voltage of stator winding *on d-q axis*

i_d, i_q: current of stator winding *on d-q axis*

Ψ_d, Ψ_q: flux-linkage *on d-q axis* ,

R_s: resistance of primary winding,

L_d,L_q: inductance *on d ,q axis,*

Ψ_f: flux generated by permanent magnet

ω : electric angular speed,

p : differential operator,

From equation (1), we can get (2) as follow:

$$\begin{cases} pi_d = -\dfrac{R_s i_d}{L_d} + \dfrac{L_q \omega i_q}{L_d} + \dfrac{u_d}{L_d} \\ pi_q = -\dfrac{L_d \omega i_d}{L_q} - \dfrac{R_s i_q}{L_q} + \dfrac{u_q}{L_q} - \dfrac{\psi_f \omega}{L_q} \end{cases} \tag{2}$$

The electromagnetic thrust force can be expressed as:

$$F_{em} = p_n \frac{3\pi}{2\tau}[\psi_f i_q + (L_d - L_q) i_d i_q] \tag{3}$$

Where, p_n: pole pairs,

τ : pole pitch.

When L_d=L_q=L_s, equation (3) can be described as:

$$F_{em} = p_n \frac{3\pi}{2\tau}\psi_f i_q = p_n \frac{3\pi}{2\tau}\frac{1}{L_s}|\psi_s|\psi_f \sin\delta \tag{4}$$

Where, Ψ_s: primary winding flux linkage,

δ: load angle.

PMLSM has a motion equation (5):

$$Mpv = F_{em} - F_l - Bv \tag{5}$$

Where, v is mover velocity, M is mover mass, F_r is the friction force, F_l is load, p is differential operator.

In(3) and (4)，it is easy to understand thrust force varying with Ψ_s and δ when other parameters are taken as constant. In other words, the thrust force in d-q flame is to be controlled uniquely if controlling the amplitude of the Ψ_s and load angle δ.

4.2 Voltage space-vector

Fig.8 shows the circuit of 3-phase voltage type inverter for PMLSM direct thrust force control. It uses eight space voltage vectors to generate flux circle approaching stator flux circle of the motor.

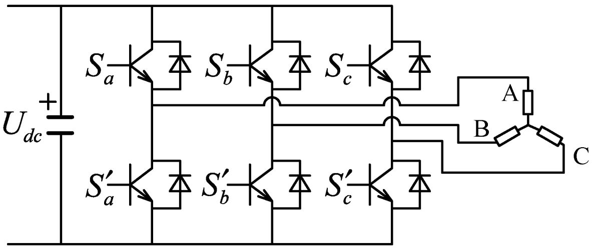


Fig.8: Three-phase voltage type inverter

If we define state of transistor in the upper bridge arm is on and the below is off is 1, otherwise is 0, there are eight on-off modes in the inverter. The inverter's eight output voltages are shown as Fig.9. On-off modes (000) and (111) are zero voltage vectors, while others are called nonzero effective voltage vectors.

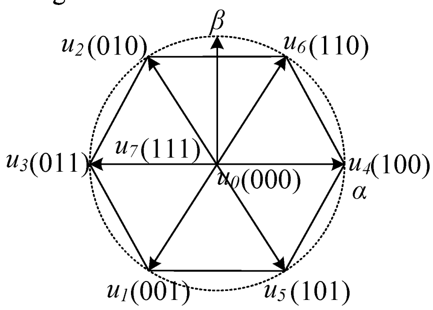


Fig.9: Voltage space vectors

The relationship between three-phase inverter output voltage and switch state vector S_a, S_b, S_c can be derived as:

$$\begin{bmatrix} U_A \\ U_B \\ U_C \end{bmatrix} = \frac{1}{3}U_{DC}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{6}$$

4.3 Direct thrust force control

From Equation (4), we can get,

$$\Delta F_{em} = p_n \frac{3\pi}{2\tau}\frac{1}{L_s}\psi_f|\psi_s|\cos\delta\cdot\omega\Delta t \tag{7}$$

The change rate of thrust is proportional to the change rate of power angle δ. Flux Ψ_f is generated by permanent magnet, which is independent of primary winding flux Ψ_s. Electromagnetic thrust changes with power angle.

When the voltage space vector of primary in advance to the primary flux, and velocity of the primary flux is greater than the velocity of the secondary flux, power-angle increased, and then the electromagnetic repulsion increases. In contrary, if the voltage space vector of primary lagging behind the primary flux, the velocity of the primary flux is smaller than the velocity of the secondary flux, power-angle reduced, and the electromagnetic repulsion decreases. If imposed a zero voltage vectors, primary flux is still, and secondary will move continually due to inertia, power angle reduced and electromagnetic thrust is also reduced. When the primary flux maintains a constant value, motor thrust changes with power angle δ. The change of power angle can be achieved by changing the primary flux speed and direction. When keeping thrust consistent with power angle changing direction and maintaining the primary flux amplitude invariant, we can control the thrust force of

PMLSM by controlling power angle between primary and secondary flux. Rapid thrust response can be achieved through a rapidly changing power angle [18-20]. The system diagram of DTFC drive is shown in Fig.10.

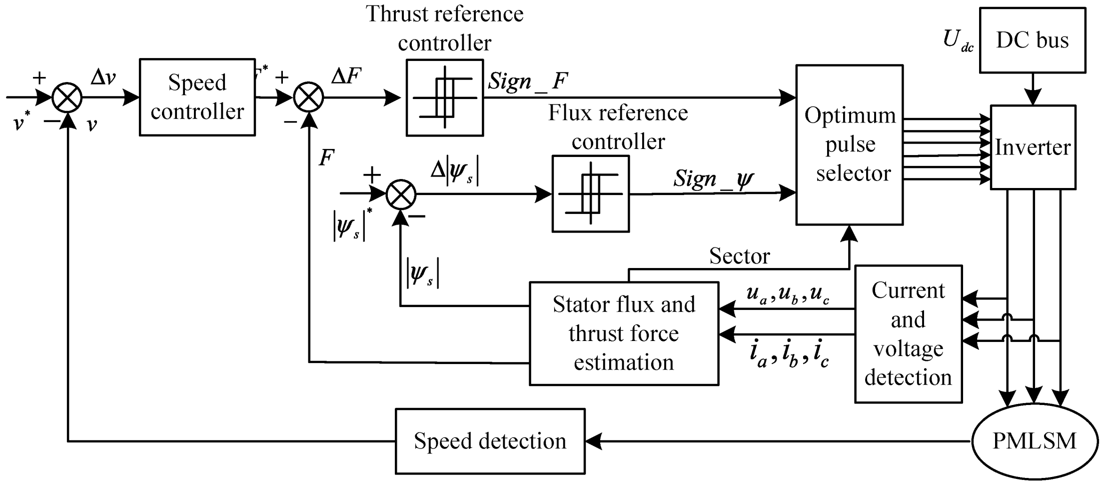


Fig.10: System diagram of DTFC drive

The system is divided into three parts, the first part is PMLSM State observation, through voltage, current and speed feedback gets feedback values of thrust F, stator flux ψs and flux position signal Sector. The second part is the compare and select, which compares the feedback values and the given values, computes the thrust regulating signal Sign_F, and flux regulating signal Sign_flux. The third part is the vector selection and control, by selecting voltage space vector control inverter output suitable PMLSM thrust changes. Voltage space vector switch table is shown in Table.2. According to the primary flux sector signal, primary flux control Sign_flux and thrust control signals Sign_F, we can select the appropriate voltage space vector to realize direct thrust control. The outputs are inverter's switch status signals. For tabulation and table look-up convenience, define the variable M=2Sign_flux+Sign_F+1.

Table 2: Voltage space vector switch table

M	*Sign_flux*	*Sign_F*	Sector					
			1	2	3	4	5	6
1	0	0	u_1(001)	u_5(101)	u_4(100)	u_6(110)	u_2(010)	u_3(011)
2	0	1	u_2(010)	u_3(011)	u_1(001)	u_5(101)	u_4(100)	u_6(110)
3	1	0	u_5(101)	u_4(100)	u_6(110)	u_2(010)	u_3(011)	u_1(001)
4	1	1	u_6(110)	u_2(010)	u_3(011)	u_1(001)	u_5(101)	u_4(100)

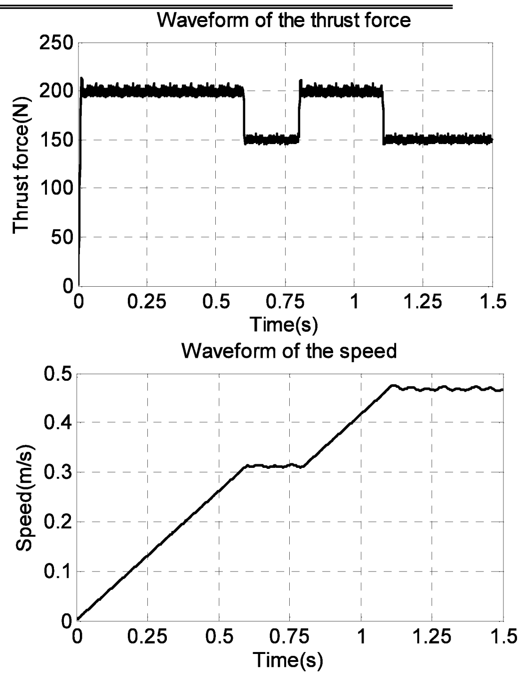
5 Simulation of DTFC

Simulation using a single side structure PMLSM, the parameters of PMLSM is shown in Table.3.

Table 3: Parameters of PMLSM used in the simulation

U_N(V)	24.5	L_d (H)	0.01391
v_N (m/s)	0.78	L_q (H)	0.01391
M(kg)	96	n_p	3
R_s (Ω)	1	τ(mm)	39
ψ_f(Wb)	0.2324	B	0.1
ψ_f(Wb)	0.2324	L_d (H)	0.01391

Set thrust hysteresis tolerance ± 10N, primary flux linkage hysteresis tolerance ± 0.005Wb, sampling period T_s =1e-5s, given velocity v*=0.312m/s (4Hz), ψ_f*=0.2324Wb. The simulation results of acceleration to 0.468m/s after starting 0.8s with 150N load are shown in Fig.11.



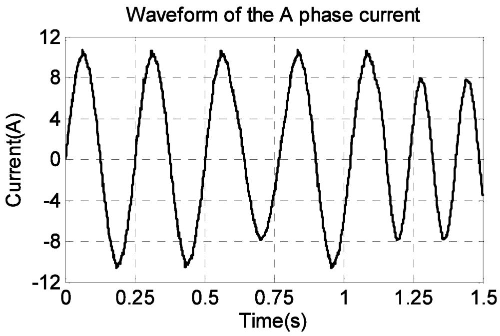


Fig.11 Thrust, speed, phase current waveforms for PMLSM DTFC

When changing the given speed to 0.468m/s at 0.8s, the system accelerated to a steady-state 0.468m/s with an acceleration constant approximately 0.52m/S2 and 200N thrust. It spends 0.3s. When the speed is stable, the current valid values are 5.66A, changes approximately with the sine rule.

6 Conclusion

A rope-less elevator driven by PMLSM with multi-segment primary has been made and tested. In the paper, the structure and features of rope-less elevator is proposed, the operational control system for rope-less elevator is designed. On the basis of theory of direct torque control in asynchronous motor, principle of Direct Thrust Force Control for PMLSM is analyzed and simulations with SIMULINK of MATLAB have been given to demonstrate validity of the control system. The simulation results show that when the system entering the steady-state and speed changes, although the thrust and velocity response exist disturbances, they can quickly achieve a given value. The DTFC provides robust and fast thrust response.

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