Full Speed Range DTC Scheme of LIM for Maglev Vehicle with Efficiency Optimization

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ABSTRACT: This paper discusses the traction control schemes of linear induction motor (LIM) for the Low-speed Maglev Train. A full speed range direct thrust control (DTC) scheme is proposed considering the parameters dynamic variation of LIM. Efficiency optimization strategy is also utilized to reduce the power loss and attractive force of the motor in light load operation. Experiment results show that the proposed schemes have great dynamic and steady state performance. The proposed method has good application prospect in the traction control of LIM driven Maglev Train.

1 INTRODUCTION

Magnetic levitation subway vehicles propelled by linear induction motor (LIM) have the merits of low noise and the strong ability to run over steep slopes and sharp curve. However, due to parameters variations caused by end-effects, high performance control of LIM is still a challenge. Moreover, the mechanic clearance of LIM is comparative large, which results in lower efficiency compared to that of RIM. On the other hands, large attractive normal force exists due to the asymmetric structure, which will bring additional power loss to the magnetic levitated systems.

In this paper, direct thrust control scheme (DTC), which is robustness against parameter variation, is proposed for the LIM traction control of maglev subway vehicles, efficiency optimization strategy is also utilized to reduce the power loss and attractive force of the motor in light load operation. Firstly, the dynamic mathematic model of linear induction motor is developed based on the analysis of the influences of end effect and the operation condition on LIM's parameters. Then different direct thrust control schemes are developed for low speed, medium speed and field weakening operation separately. In low speed range, an improved indirect stator-quantities control (ISC) scheme taken the characteristic of LIM into consideration is proposed, which has maintained the robustness of conventional ST-DTC. In medium and high speed range, direct thrust control with hexagonal flux track is utilized to reduce the switching frequency. Then the efficiency optimization control strategy based on the combination of loss model and on-line search controller together is proposed for LIM drives.

The proposed strategy is implemented on a 12KW arc type LIM setup. Experiments results show that the thrust ripple of the improved ISC can be reduced effectively compared with the conventional ST-DTC. As for the switch process between schemes in different speed range, the transition of current and flux are very smooth. The power consumption and average normal force decrease remarkably with the efficiency optimization strategy. The proposed method has good application prospect in the traction control of LIM for low speed Maglev Train.

2 FULL SPEED RANGE DIRECT THRUST CONTROL SCHEME OF LIM

2.1 Dynamic Mathematic Model of LIM

Due to the existence of noncontinuity of the magnetic field, LIM has some special characteristics and inherent problems which include end-effects, large normal force and so on. The key parameters in the equivalent circuit of the machine, will vary as a result of changes in operation condition like slip frequency, rail temperature and so on. Among the parameters in the equivalent circuit, the magnetizing inductance and the secondary resistance are the most variable for LIM. The T-type equivalent circuit of LIM considering dynamic parameters variation is shown in Fig. 1. k_m and k_r are the coefficients introduced to denote the influences of end-effects and other variations on the magnetizing inductance and the secondary resistance.

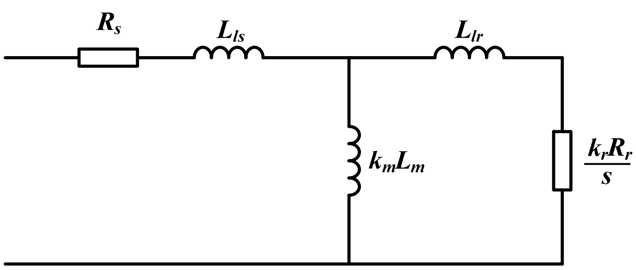


Figure 1. T-type equivalent circuit of LIM.

Based on the analysis above, the mathematic model of LIM in stationary reference frame (α−β) is described by:

$$u_{\alpha,\beta s} = R_s i_{\alpha,\beta s} + p\psi_{\alpha,\beta s} \tag{1}$$

$$0 = k_r R_r i_{\alpha,\beta r} + p\psi_{\alpha,\beta r} \pm j\omega_r \psi_{\beta,\alpha r} \tag{2}$$

$$\psi_{\alpha,\beta s} = (L_{ls} + k_m L_m) i_{\alpha,\beta s} + k_m L_m i_{\alpha,\beta r} \tag{3}$$

$$\psi_{\alpha,\beta r} = (L_{lr} + k_m L_m) i_{\alpha,\beta r} + k_m L_m i_{\alpha,\beta s} \tag{4}$$

$$F_t = \frac{3}{2}\frac{\pi}{\tau}\frac{k_m L_m}{\sigma L_s L_r}\psi_r \otimes \psi_s \tag{5}$$

2.2 Indirect Stator-Quantities Control in Low-Speed Range

During starting and very-low-speed operation, the basic ST-DTC scheme selects many times zero voltage vectors resulting in large thrust ripple and noises. Here, an improved indirect stator-quantities control (ISC) with space vector modulation controller is applied to replace the hysteresis controller and switching table in traditional DTC with the diagram shown in Fig. 2.

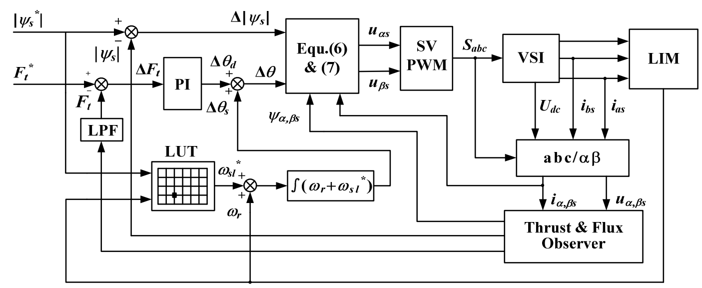


Figure 2. Block diagram of DTC of LIM in medium & high speed range.

As shown in Fig. 2, both torque and stator flux are controlled in a closed-loop way. The primary flux phase angle increment $\Delta\theta$ is composed of two parts: the stationary part $\Delta\theta_s$ and dynamic part $\Delta\theta_d$. $\Delta\theta_s$ represents for the angle increment if both thrust and primary flux are equal to the reference values, while $\Delta\theta_d$ is used to regulate the error. The stationary angle increment $\Delta\theta_s$ is calculated from measured motor speed ω_r and reference angular slip frequency ω_{sl}^*. In that of RIM, ω_{sl}^* can be easily obtained from the torque equation. However, in the case of LIM, the secondary resistance R_r and magnetizing inductance L_m are dynamic variable. The actual value of ω_{sl}^* cannot be directly calculated from the reference thrust. Moreover, the slip frequency of LIM is far larger than that of RIM. In the proposed ISC scheme for LIM, ω_{sl}^* is acquired from the look-up table (LUT) which is calculated off-line according to different thrust level and motor speed. $\Delta\theta_d$ is regulated by a PI controller with thrust error ΔF_t as input.

With the estimated value $\psi_{\alpha,\beta s}$, $\Delta\theta$ and $\Delta|\psi_s|$ together, the appropriate voltage vector reference which is applied to the PWM generator is calculated as following:

$$u_{\alpha s} = R_s i_{\alpha s} + \frac{1}{T_s}\left[A\cos(\Delta\theta) - 1\right]\psi_{\alpha s}(n) - \frac{1}{T_s}A\sin(\Delta\theta)\psi_{\beta s}(n) \tag{6}$$

$$u_{\beta s} = R_s i_{\beta s} + \frac{1}{T_s}A\sin(\Delta\theta)\psi_{\alpha s}(n) + \frac{1}{T_s}\left[A\cos(\Delta\theta) - 1\right]\psi_{\beta s}(n) \tag{7}$$

Where: $A = 1 + \frac{\Delta|\psi_s|}{|\psi_s(n)|}$

2.3 Direct Thrust Control in Medium & High-Speed Range

When the motor runs above 30% rated speed, direct thrust control scheme with hexagonal flux track is utilized to reduce the switching frequency with the block diagram shown in Fig. 3.

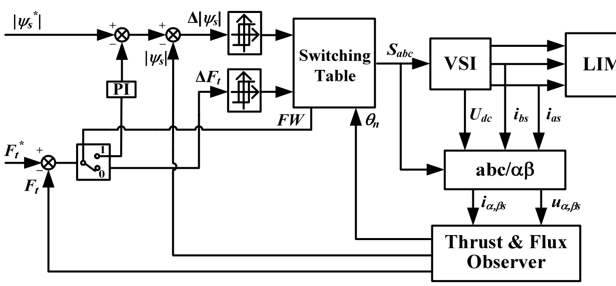


Figure 3. Block diagram of DTC of LIM in medium & high speed range.

As shown in Fig. 3, FW is the field weakening control signal. When FW is '0', both thrust and flux hysteresis controllers are activated, the inverter is controlled by switching table with thrust and flux error as input. In fielding weakening region, FW is set to be '1', thrust hysteresis controller is deactivated, inverter is operated in six-pulse square wave mode, output power (thrust) is regulated by adjusting the reference of flux magnitude, which is equal to change the instantaneous slip frequency.

3 EFFICIENCY OPTIMIZATION CONTROL STRATEGY

Due to the variations of on-board passenger and limitation of grade and curves of rails, the traction motors for Maglev train are not always in full-load operations. By choosing the optimal flux with load variations, both power loss and normal force can be reduced effectively, which are corresponding to the reduction of traction and levitation power consumptions separately.

The mainly approaches of efficiency optimization control for LIM can be divided into two categories: the first is based on the loss-model of induction motor. This method is fast but highly depends on the motor parameters, which are variable and not easy to be obtained for LIM. The second method is based on search controller. It is independent of motor parameters but relatively slow, for which it can only be applied in the constant speed operation. It is not suitable either for the traction control since its convergence is rather slowly than the dynamic transition of vehicle speed.

Base on the analysis above, a novel efficiency optimization strategy for LIM traction control is proposed: the mathematic model of the LIM drives are firstly modeled by simulation software. Then off-line searching process with different control schemes is performed by repeated stepwise changes to motor flux linkage to find minimum summation of input power and additional normal force power loss (levitation power loss). The resulting flux linkage values for a range of operating points stored in memory as a look-up table. During the operation, the flux linkage corresponding to the present operating point is applied to the machine as a command variable.

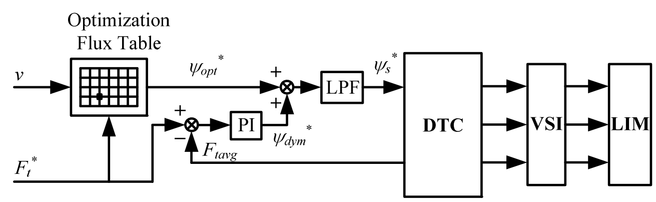


Figure 4. Block diagram of the proposed efficiency optimization strategy.

Fig. 4 is the block diagram of the proposed efficiency optimization control strategy. ψ_s^*, which denotes the primary flux reference according to different control schemes DTC, is composed of two parts: the stationary part ψ_{sopt}^* and dynamic part ψ_{sdym}^*. ψ_{sopt}^* is obtained from the look-up table (LUT) according to different speed and thrust reference. The dynamic part of the optimum flux, which can ensure the fast dynamic response to the change of thrust input, is regulated by the PI controller:

$$\varphi_{sdym}^* = K_P \Delta F + K_I \int \Delta F dt \quad (8)$$

$$\Delta F = \left(F_t^* - F_{tavg}\right) \quad (9)$$

Where: F_{tavg} is the observed average output thrust of the motor.

The low pass filter (LPF) unit can reduce the influence of high frequency component of the thrust observer on the closed-loop control of flux.

4 EXPERIMENTAL RESULTS

Experiments have been carried out on a LIM setup in the lab. The experimental set up consists of a two-level IGBT inverter, a 12kW arc type LIM with the parameters shown in Table I, a dc generator and a rheostat used as load. All the algorithms are implemented on TMS320F2812 DSP.

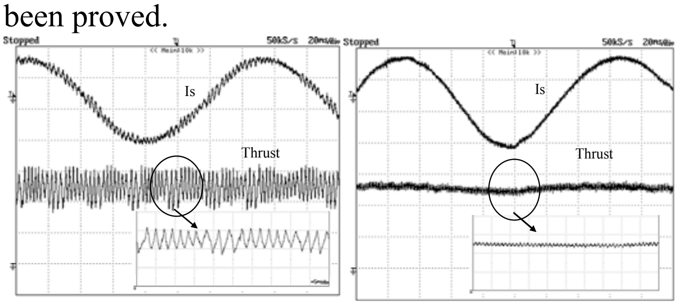
TABLE I

LINEAR IDUCTION MOTOR PARAMETERS

Parameter	Value	units
Phase number	3	
Number of poles	8	
Rated speed	11	m/s
Rated thrust	1100	N
Resistance of primary per phase	0.27	ohm
Resistance of secondary per phase	0.6	ohm
Leakage inductance of primary	4.5	mH
Magnetizing inductance	14.1	mH
Leakage inductance of secondary	1.1	mH

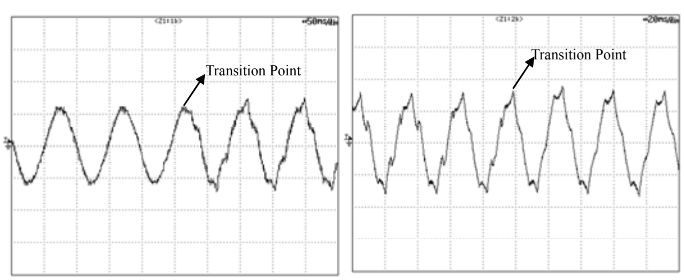
Fig. 5 shows the low speed experimental results with conventional ST-Based DTC and proposed ISC scheme. As shown in Fig. 8(a) and (b), when the motor is running at 1.1m/s (0.1p.u) with a load of 1100N (1p.u), the thrust ripples of the two schemes are ±0.12p.u and ±0.03p.u respectively, while the switching frequency are all controlled to be 500Hz. The thrust ripple has been reduced approximately 75% with the proposed switching schemes and the sinusoidal of current waveform has also been improved.

Fig. 6 shows the experimental waveforms of switch process between different operation ranges and schemes, the transition of current and flux are very smooth, the dynamic performance of the scheme has been proved.



(a) Conventional DTC (b) Proposed ISC Scheme

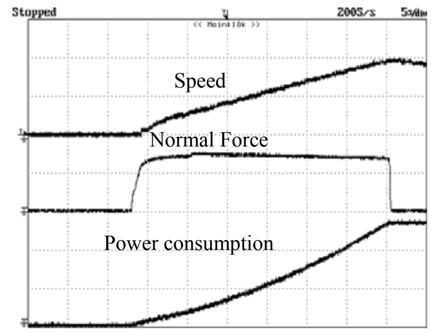
Figure 5. Experimental results with different schemes (10%rated speed)



(a) Current waveform from ISC to DTC with hexagonal flux (b) Current waveform from base speed to field weakening

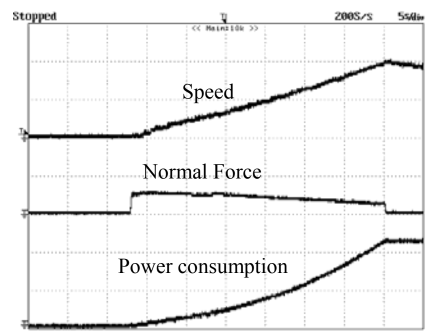
Figure 6. Transition performance between different schemes

Figs. 7 and 8 show the dynamic operation experimental results. In the experiments, the motor is accelerated from 0 to rated speed, the output thrust is 0.2p.u. It can be seen from Figs. 7 and 8 that the motor power consumption has been reduced 15.6% with the efficiency optimization, the average normal force decreases about 67%. With the proposed efficiency optimization strategy, total power loss can be reduced effectively.



(Speed: 0.5 p.u./div; Normal force: 1000N/div; Power consumption: 0.01kWh/div)

Figure 7. Experimental results without efficiency optimization



(Speed:0.5 p.u./div; Normal force:1000N/div; Power consumption: 0.01kWh/div)

Figure 8. Experimental results with the proposed efficiency optimization strategy

5 CONCLUSIONS

High performance traction control of LIM is challengeable due to its parameter dynamic variation. Moreover, the efficiency of LIM is relatively lower than that of RIM. In this paper, a full speed range DTC scheme for LIM is proposed for traction application, which can reduce the low speed range thrust ripple as well as maintain the robustness of conventional ST-DTC. Furthermore, a novel efficiency optimization strategy is proposed, which is based on the combination of loss-model and on-line search controller together, can reduce the power loss and normal force of the motor not only in constant speed mode but also in dynamic operation. Effectiveness of the proposed methods has been verified by corresponding experimentation. It can be used in the high performance traction control of LIM propulsion Maglev train.

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