A improved indirect field-oriented control scheme for linear induction motor traction drives

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- Abstract
- Introduction
- Mathematical model and characteristics of the LIM
- Analysis of the conventional control scheme
- Proposed IFOC
- Simulation result
- Experimental result
- Conclusion

Abstract

- LIM(linear induction motor) 和 RIM(rotary induction motor) 的差別
- 討論LIM不同控制手法的性能

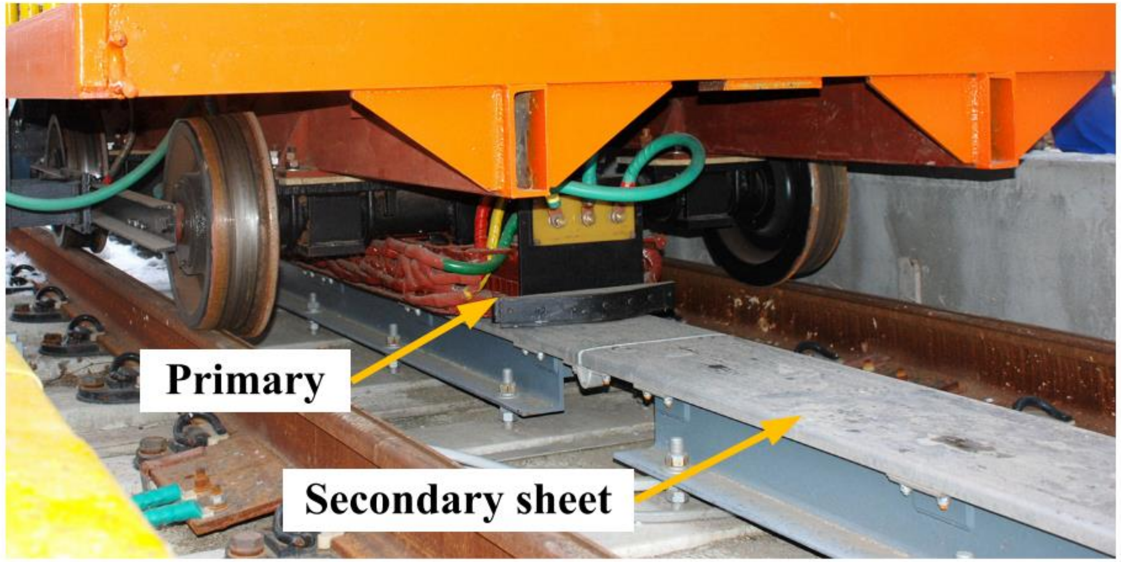
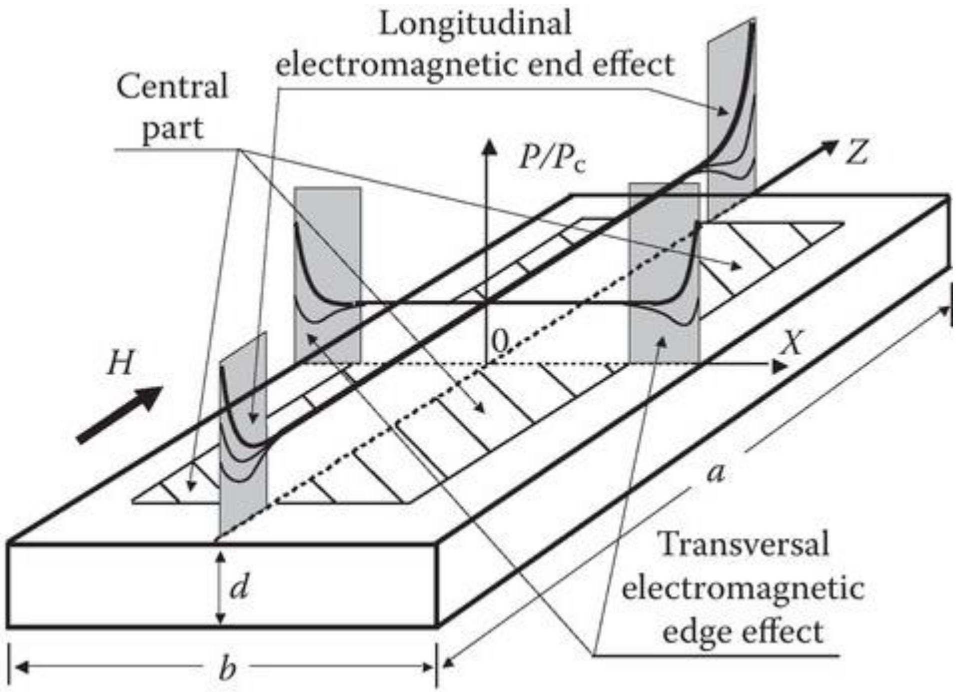


Fig. 1. Structure of a linear induction motor for a metro vehicle.



Introduction

- LIM的應用
- LIM的控制
    1. 轉差頻率控制
    2. 磁場導向控制

Mathematical model of the LIM

k_m為縱向邊緣效應係數

k_r為橫向邊緣效應係數

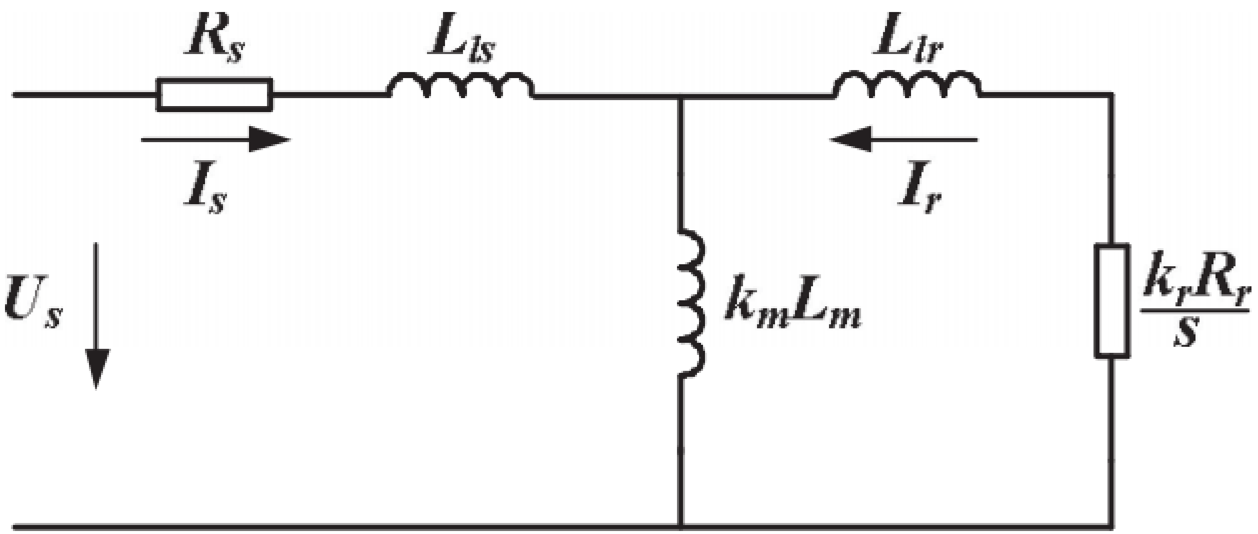


Fig. 2. T-type equivalent circuit of the LIM.

Mathematical model of the LIM

- 建立LIM在d-q軸的數學模型

$$u_{ds} = R_s i_{ds} + p\psi_{ds} - \omega_e \psi_{qs} \quad (1)$$

$$u_{qs} = R_s i_{qs} + p\psi_{qs} + \omega_e \psi_{ds} \quad (2)$$

$$0 = k_r R_r i_{dr} + p\psi_{dr} - \omega_s \psi_{qr} \quad (3)$$

$$0 = k_r R_r i_{qr} + p\psi_{qr} + \omega_s \psi_{dr} \quad (4)$$

$$\psi_{ds} = (L_{ls} + k_m L_m) i_{ds} + k_m L_m i_{dr} \quad (5)$$

$$\psi_{qs} = (L_{ls} + k_m L_m) i_{qs} + k_m L_m i_{qr} \quad (6)$$

$$\psi_{dr} = (L_{lr} + k_m L_m) i_{dr} + k_m L_m i_{ds} \quad (7)$$

$$\psi_{qr} = (L_{lr} + k_m L_m) i_{qr} + k_m L_m i_{qs} \quad (8)$$

$$F_e = \frac{3}{2}\frac{\pi}{\tau}(\psi_{qr} i_{dr} - \psi_{dr} i_{qr}). \quad (9)$$

$$F_e = \frac{3}{2}\frac{\pi}{\tau}\frac{k_m L_m}{L_{lr} + k_m L_m}\psi_r i_{qs} \quad (10)$$

$$\psi_r = k_m L_m i_{ds}. \quad (11)$$

Mathematical model of the LIM

- LIM與RIM馬達參數比較

TABLE I
PARAMETERS OF THE INVESTIGATED RIM FOR METRO TRACTION

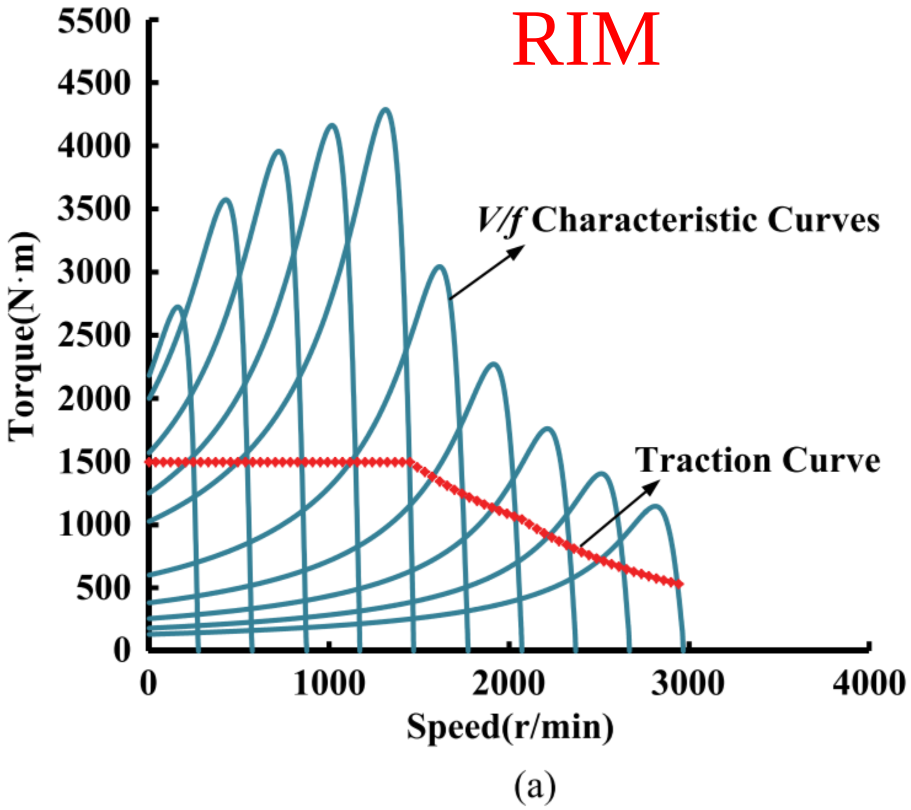
Parameter	Symbol	Value
Number of poles	n_p	4
Rated voltage (V)	U_s	1050
Rated torque (Nm)	T_e	1202
Rated speed (r/min)	n	1800
Stator resistance (Ω)	R_s	0.1425
Rotor resistance (Ω)	R_r	0.0699
Stator leakage inductance (mH)	L_{ls}	0.643
Magnetizing inductance (mH)	L_m	23.29
Stator leakage inductance (mH)	L_{lr}	0.643

TABLE II
PARAMETERS OF THE INVESTIGATED LIM FOR METRO TRACTION

Parameter	Symbol	Value
Number of poles	n_p	6
Pole pitch (m)	τ	0.288
Rated voltage (V)	U_s	550
Rated thrust (kN)	F_e	17.5
Rated speed (m/s)	v	12
Primary resistance (Ω)	R_s	0.045
Equivalent secondary resistance (Ω)	$k_r R_r$	0.128
Primary leakage inductance (mH)	L_{ls}	1.31
Equivalent magnetizing inductance (mH)	$k_m L_m$	3.65
Secondary leakage inductance (mH)	L_{lr}	0.2

Mathematical model of the LIM

- LIM與RIM特性曲線



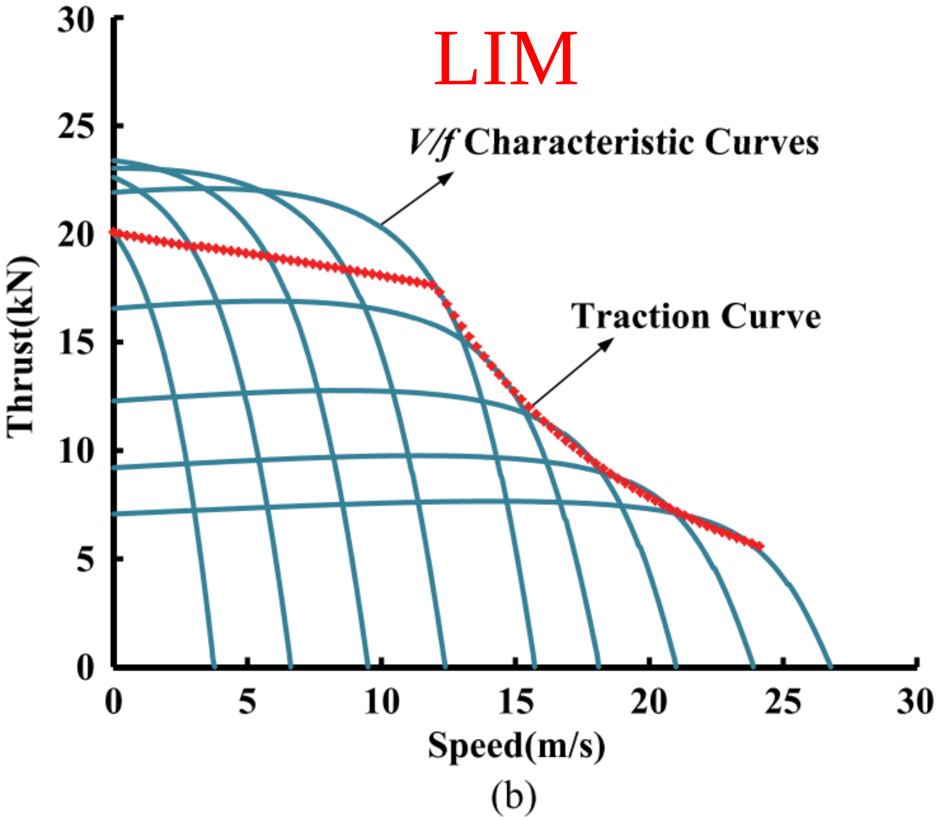
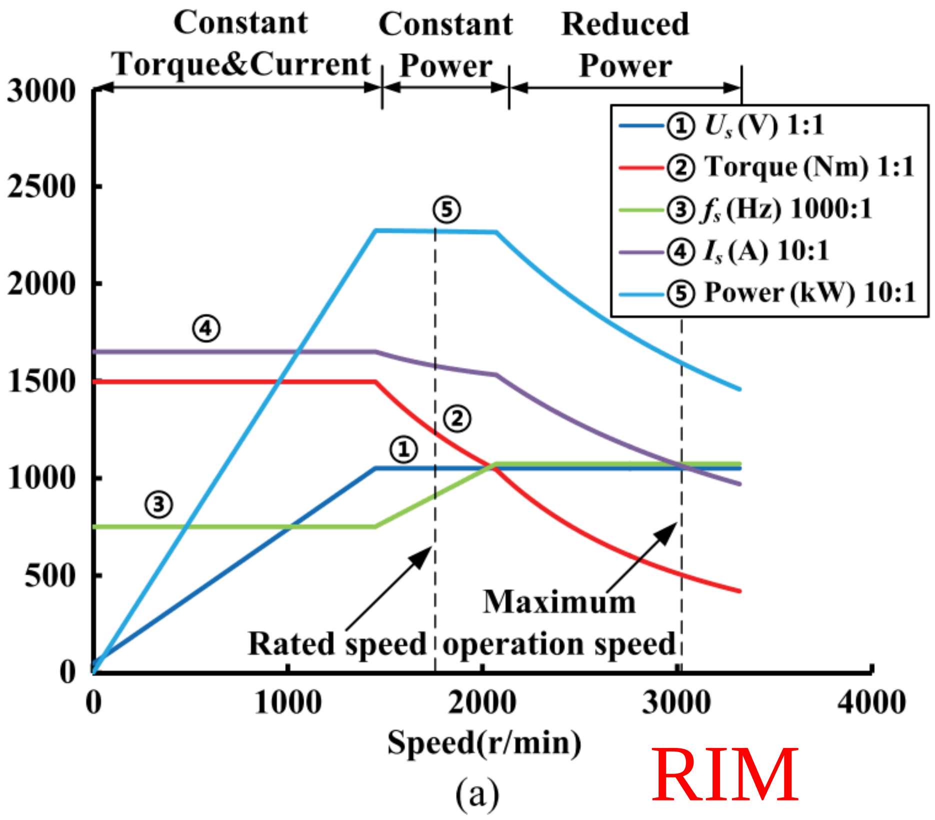


Fig. 3. Mechanical characteristic curves of RIM and LIM. (a) RIM. (b) LIM.

Mathematical model of the LIM

- LIM與RIM推力特性曲線



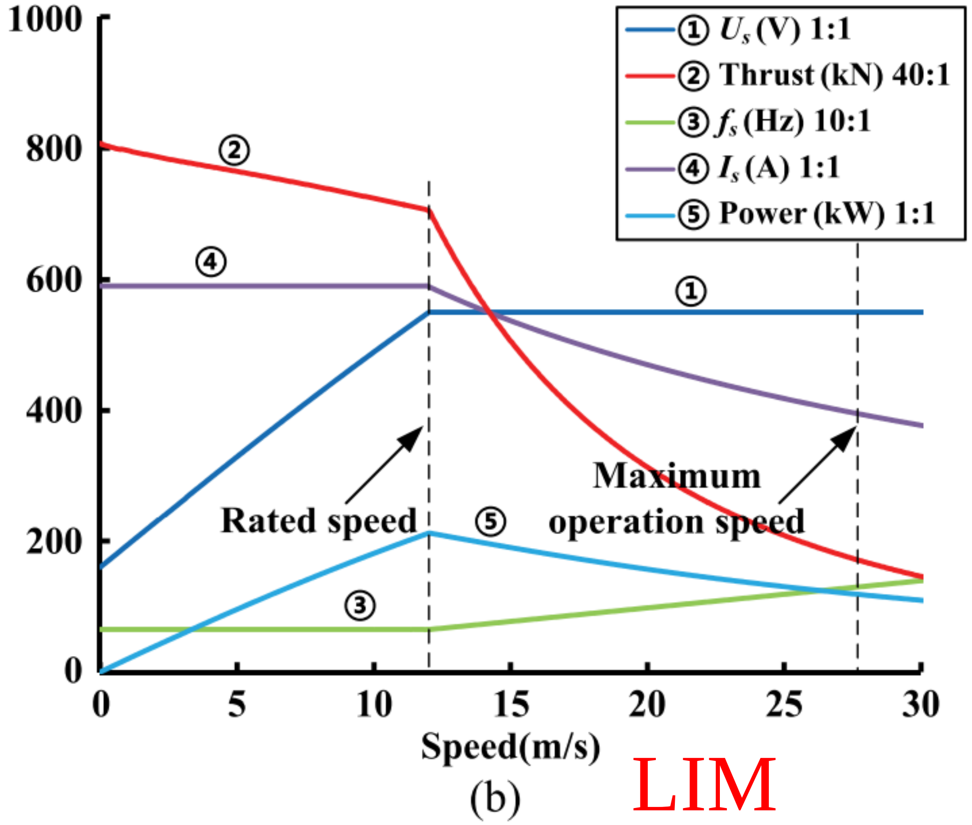


Fig. 4. Traction characteristic curves of RIM and LIM. (a) RIM. (b) LIM.

Mathematical model of the LIM

- k_m與k_r變化曲線

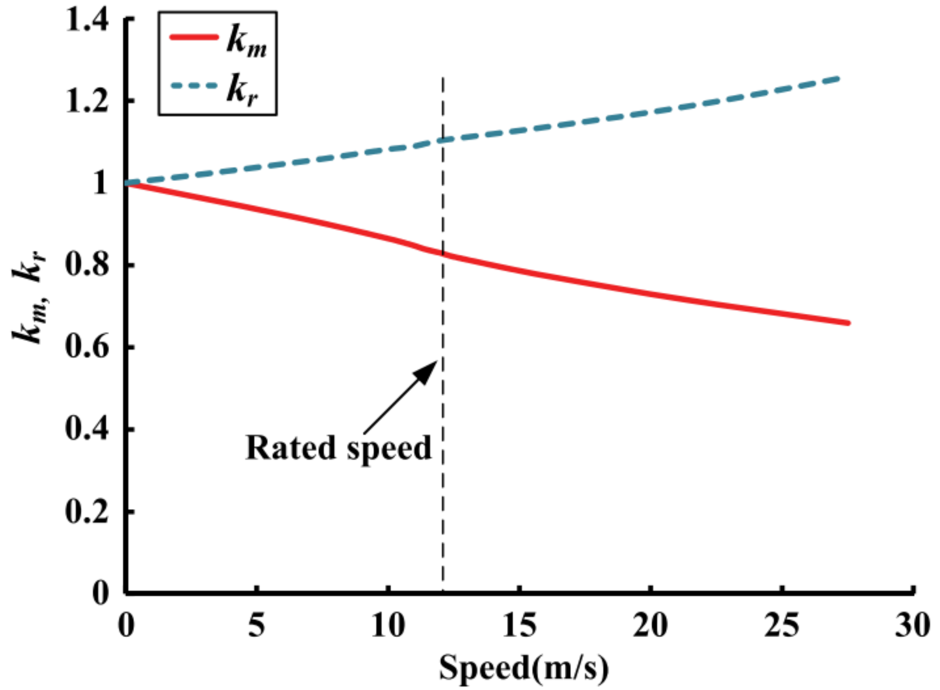


Fig. 5. End-edge effect coefficients variations of the LIM with rated output.

Analysis of the conventional control scheme

1. slip frequency control

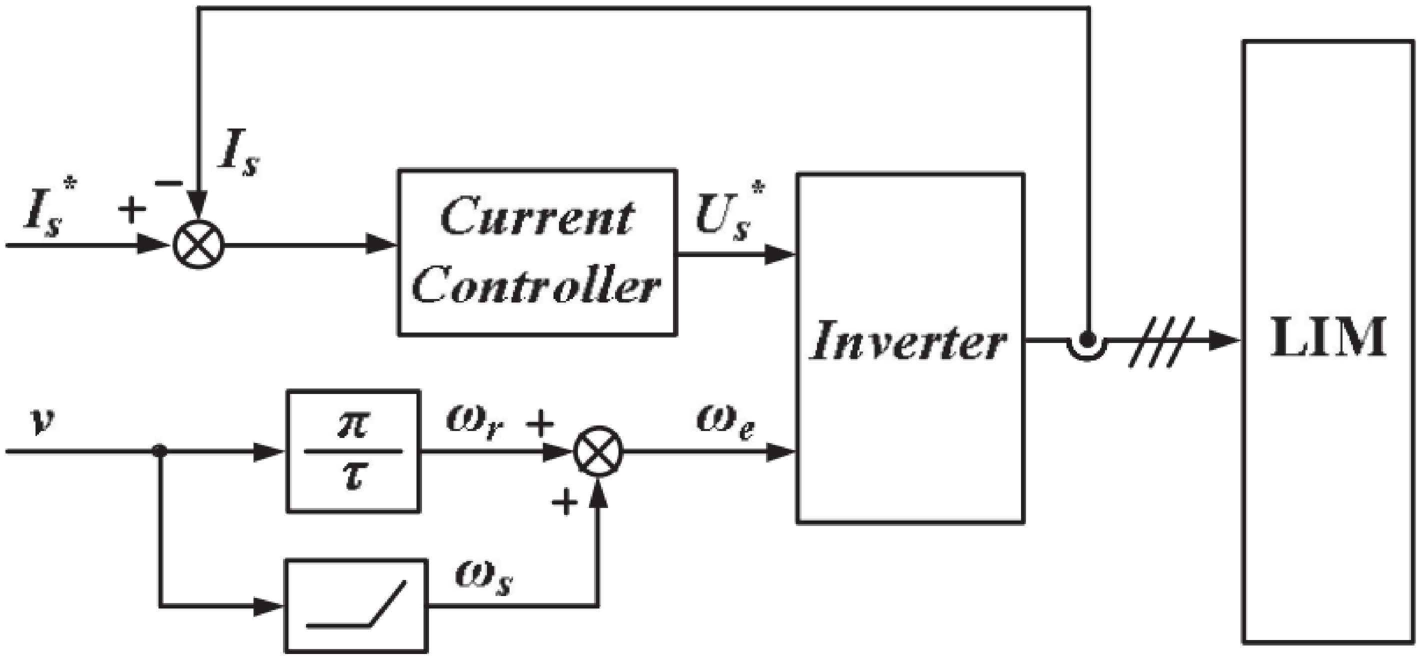


Fig. 6. Block diagram of slip frequency control for the LIM.

Analysis of the conventional control scheme

2. IFOC scheme with constant slip frequency

$$\omega_s = \frac{R_r \, i_{qs}{}^*}{(L_{lr} + L_m)\, i_{ds}{}^*}$$

$$I_s{}^* = \sqrt{(i_{ds}{}^*)^2 + (i_{qs}{}^*)^2}.$$

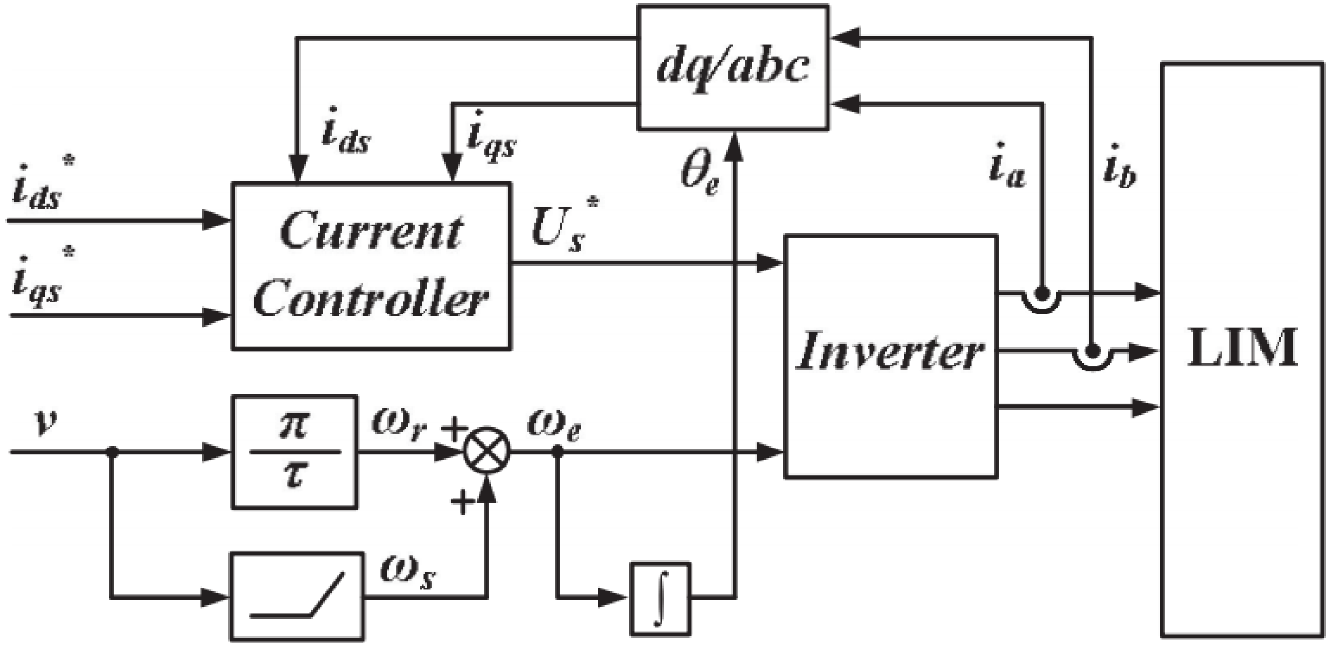


Fig. 7. Block diagram of IFOC with constant slip frequency.

Analysis of the conventional control scheme

3. IFOC scheme with flux attenuation compensation

$$\psi_r = k_m L_m {i_{dscom}}^* = k_m L_m {i_{ds}}^* \frac{1}{k_m} = L_m {i_{ds}}^*$$

$$\omega_s = \frac{R_r {i_{qs}}^*}{(L_{lr} + k_m L_m)\, {i_{dscomm}}^*} \cdot \quad (15)$$

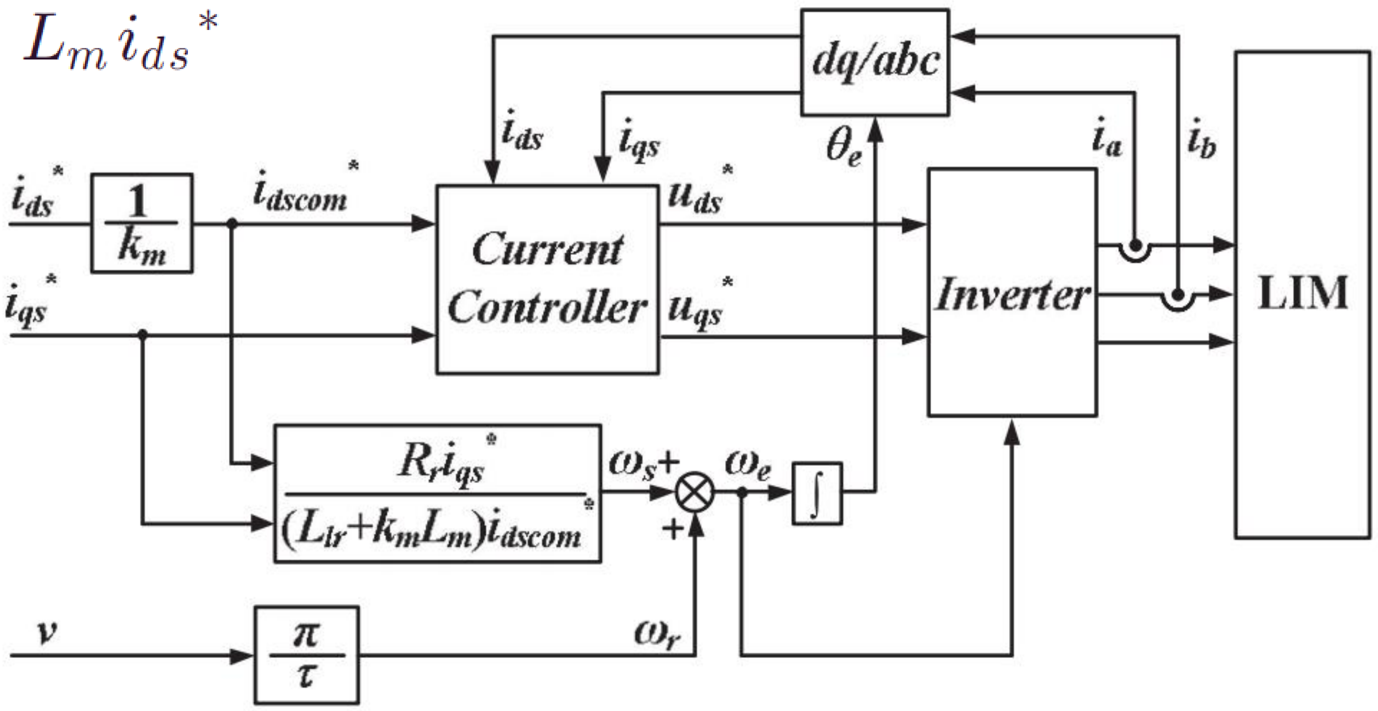


Fig. 8. Block diagram of IFOC with flux attenuation compensation.

Proposed IFOC scheme

- 最佳化轉差頻率

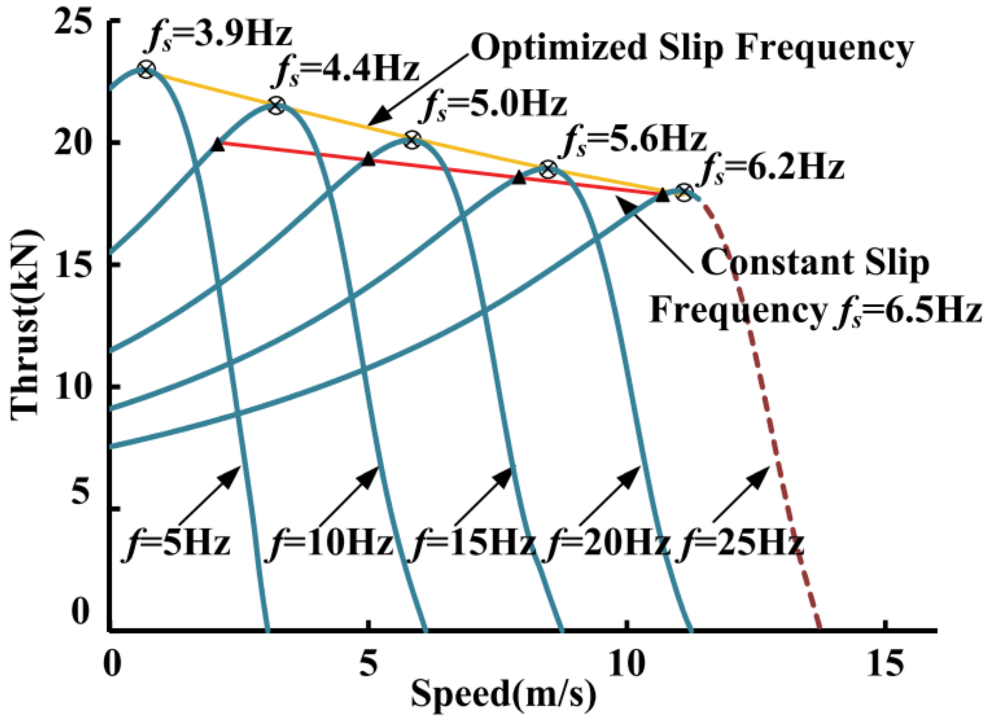


Fig. 9. Thrust curves with constant current and various supply frequency.

Proposed IFOC scheme

- 基於最佳化轉差頻率的間接磁場導向

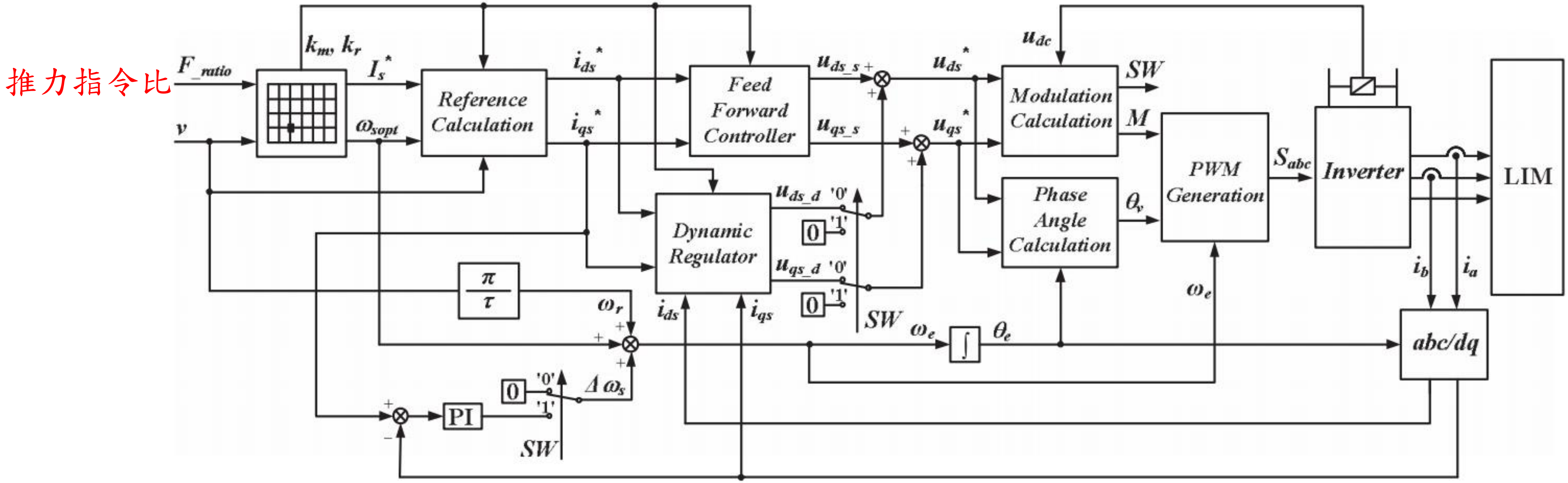


Fig. 10. Block diagram of the IFOC scheme based on optimized slip frequency for LIM traction drives.

Proposed IFOC scheme

- 前饋控制器

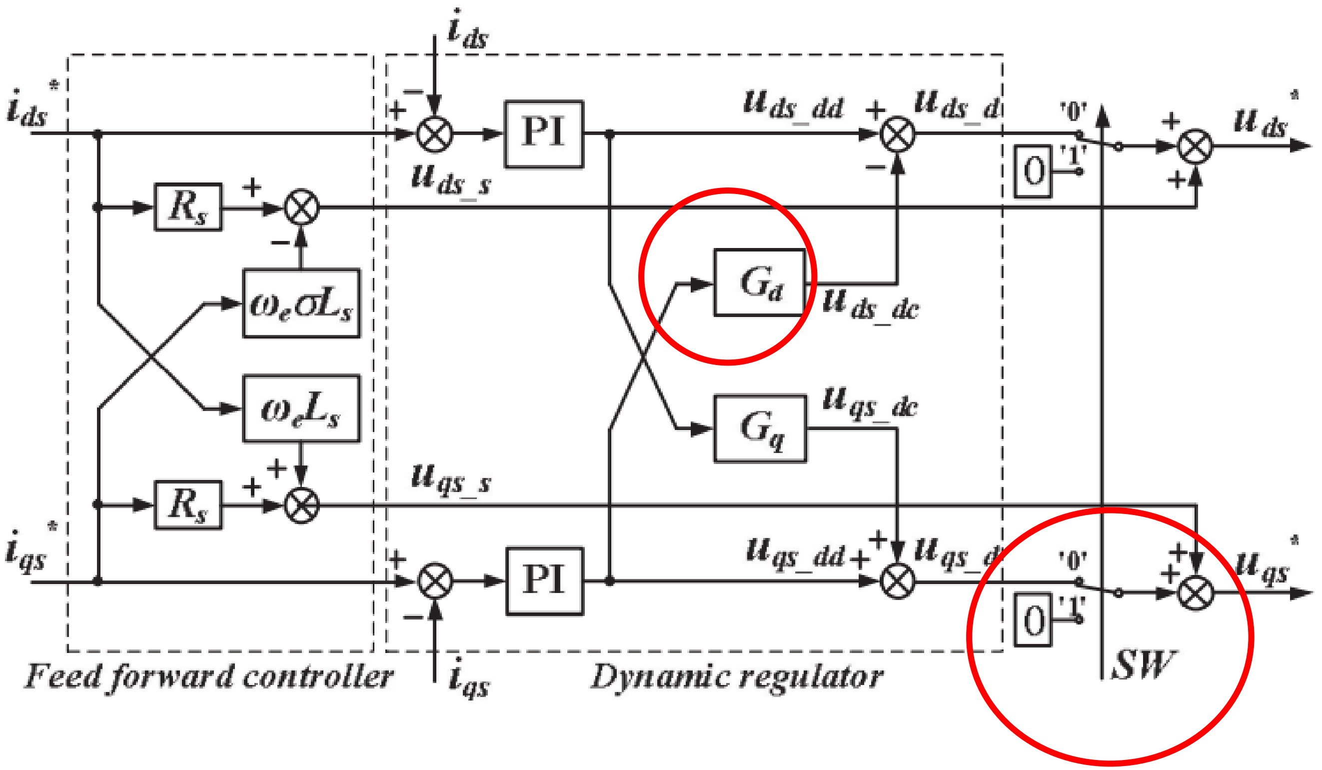


Fig. 11. Block diagram of the feed-forward controller and dynamic regulator of the IFOC scheme.

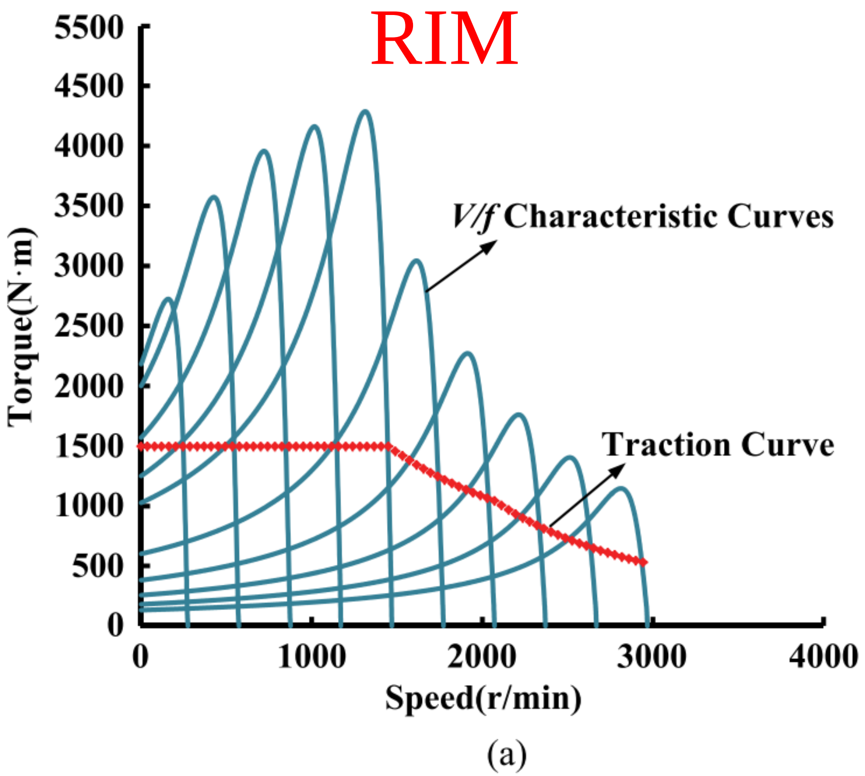
$$u_{ds\_s} = R_s i_{ds}{}^* - \omega_e \sigma L_s i_{qs}{}^*$$

$$u_{qs\_s} = R_s i_{qs}{}^* + \omega_e L_s i_{ds}{}^*$$

$$G_d = G_q = K_{dq} \frac{\omega_e \sigma L_s}{R_s + \sigma L_s p}$$

Proposed IFOC scheme

- 最佳化的轉差頻率間接磁場導向控制優缺點



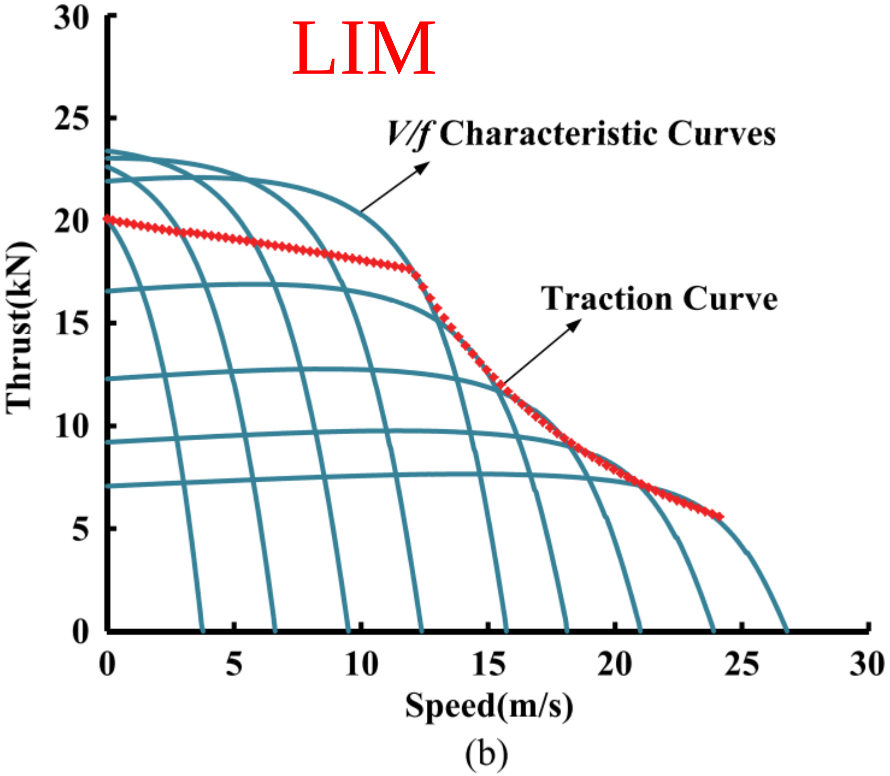


Fig. 3. Mechanical characteristic curves of RIM and LIM. (a) RIM. (b) LIM.

Simulation results

固定頻率IFOC　　磁通補償IFOC　　建議的IFOC

標準　　時間減少，電流增加　　時間減少，電流不變

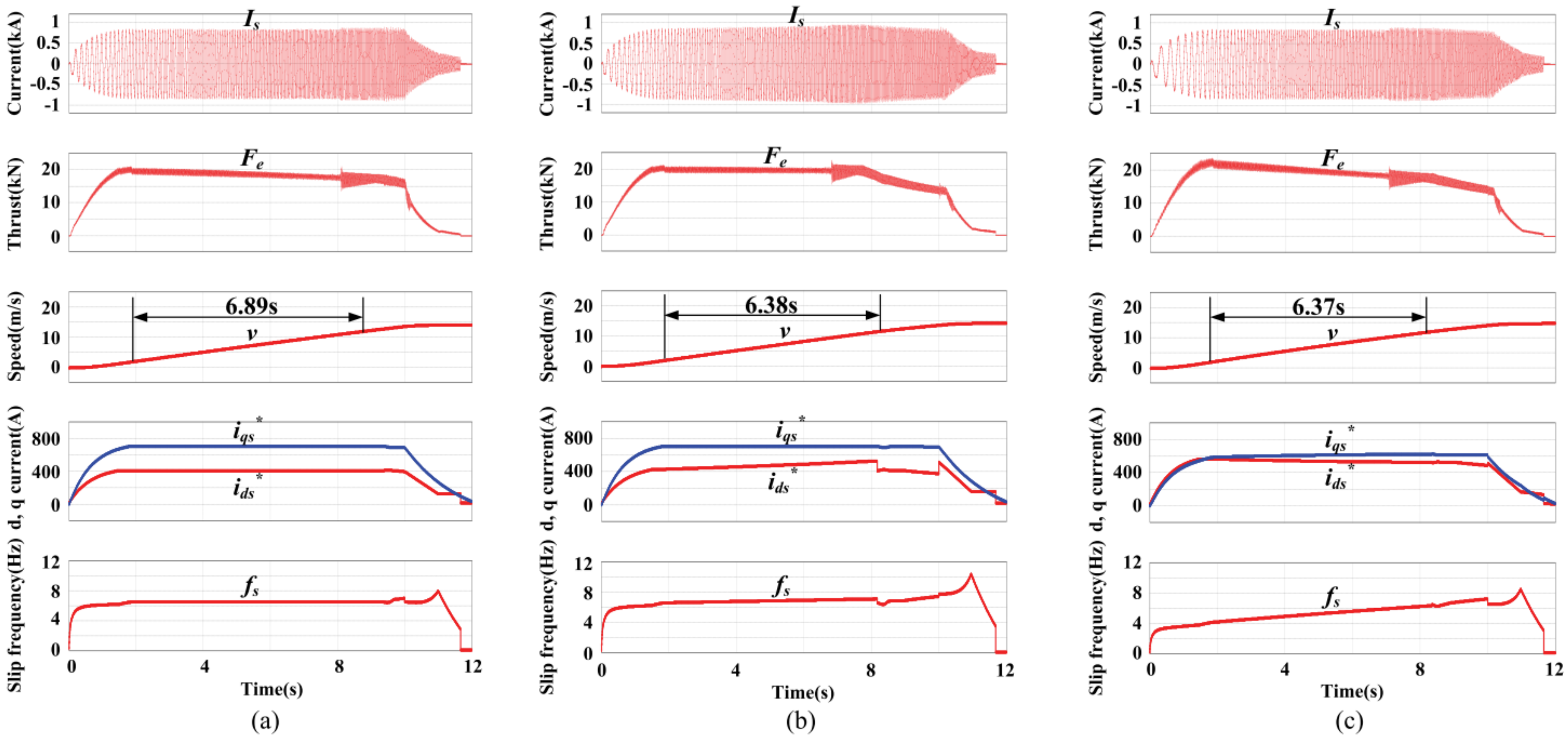


Fig. 12. Simulation results with different control schemes. (a) IFOC with constant slip frequency. (b) IFOC with flux attenuation compensation. (c) Proposed IFOC scheme.

Experimental results

實驗設備

Fig. 15. LIM metro vehicle for experiments.

Fig. 16. LIM traction inverter for experiments.

Experimental results

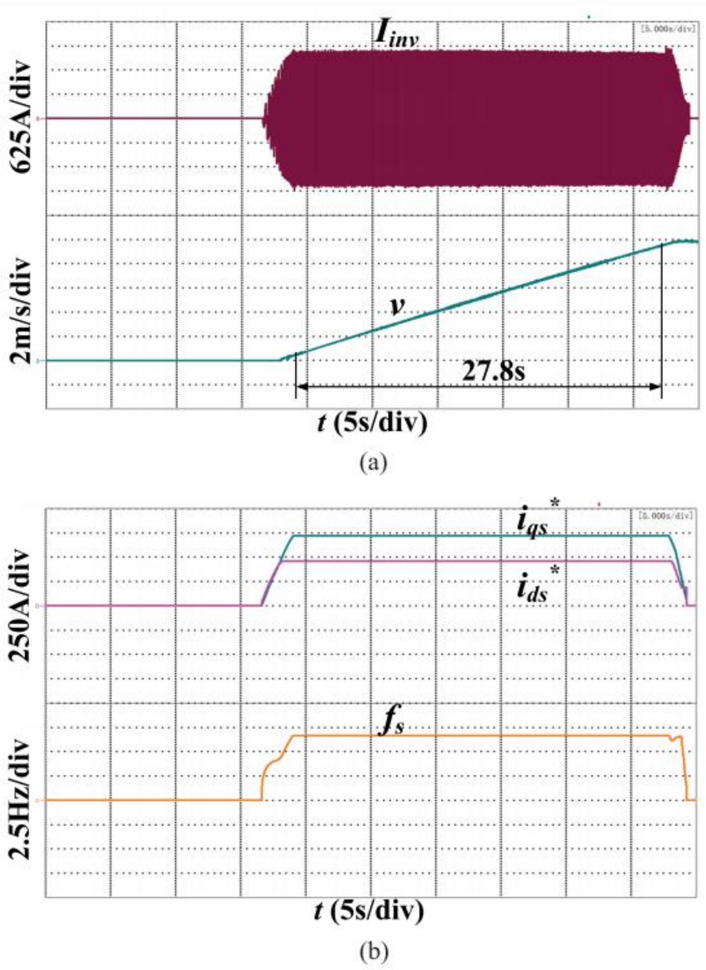


Fig. 17. Experimental results with a constant slip frequency IFOC control scheme. (a) Inverter current and vehicle speed. (b) d- and q-axis reference currents, slip frequency.

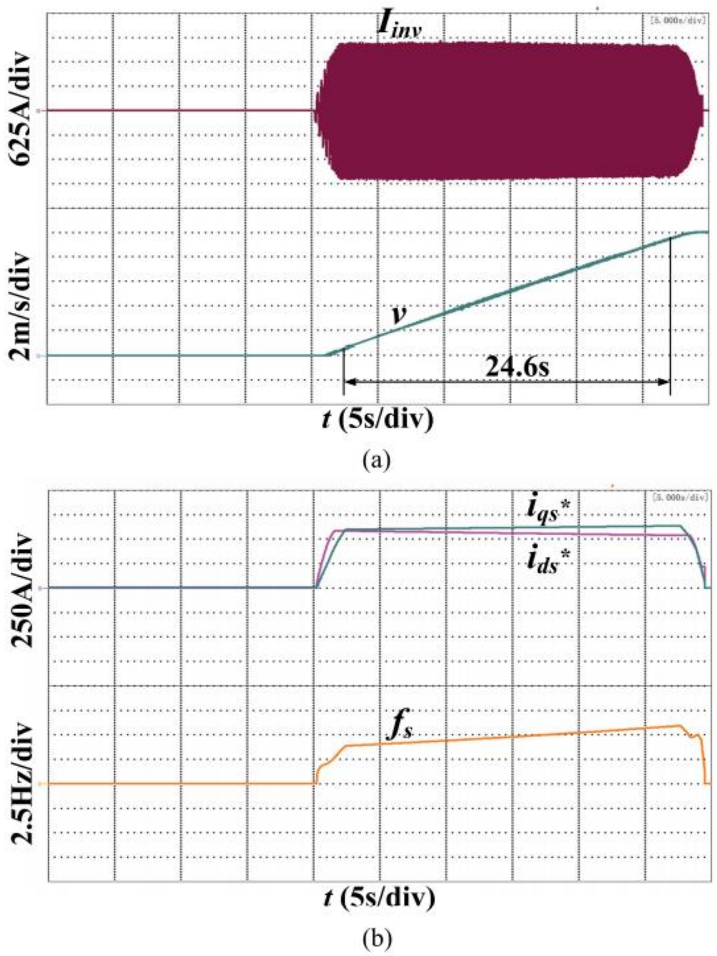


Fig. 18. Experimental results with the proposed scheme. (a) Inverter current and vehicle speed. (b) d- and q-axis reference currents, slip frequency.

Experimental results

- 高速運行實驗

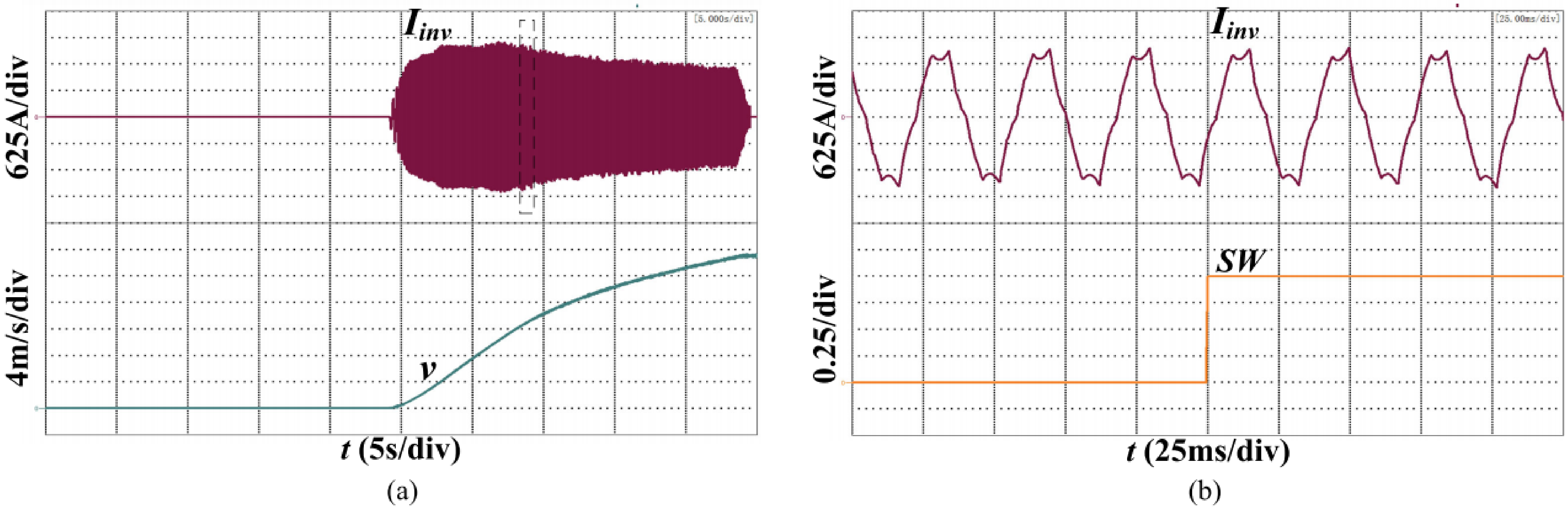


Fig. 19. Wide speed range operation experimental results with the proposed scheme. (a) Inverter current and vehicle speed. (b) Enlarged inverter current and switching index waveforms in transition.

Conclusion

- 考慮了邊緣效應，對LIM的牽引特性進行了分析
- 討論了LIM不同控制方法的性能
- 提出了一種基於最佳化轉差頻率的間接磁場導向控制

心得

- 報告這篇論文讓我了解到線性感應馬達的很多特性，並且知道感應馬達在控制上的困難點是轉差頻率的量測。了解到線性馬達跟旋轉馬達在實作上的差異性，還有他在未來的發展空間。