Deadbeat Predictive Control of Dual Three-Phase Linear Motors Based on Sliding Mode Observer

Presenter: Huifei Cheng
College of Transportation, Tongji University

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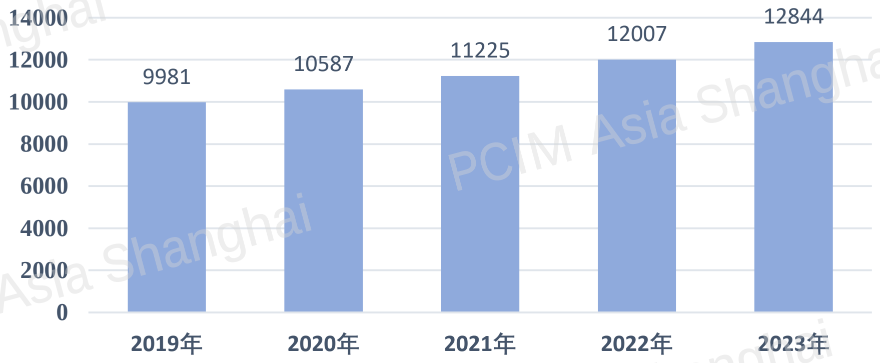
1.1 Background

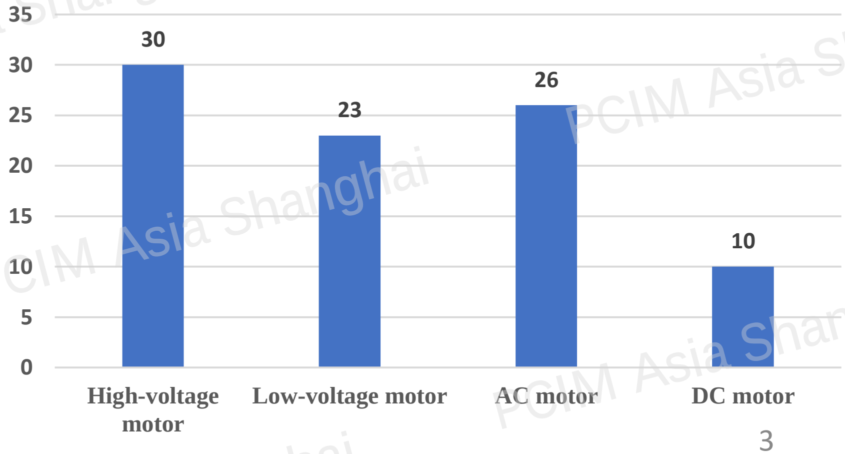
- **Background：** Against the backdrop of China's "dual-carbon" goals – "carbon peak" and "carbon neutrality", the usage of electric motors is increasing day by day to achieve green, economic and sustainable development, while their types and design methods are also constantly evolving.

- Dual three-phase linear motors exhibit significant advantages in application scenarios with high line power requirements, including:
- **Reduced thrust ripple**
- **Enhanced fault tolerance capability**
- **Improved efficiency and higher power density**

The scale of China's motor market from 2019 to 2023 (billion yuan)



2023 market share (%) of Top 10 motor enterprises in China's segmented motor sector



1.2 Challenges and Objectives

Current Challenges:

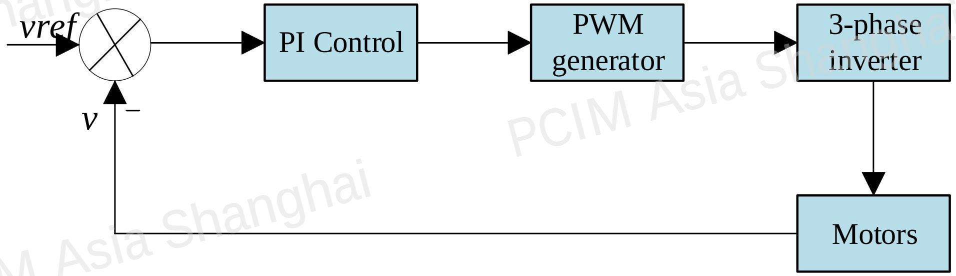
- Positioning errors caused by load mutations/parameter mismatches

Control Bottlenecks:

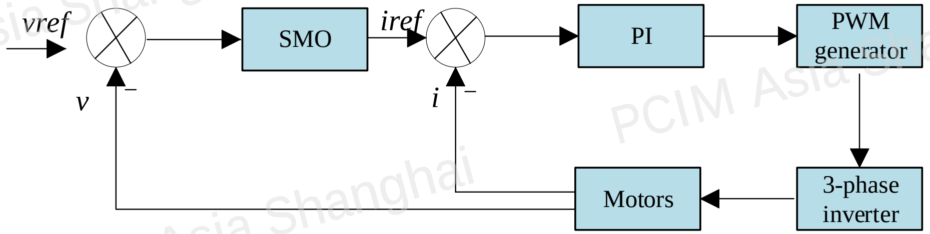
- **PI Control:** Limited harmonic suppression
- **Traditional Sliding Mode Control (SMC):** Severe chattering issues

Objectives:

- High-precision + Enhanced robustness
- Integration of DBPC (Deadbeat Predictive Control) and SMO (Sliding Mode Observer)



PI control method



Sliding mode control method

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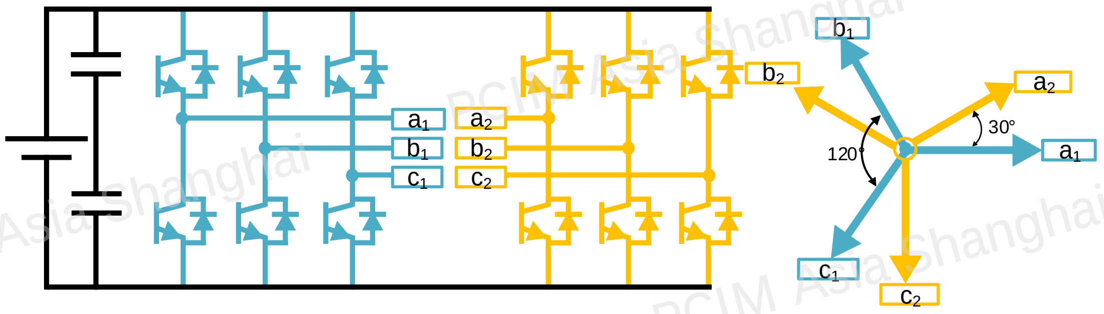
2 Model of Dual-Three Phase Linear Motors

- The Dual-Three Phase Linear Motors (DTP-LMs) comprises two identical three-phase winding sets with a **30° electrical phase shift** between them and **isolated neutral points**.



The structure of DTP-LMs

$$\begin{bmatrix} u_{a1}(t) \\ u_{b1}(t) \\ u_{c1}(t) \end{bmatrix} = R_s \begin{bmatrix} i_{a1}(t) \\ i_{b1}(t) \\ i_{c1}(t) \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_{a1}(t) \\ \psi_{b1}(t) \\ \psi_{c1}(t) \end{bmatrix}$$

$$\begin{bmatrix} u_{a2}(t) \\ u_{b2}(t) \\ u_{c2}(t) \end{bmatrix} = R_s \begin{bmatrix} i_{a2}(t) \\ i_{b2}(t) \\ i_{c2}(t) \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_{a2}(t) \\ \psi_{b2}(t) \\ \psi_{c2}(t) \end{bmatrix}$$

Six-phase voltage equation

- There are two control models for dual three-phase linear motors:
- **The dual dq model**
- **The Vector Space Decomposition (VSD)**

2 Model of Dual-Three Phase Linear Motors

- The VSD of DTP-LMs

- Building upon the aforementioned VSD theory, six-phase voltages or currents are decomposed into three orthogonal subspaces—**αβ, xy, and o_1o_2**—through the following transformation matrix.

$$T_1=\frac{1}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & 0 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & -\frac{1}{2} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & 0 \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} & \frac{1}{2} & -1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \qquad \begin{bmatrix} x_\alpha \\ x_\beta \\ x_x \\ x_y \\ x_{0_1} \\ x_{0_2} \end{bmatrix} = T_1 \cdot \begin{bmatrix} x_{a1} \\ x_{b1} \\ x_{c1} \\ x_{a2} \\ x_{b2} \\ x_{c2} \end{bmatrix}$$

Transformation matrix

- Subsequently, the αβ model is transformed into the dq reference frame via the Park transformation.

$$\begin{cases} u_d = u_\alpha \cos\theta + u_\beta \sin\theta \\ u_q = -u_\alpha \sin\theta + u_\beta \cos\theta \end{cases}$$

$$\begin{bmatrix} u_d(t) \\ u_q(t) \end{bmatrix} = R_s \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix}$$
$$+\omega_e \begin{bmatrix} -\psi_q \\ \psi_d \end{bmatrix}$$

d-q voltage equations

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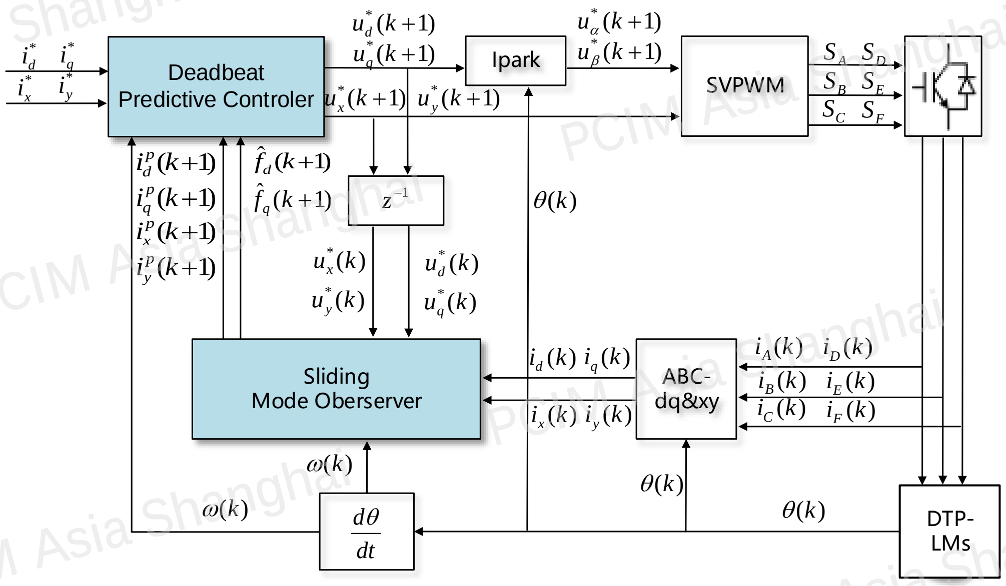
3.1 The structure of Sliding Mode Observer

- The core control unit adopts a deadbeat predictive control model to output the optimal voltage vector, which is then modulated by SVPWM to generate drive signals for motor operation.

- When calculating the optimal vector, direct computation based on motor parameters yields significant errors due to the presence of disturbance errors. Therefore, a sliding mode observer is introduced for disturbance observation and calculation, which predicts the current value at the next moment based on the current moment.



DBPC with SMO block diagram

3.2 Disturbance compensation

- Disturbance compensation and model reconstruction

  - Considering the interference from external disturbances and measurement noise, the original model is extended to a disturbance model:

$$\begin{bmatrix} u_d(t) \\ u_q(t) \end{bmatrix} = R_s \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} + \omega_e \begin{bmatrix} -\psi_q \\ \psi_d \end{bmatrix} + \begin{bmatrix} f_d \\ f_q \end{bmatrix}$$

  - Since system disturbances are unknown, disturbance reconstruction must be constructed according to sliding mode variable structure control principles:

$$\begin{bmatrix} u_d(t) \\ u_q(t) \end{bmatrix} = R_s \begin{bmatrix} \hat{i}_d(t) \\ \hat{i}_q(t) \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} \hat{i}_d(t) \\ \hat{i}_q(t) \end{bmatrix} + \omega_e \begin{bmatrix} -\psi_q \\ \psi_d \end{bmatrix} + \begin{bmatrix} \hat{f}_d \\ \hat{f}_q \end{bmatrix} + \begin{bmatrix} U_{dsm} \\ U_{qsm} \end{bmatrix}$$

  - The sliding surface and a novel reaching law are defined as follows:

$$\begin{cases} s_d = e_d = i_d^p - i_d \\ s_q = e_q = i_q^p - i_q \end{cases}$$

$$\dot{s} = -\varepsilon \operatorname{sgn}(s), (\varepsilon > 0)$$

$$\dot{s} = -\varepsilon \operatorname{sgn}(s) - ks, (\varepsilon > 0, k > 0)$$

$$\dot{s} = -k_1 |e|^{1/2} \tanh(e) - \lambda e$$

3.2 Disturbance compensation

- The **sliding mode control function** can be derived from the disturbance model and the formula reconstructed based on the sliding mode principle.

- The observed value of the disturbance follows the following relational expression:

$$\begin{cases} U_{dsm} = (L_d\lambda - R_s)e_d(k) + L_d k_1 |e_d|^{1/2}\tanh\left(e_d\right) \\ U_{qsm} = (L_q\lambda - R_s)e_q(k) + L_q k_1 |e_q|^{1/2}\tanh\left(e_q\right) \end{cases}$$

$$\begin{cases} \hat{f}_d(k+1) = \hat{f}_d(k) + T_s g U_{dsm} \\ \hat{f}_q(k+1) = \hat{f}_q(k) + T_s g U_{qsm} \end{cases}$$

- By applying the forward Euler method to the current-voltage formula on the left, the compensated current result in the right formula can be obtained.

$$\begin{bmatrix} u_d(t) \\ u_q(t) \end{bmatrix} = R_s \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} + \omega_e \begin{bmatrix} -\psi_q \\ \psi_d \end{bmatrix} + \begin{bmatrix} f_d \\ f_q \end{bmatrix}$$

$$\begin{cases} i_d^p(k+1) = \left(1 - \dfrac{T_s R_s}{L_d}\right) i_d^p(k) + \dfrac{T_s L_q}{L_d}\omega_e i_q(k) \\ + \dfrac{T_s}{L_d} u_d^*(k) - \dfrac{T_s}{L_d}\hat{f}_d(k) - \dfrac{T_s}{L_d} U_{dsm} \\ i_q^p(k+1) = \left(1 - \dfrac{T_s R_s}{L_q}\right) i_q^p(k) - \dfrac{T_s L_d}{L_q}\omega_e i_d(k) \\ + \dfrac{T_s}{L_q} u_q^*(k) - \dfrac{T_s}{L_q} M_{sm} i_f \omega_e - \dfrac{T_s}{L_q}\hat{f}_q(k) - \dfrac{T_s}{L_q} U_{qsm} \end{cases}$$

3.3 Deadbeat prediction control

- The deadbeat prediction result of the optimal vector will be comprehensively compensated based on the predicted current value and the reference value to obtain the final optimal vector:

$$
\begin{cases}
u_d^*(k+1) = \dfrac{L_d}{T_s} i_d^* + \left(R_s - \dfrac{L_d}{T_s} \right) i_d^p(k+1) \\
-\omega_e L_d i_q^p(k+1) + \hat{f}_d(k+1) \\
u_q^*(k+1) = \dfrac{L_q}{T_s} i_q^* + \left(R_s - \dfrac{L_q}{T_s} \right) i_q^p(k+1) \\
+\omega_e L_d i_d^p(k+1) + \hat{f}_q(k+1) \omega_e M_{sm} i_f
\end{cases}
$$

Motor control loop cycle

DBPC Command Reception

DBPC receives target commands and SMO feedback

Optimal Voltage Calculation

Predictive controller computes dq-axis voltages

Signal Modulation Process

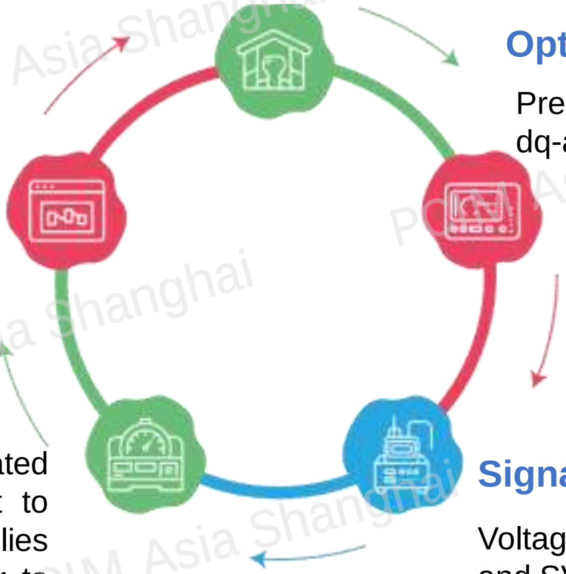
Voltages undergo transformation and SVPWM modulation

Motor Drive

Switching signals are generated through modulation and sent to the inverter, which supplies electrical energy to the motor to drive its operation.

SMO Disturbance Compensation

The SMO uses motor signals and built-in functions to perform disturbance compensation and calculate the disturbance value.



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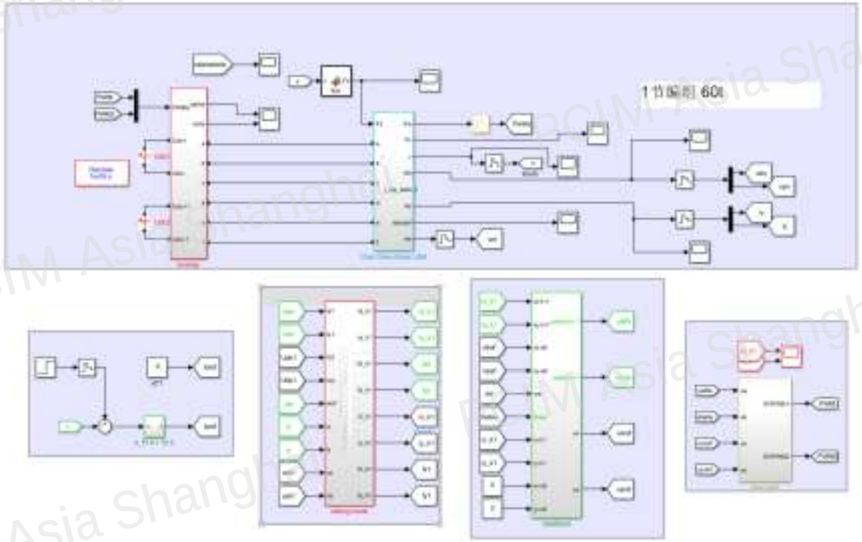
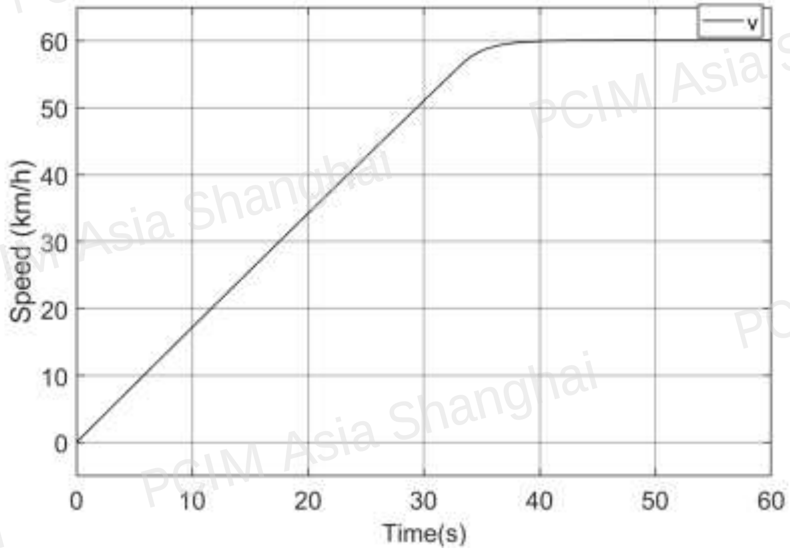
4 Simulation and Results

- To verify the control performance of the proposed deadbeat predictive control based on a sliding mode observer (DBPC-SMO) in a dual three-phase linear motor system, Simulink-based simulations were conducted, and comparisons were made with the traditional PI control method.
- The simulation conditions are as follows: DC voltage is 5000 V, inverter switching frequency is 1 kHz, and speed ranges from 0 to 60 km/h.


Simulink simulation model



Simulation speed variation curve

4 Simulation and Results

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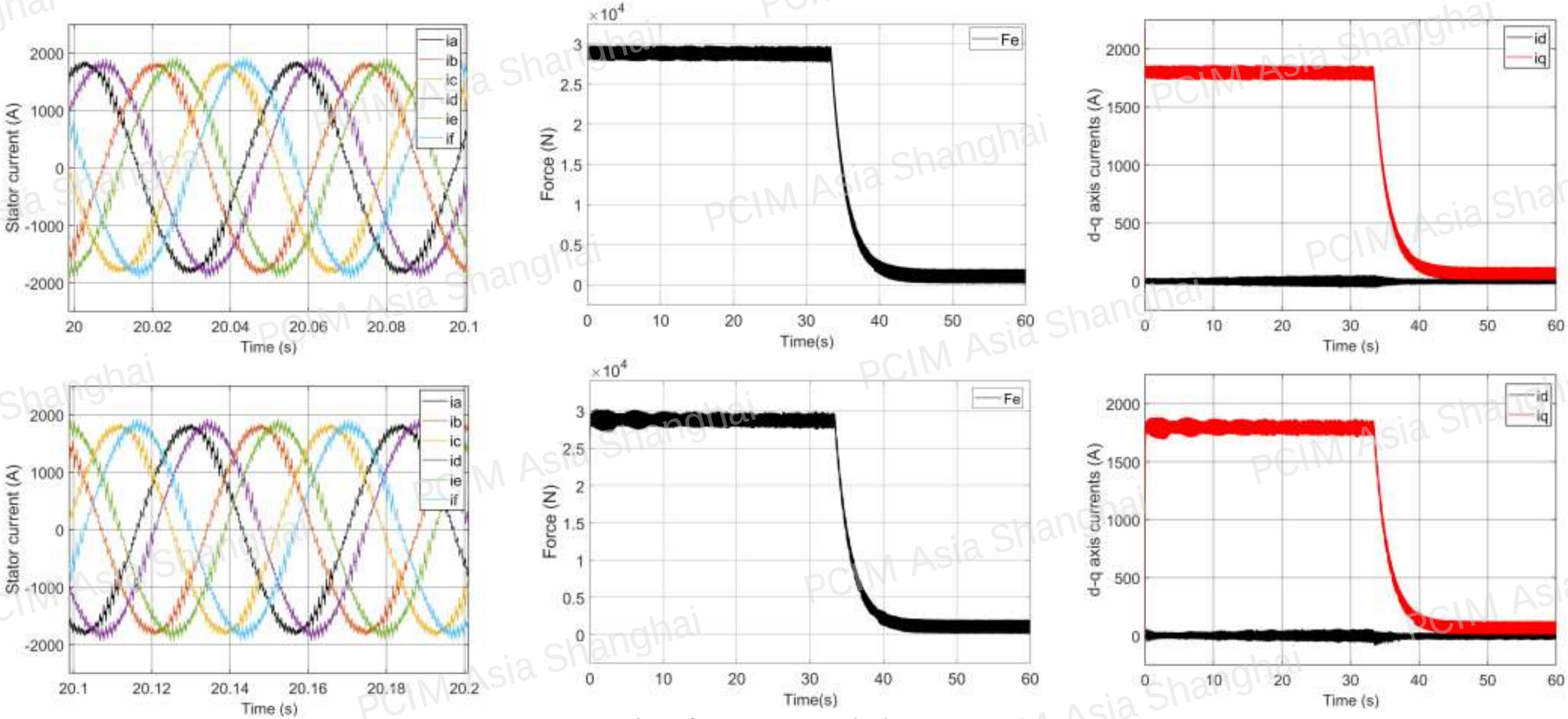
DBPC-SMO

PI Control



The stator current

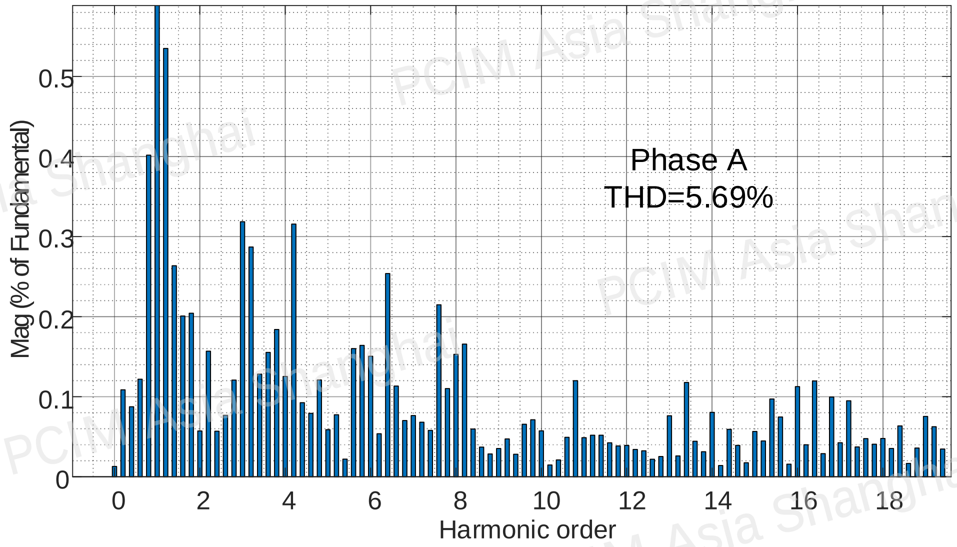
The electromagnetic force

The d-q axis current

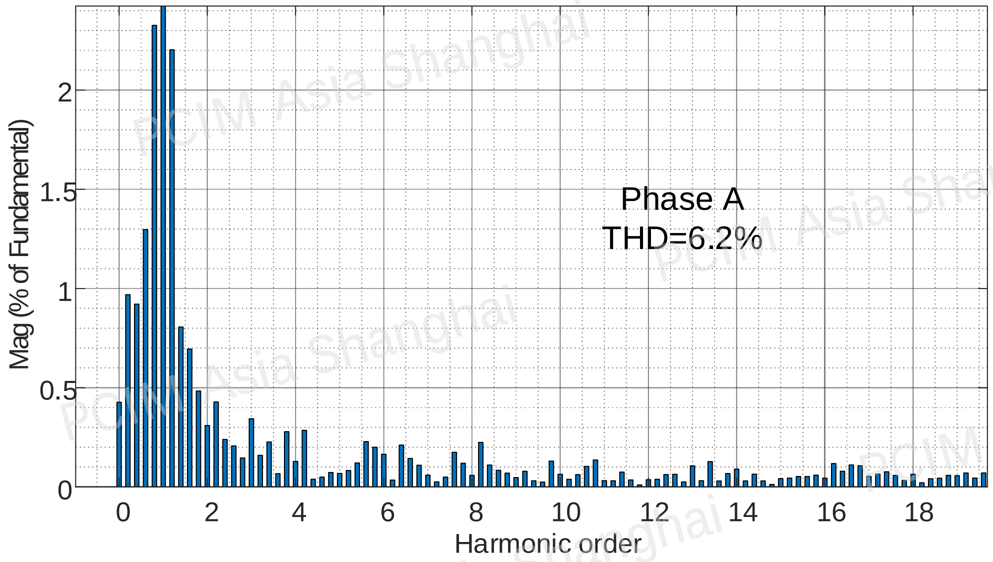
- The results show that the fluctuation amplitude of the proposed DBPC-SMO method is significantly smaller than that of the PI method, and the fluctuation of the d-axis current at the jump point is smoother.

4 Simulation and Results

- In addition, in order to further visualize above results analysis, the following two figures show the simulation results of total harmonic distortion (THD). The THD of the stator current has decreased from 6.20% to 5.69%.



Total harmonic distortion of DBPC-SMO



Total harmonic distortion of PI control

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5 Conclusion

- **Advantages:**
- A DBPC-SMO control strategy is proposed for dual three-phase linear motors to solve the key technical problem of suppressing thrust ripple.
- This scheme innovatively adopts a new sliding mode control rate, and simulation results show that its thrust ripple is significantly lower than that of traditional methods.

Performance	PI Control	DBPC-SMO	Improvement
dq-axis current	High oscillation	Smooth tracking	Significantly reduce
Thrust fluctuation	Significant	Suppressed	Matches q-current
Current THD	6.20%	5.69%	8.2% ↓

- **Future work:**
- The control effect on the xy-axis current is not ideal. In the future, adjustments to the algorithm or parameters for the xy-axis currents will be needed to achieve better results.

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