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A Novel Fundamental PWM Excitation-Based Rotor Position Estimation Method for Precision Sensorless Control of IPMSMs

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Content

Content

1.1 Backgrounds

➢ **IPMSMs** (Interior Permanent Magnet Synchronous Motors) **are widely used in many aspects**

CNC machine

mechanical arm

Electric vehicle

quadruped robot

elevator

- ★ **High efficiency**
- ★ **Compact size**
- ★ **Wide speed range**
- ★ **High torque performance**
- ★ **Fast dynamic response**

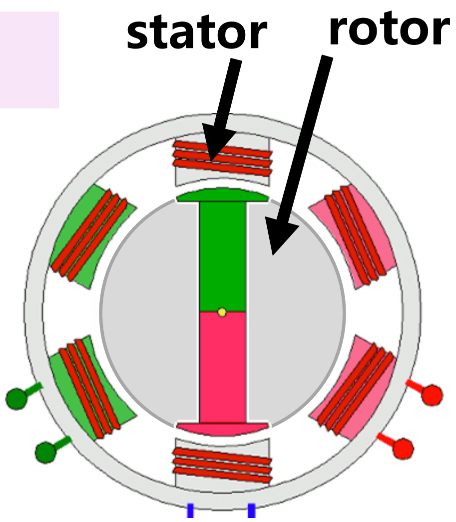
1.2 Rotor position feedback of IPMSM

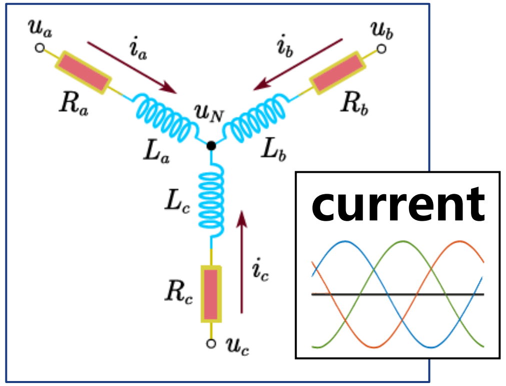
➢ Structure and working principle of IPMSM

stator windings

rotor with interior PMs (permanent magnets)

simplify



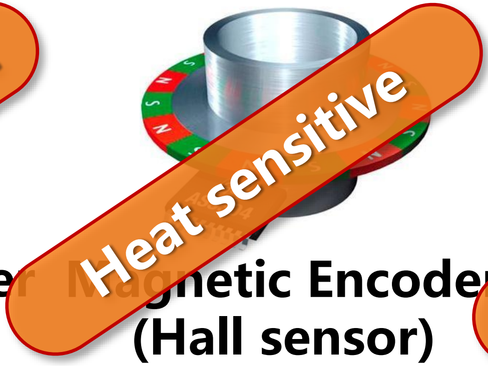


stator 3-phase circuit

➢ Field-oriented control (FOC) of IPMSM requires rotor position feedback

➢ Hardware position sensors are currently used

Rotary transformer (Resolver)



Magnetic Encoder (Hall sensor)

Circular grating encoder

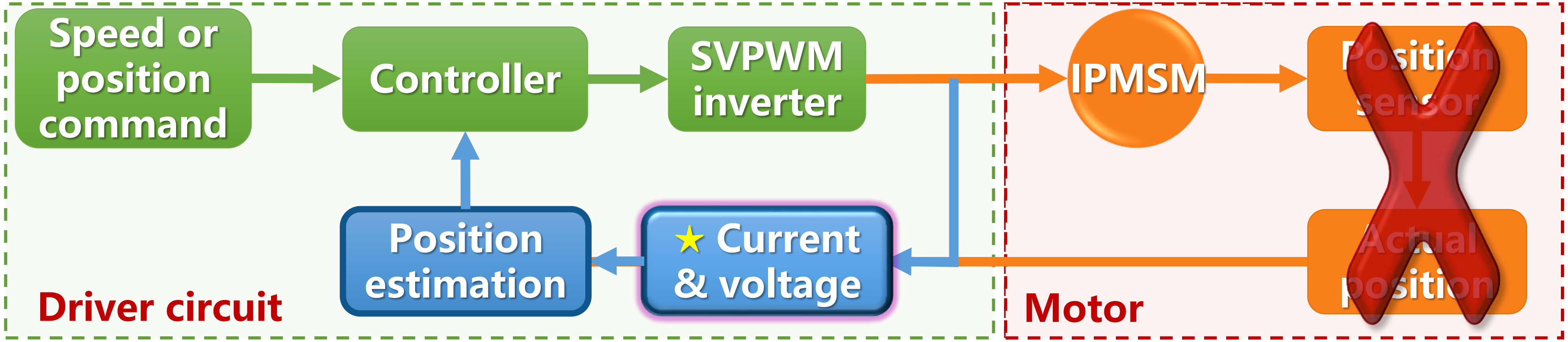
➢ Industrial challenges

- ★ Long-term reliability
- ★ Reduction of cost
- ★ Mass & volume compression
- ★ Thermal stability

Any other methods to meet these challenges?

1.3 (Position) Sensorless control

➢ Sensorless control —— a promising solution in many applications



advantages:

★ Cost ↓

★ Volume ↓

★ Power density ↑

★ Reliability ↑

➢ Ideal——**perfect** sensorless control

- ➢ **The rotor position is estimated from phase current and voltage;**
- ➢ **Closed-loop servo control just like a physical position sensor is installed:**
  - ➢ **Whole speed range;**
  - ➢ **Irrelevant to load;**
  - ➢ **No extra disturbance.**

application merits

➡ **More compact structure; Much cheaper;**

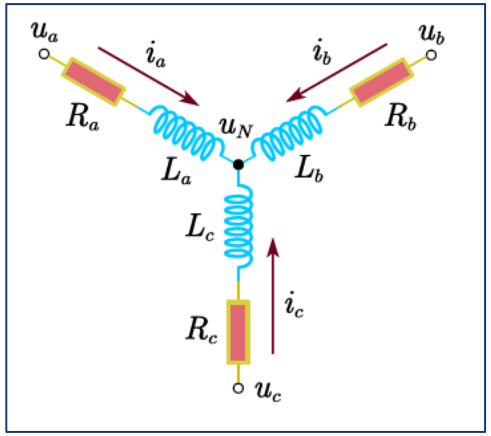
➡ **Higher reliability; Easier to maintain;**

➡ **Simpler design; Longer battery life;**

Content

2.1 Technical routes of sensorless control

IPMSM circuit



$$\begin{cases} 0 = i_A + i_B + i_C \\ u_A = e_A + i_A R + L_{AA}\dfrac{\mathrm{d}i_A}{\mathrm{d}t} + L_{AB}\dfrac{\mathrm{d}i_B}{\mathrm{d}t} + L_{AC}\dfrac{\mathrm{d}i_C}{\mathrm{d}t} \\ u_B = e_B + i_B R + L_{BA}\dfrac{\mathrm{d}i_A}{\mathrm{d}t} + L_{BB}\dfrac{\mathrm{d}i_B}{\mathrm{d}t} + L_{BC}\dfrac{\mathrm{d}i_C}{\mathrm{d}t} \\ u_C = e_C + i_C R + L_{CA}\dfrac{\mathrm{d}i_A}{\mathrm{d}t} + L_{CB}\dfrac{\mathrm{d}i_B}{\mathrm{d}t} + L_{CC}\dfrac{\mathrm{d}i_C}{\mathrm{d}t} \end{cases}$$

- **Known: Voltage u, current i**
- **Aim: Solve rotor position θ**

IPMSM circuit equation (matrix format)

$$\boldsymbol{u} = \boldsymbol{e}(\theta,\omega) + R\boldsymbol{i} + \boldsymbol{L}(\theta)\cdot\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}$$

$$\begin{aligned} e_A &= K_e\omega\sin(\theta) \\ e_B &= K_e\omega\sin(\theta - 120°) \\ e_C &= K_e\omega\sin(\theta + 120°) \end{aligned}$$

$$L_{xx}(\theta) = L_\Sigma + L_\Delta\cos(2\theta + \varphi)$$

Back EMF-based

- Disturbance observer;
- Sliding mode observer;
- Extended Kalman filter;
- Flux linkage observer;
- …

Injection-based

- INFORM (Indirect Flux Online React Measurement) method;
- Rotary high-frequency signal injection;
- Stationary frame high-frequency injection;
- …

2.2 Back EMF(electromotive force)-based methods

Back EMF-based sensorless control methods

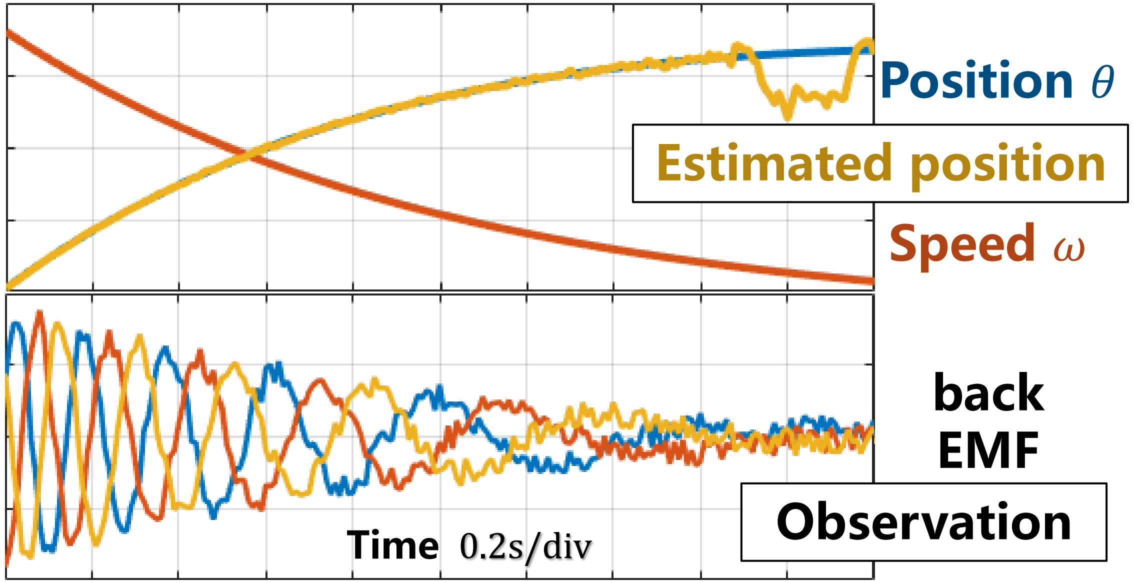
$$\hat{\boldsymbol{e}} = \boldsymbol{u} - R\boldsymbol{i} - \boldsymbol{L} \cdot \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}$$

(1) → back EMF observation

$$e_i = K_e \omega \sin(\theta - \varphi_i)$$

(2) → relation of back EMF to position & speed

where $\varphi_A = 0, \varphi_B = 120°, \varphi_C = 240°$



- a basic algorithm to estimate rotor position:

$$\hat{\theta} = \mathrm{atan}\left(\frac{2e_A - e_B - e_C}{\sqrt{3}(e_C - e_B)}\right)$$

standstill

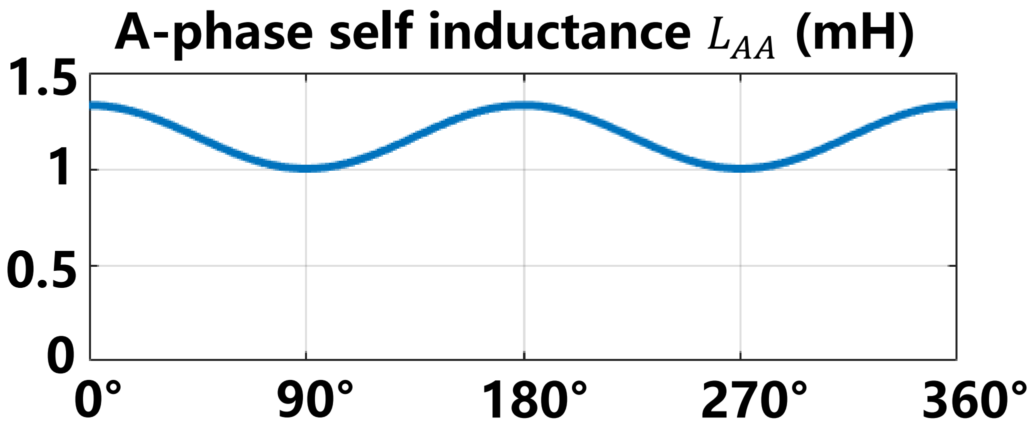
$$\hat{x} = \mathrm{atan}\left(\frac{0}{0}\right)$$

- Works well at high-speed
- Performs poor in the low-speed range due to low SNR
- Sensitive to R change

Fails at long-term standstill
NOT "perfect sensorless"

2.3 Injection-based methods

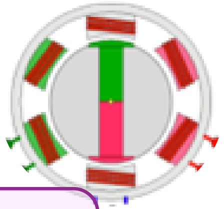
Injection-based sensorless control methods



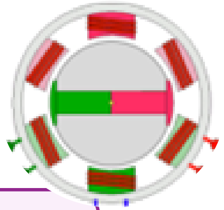
- ★ $L(\theta)$ is independent of speed
- ★ How to measure?

$$\boldsymbol{u} = \boldsymbol{e}(\theta, \omega) + R\boldsymbol{i} + \boldsymbol{L}(\theta) \cdot \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}$$

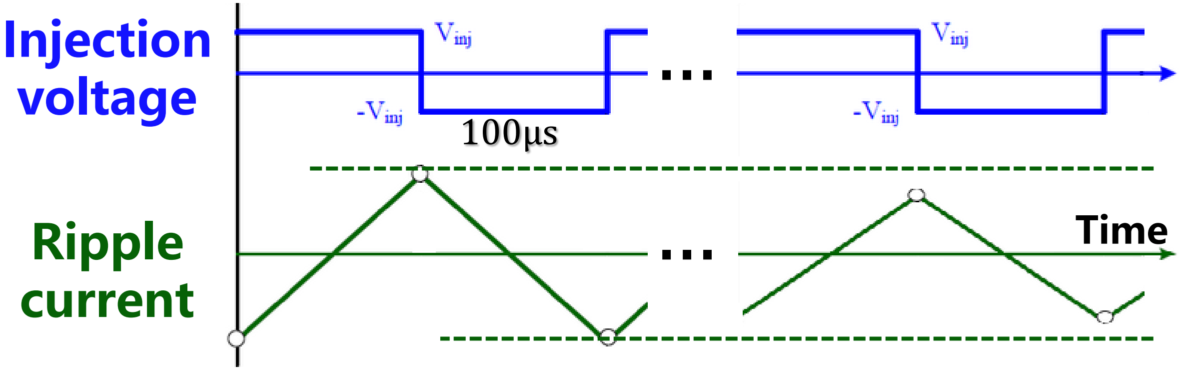
- ★ L can only be measured through **high-frequency** response!



$\theta = 90°$
$L_{AA} = 1.00\mathrm{mH}$



$\theta = 180°$
$L_{AA} = 1.33\mathrm{mH}$



- ✔ $L(\theta)$ is independent of speed
- ⚠ **High-speed** difficulty distinguishing back EMF and response signal
- ⚠ **Injection causes extra heating**, hearable noise and disturbance

Also inperfect

2.4 The contradiction

Back EMF-based

- ✓ Good at high-speed
- × Standstill failure
- × Sensitive to R change

Injection-based

- ✓ Good at standstill & low-speed
- × Extra energy loss and noise
- × Injected signals disturb control

Demands of IPMSM applications

- ★ Standstill stability
- ★ High dynamics load variation
- ★ Whole speed range servo control
- ★ High efficiency & low noise
- ★ Complex thermal environment

- Existing commercial sensorless solutions

Applicable



NOT applicable



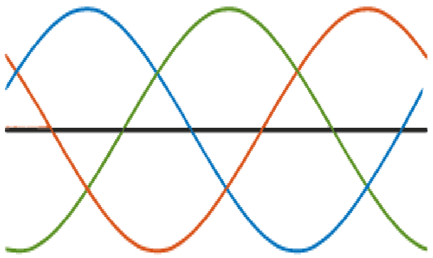
The need for perfect sensorless

Content

3.1 The idea of Fundamental PWM Excitation (FPE)

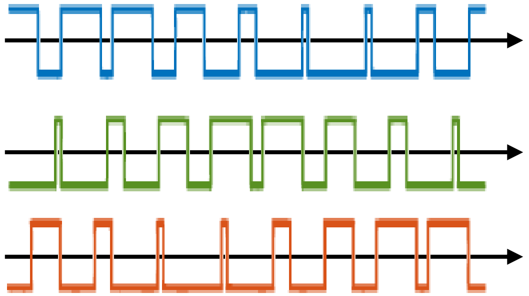
➢ commonly-used Pulse Width Modulation (PWM) drive of IPMSM

Required voltage waveform

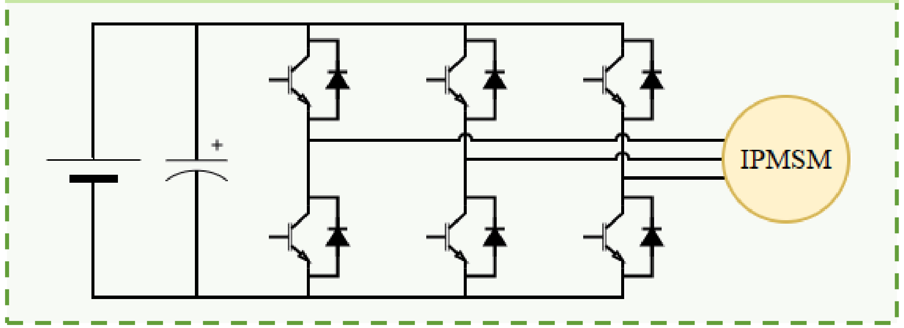


Volt-Second principle

PWM voltage



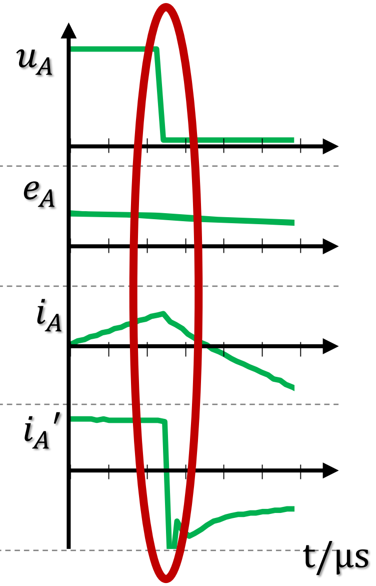
3-phase IPMSM inverter



➢ Directly consider PWM switching as excitation

IPMSM model

$$\boldsymbol{u} = \boldsymbol{e}(\theta, \omega) + R\boldsymbol{i} + \boldsymbol{L}(\theta) \cdot \frac{\mathrm{d}\boldsymbol{i}}{\mathrm{d}t}$$



★ voltage switch in a short time (~1μs)

★ θ, ω approximately unchange

★ current $\boldsymbol{i}$ is continuous (appr.

★ $$\Delta \boldsymbol{u} = \boldsymbol{L}(\theta) \cdot \Delta \left(\frac{\mathrm{d}\boldsymbol{i}}{\mathrm{d}t} \right)$$ ➡ **Transient model of IPMSM**

Speed irrelevant;
R insensitive;
No injection

3.2 The proposed FPE method

Transient model

$$\Delta \boldsymbol{u} = \boldsymbol{L}(\theta) \cdot \Delta\left(\frac{\mathrm{d}\boldsymbol{i}}{\mathrm{d}t}\right)$$

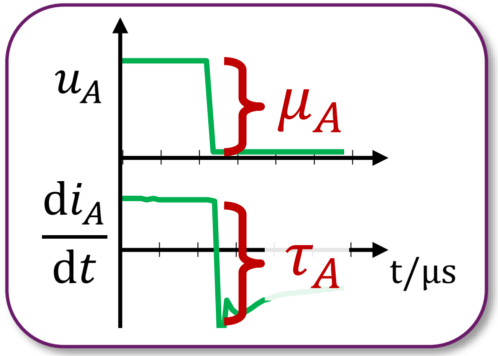
denote:

$$\Delta \boldsymbol{u} \triangleq \boldsymbol{\mu} = [\mu_A \quad \mu_B \quad \mu_C]$$
$$\Delta(\mathrm{d}\boldsymbol{i}/\mathrm{d}t) \triangleq \boldsymbol{\tau} = [\tau_A \quad \tau_B \quad \tau_C]$$

$$\begin{bmatrix} \mu_A \\ \mu_B \\ \mu_C \end{bmatrix} = \begin{bmatrix} L_{AA} & L_{AB} & L_{AC} \\ L_{BA} & L_{BB} & L_{BC} \\ L_{CA} & L_{CB} & L_{CC} \end{bmatrix} \cdot \begin{bmatrix} \tau_A \\ \tau_B \\ \tau_C \end{bmatrix}$$

$$\begin{bmatrix} L_{AA} & L_{AB} & L_{AC} \\ L_{BA} & L_{BB} & L_{BC} \\ L_{CA} & L_{CB} & L_{CC} \end{bmatrix} = L_\Sigma \begin{bmatrix} 1 & -1/2 & -1/2 \\ -1/2 & 1 & -1/2 \\ -1/2 & -1/2 & 1 \end{bmatrix} + L_\Delta \begin{bmatrix} \cos(2\theta) & \cos(2\theta - 120°) & \cos(2\theta + 120°) \\ \cos(2\theta - 120°) & \cos(2\theta + 120°) & \cos(2\theta) \\ \cos(2\theta + 120°) & \cos(2\theta) & \cos(2\theta - 120°) \end{bmatrix}$$

- ★ **each rising/falling edge of PWM →one $(\boldsymbol{\mu}, \boldsymbol{\tau})$ observation group.**
- ❓ **Aim: find the best θ to fit all groups → estimated rotor position $\hat{\theta}$.**
- ✅ **Use Nonlinear Least-Squares (LS) algorithm!**



objective function:

$$\boxed{\min_{\theta} F(\theta) = \sum_{i=1}^{n} \left\| \boldsymbol{\mu}^{(i)} - \boldsymbol{L}(\theta) \cdot \boldsymbol{\tau}^{(i)} \right\|_2^2}$$

Major innovation: FPE position estimation → Nonlinear LS problem

3.3 Solving the nonlinear LS problem

- **Known: a group of (μ, τ) observations.**
- **Aim: minimize the objective function**

$$\min_{\theta} F(\theta) = \sum_{i=1}^{n} \left\| \boldsymbol{\mu}^{(i)} - \boldsymbol{L}(\theta) \cdot \boldsymbol{\tau}^{(i)} \right\|_2^2$$

Numerical solutions are computational **,However**

$$\min_{\theta} F(\theta) \Leftrightarrow \min_{\theta} \left(\cos(2\theta) \cdot \left[\sum_{i=1}^{n} g\left(\boldsymbol{\mu}^{(i)}, \boldsymbol{\tau}^{(i)}\right) \right] + \sin(2\theta) \cdot \left[\sum_{i=1}^{n} h\left(\boldsymbol{\mu}^{(i)}, \boldsymbol{\tau}^{(i)}\right) \right] \right)$$

$\rightarrow F$ is sinusoidal

$$\Leftrightarrow 2\hat{\theta} = \mathrm{atan2}\left(-\sum_{i=1}^{n} g\left(\boldsymbol{\mu}^{(i)}, \boldsymbol{\tau}^{(i)}\right), -\sum_{i=1}^{n} h\left(\boldsymbol{\mu}^{(i)}, \boldsymbol{\tau}^{(i)}\right) \right)$$

$\rightarrow$ analytical solution
Computational cost is small

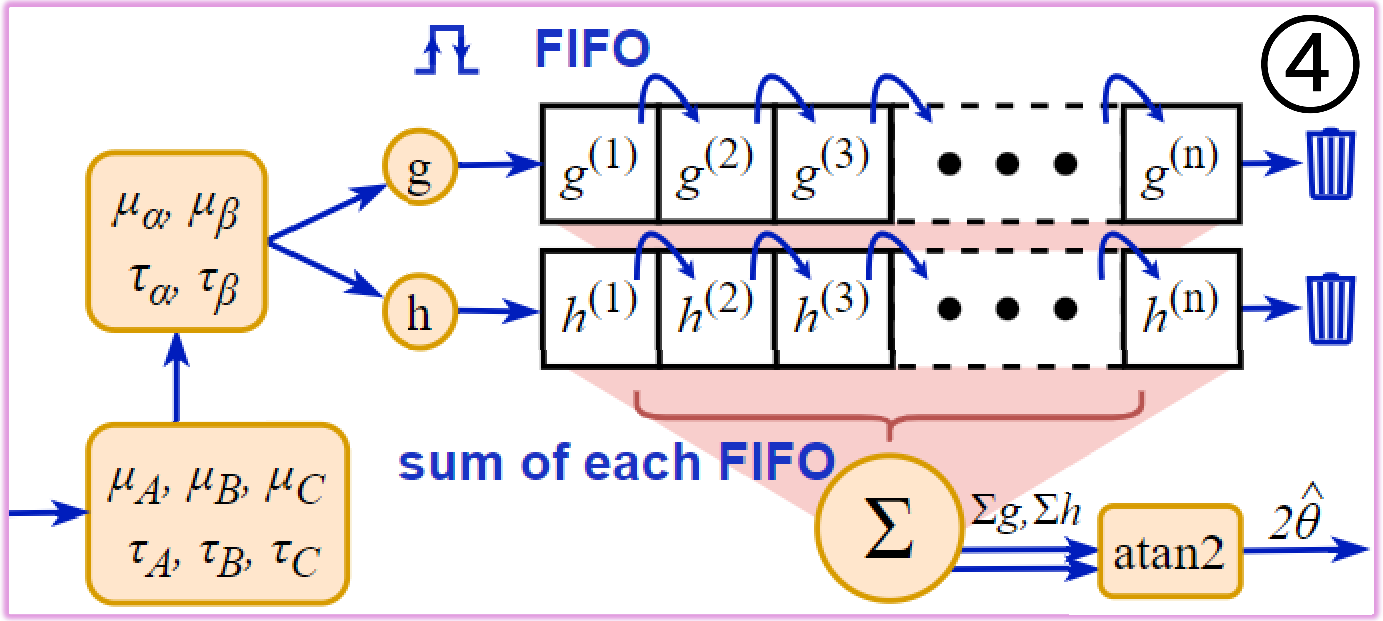
where

$$\begin{cases} g(\boldsymbol{\mu}, \boldsymbol{\tau}) = L_\Sigma(\tau_\alpha + \tau_\beta)(\tau_\alpha - \tau_\beta) + (\mu_\alpha \tau_\alpha - \mu_\beta \tau_\beta) \\ h(\boldsymbol{\mu}, \boldsymbol{\tau}) = L_\Sigma(2\tau_\alpha \tau_\beta) + (\mu_\alpha \tau_\beta + \mu_\beta \tau_\alpha) \end{cases}$$

and

$$\begin{cases} \mu_\alpha = (2\mu_A - \mu_B - \mu_C)/3 \\ \mu_\beta = \sqrt{3}(\mu_B - \mu_C)/3 \\ \tau_\alpha = (2\tau_A - \tau_B - \tau_C)/3 \\ \tau_\beta = \sqrt{3}(\tau_B - \tau_C)/3 \end{cases}$$

➢ Proposed FIFO-based Nonlinear LS rotor position estimation algorithm

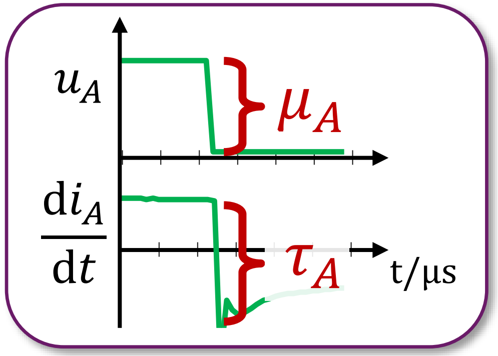


Calculation count	Add/Sub	Mult	Div	Paral_add	CORDIC
	0	0	0	0	0

⑤

$$2\hat{\theta} = \mathrm{atan2}\left(-\sum_{i=1}^{n} g\left(\boldsymbol{\mu}^{(i)}, \boldsymbol{\tau}^{(i)}\right), -\sum_{i=1}^{n} h\left(\boldsymbol{\mu}^{(i)}, \boldsymbol{\tau}^{(i)}\right)\right)$$

$$\Delta\boldsymbol{u} \triangleq \boldsymbol{\mu} = [\mu_A \quad \mu_B \quad \mu_C]$$
$$\Delta(\mathrm{d}\boldsymbol{i}/\mathrm{dt}) \triangleq \boldsymbol{\tau} = [\tau_A \quad \tau_B \quad \tau_C]$$



① obtain $\Delta\boldsymbol{u}$ and $\Delta(\mathrm{d}\boldsymbol{i}/\mathrm{dt})$

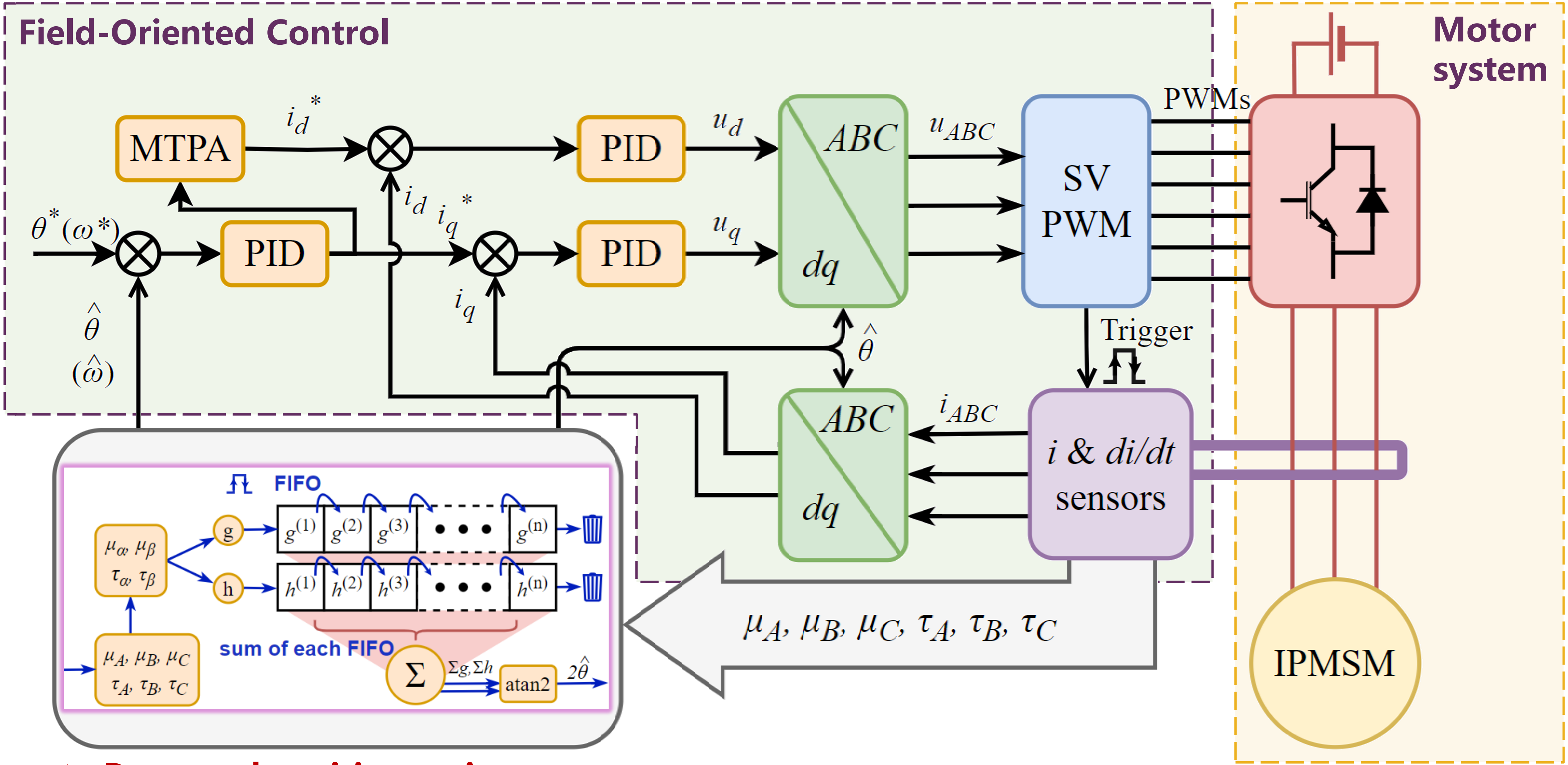
$$\begin{cases} \mu_\alpha = \mu_A + \mu_A - \mu_B - \mu_C \\ \mu_\beta = 1.732(\mu_B - \mu_C) \\ \tau_\alpha = \tau_A + \tau_A - \tau_B - \tau_C \\ \tau_\beta = 1.732(\tau_B - \tau_C) \end{cases}$$

② Clarke transform

$$\begin{cases} g^{(i)} = L_\Sigma(\tau_\alpha + \tau_\beta)(\tau_\alpha - \tau_\beta) + (\mu_\alpha\tau_\alpha - \mu_\beta\tau_\beta) \\ h^{(i)} = L_\Sigma(2\tau_\alpha\tau_\beta) + (\mu_\alpha\tau_\beta + \mu_\beta\tau_\alpha) \end{cases}$$

③

3.5 Sensorless control based on the proposed method



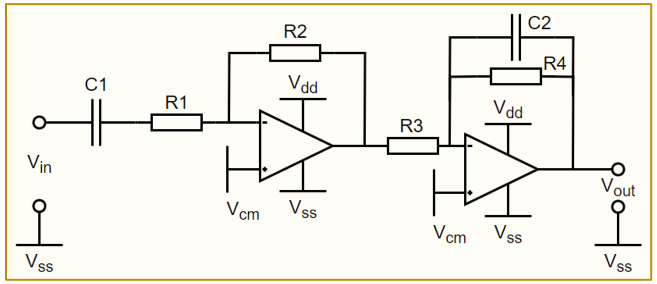
★ Proposed position estimator

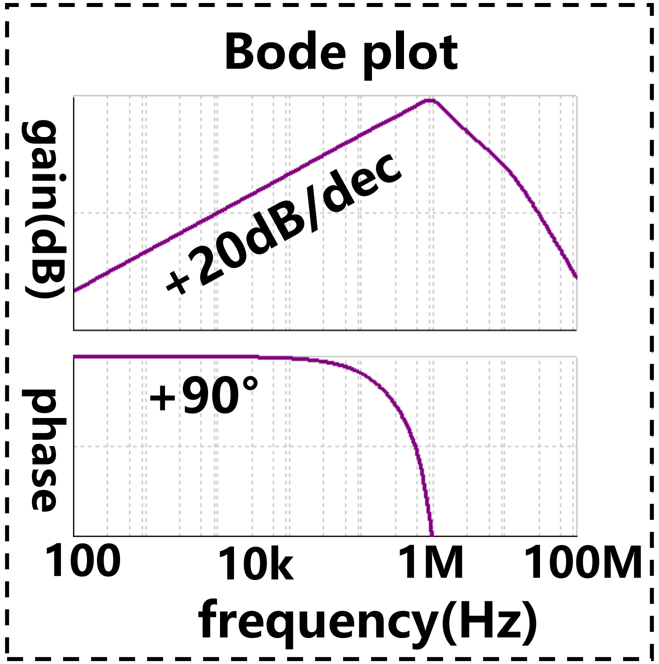
Content

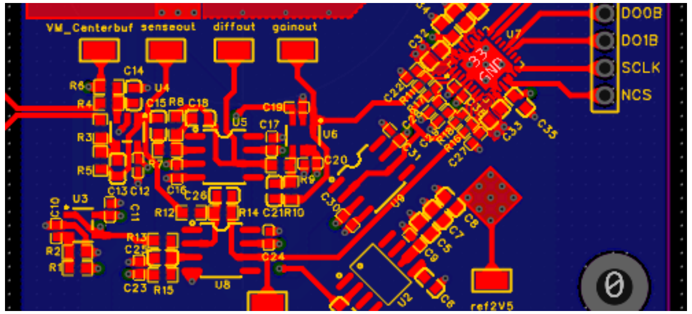
4.1 Actual implementation issues

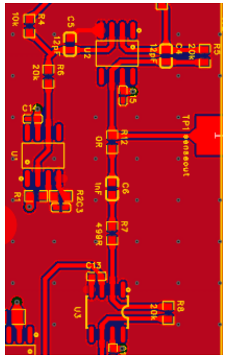
➢ **How to measure instantaneous $\mathrm{d}i/\mathrm{d}t$ in practice ?**

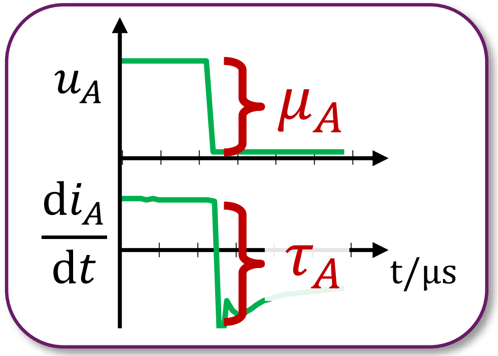
$$\Delta \boldsymbol{u} = \boldsymbol{L}(\theta) \cdot \Delta \left(\frac{\mathrm{d}\boldsymbol{i}}{\mathrm{d}t} \right)$$

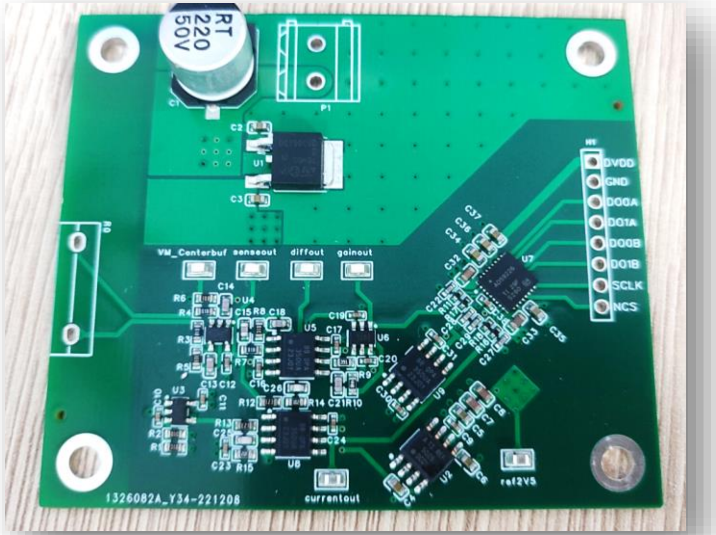








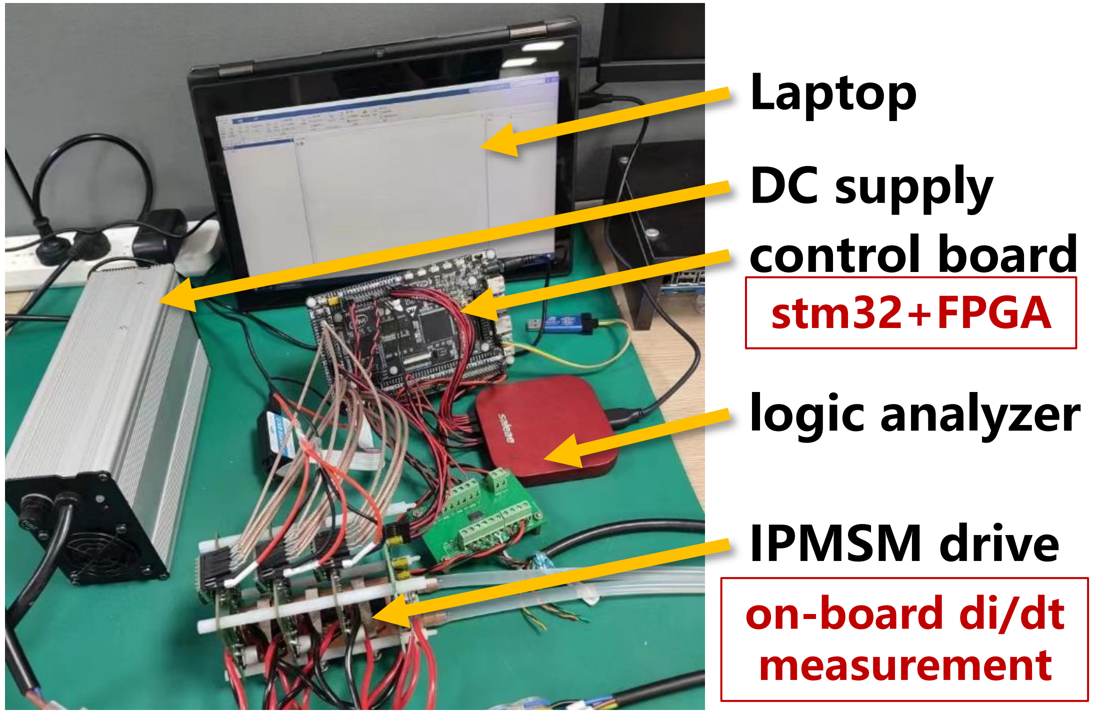




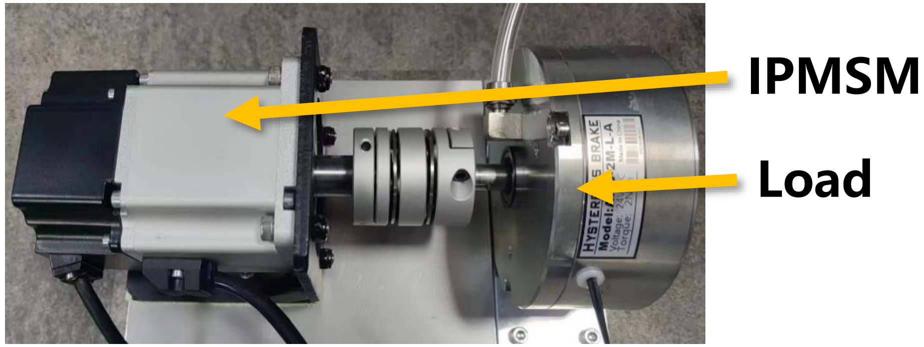
Final version: SNR>93dB

"mother of success"

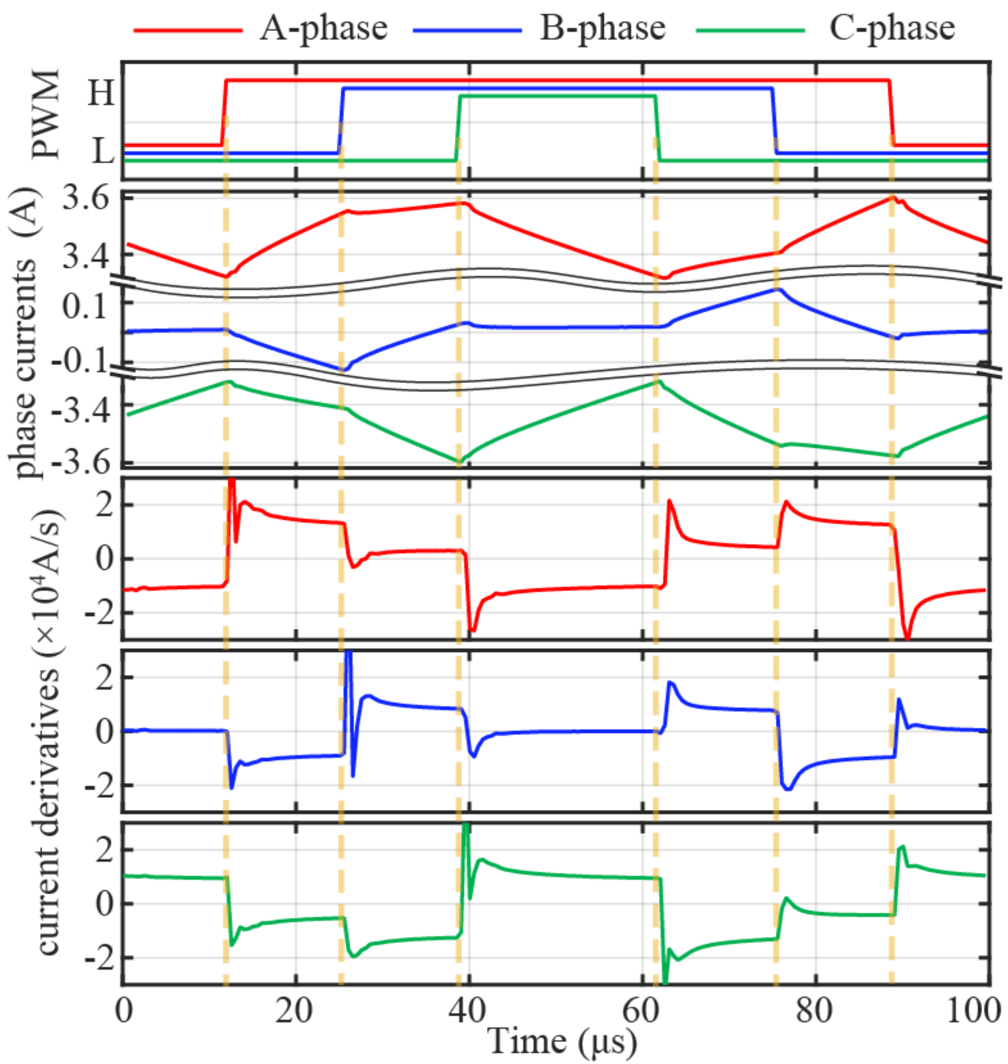
4.2 Experimental setup



Controller & driver



test IPMSM

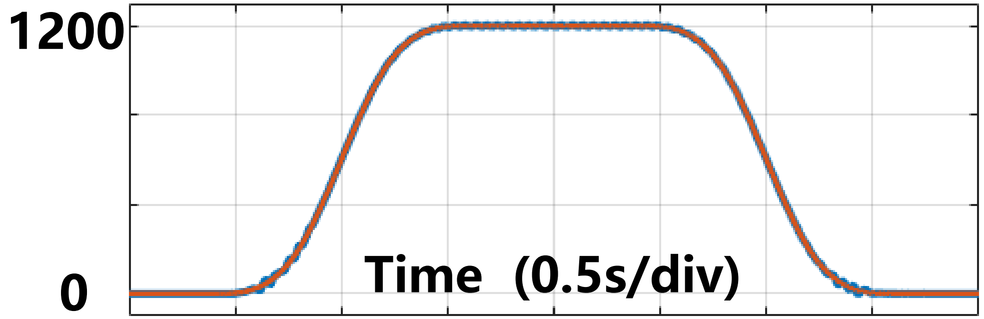


measured current & di/dt waveform (2Msps)

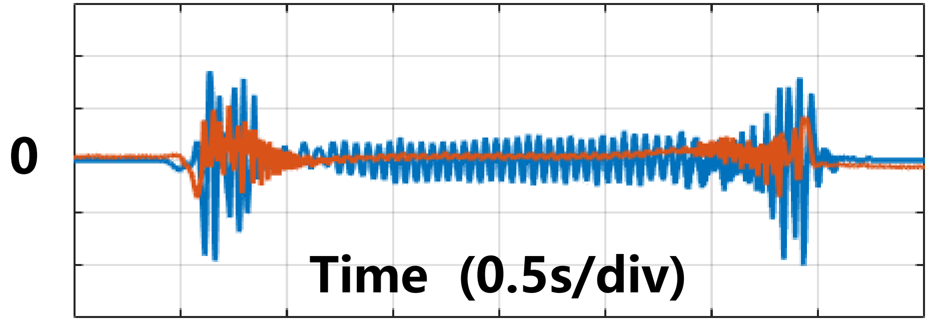
4.3 Experimental results

- Sensorless speed servo control: Trapezoidal speed trajectory

reference speed & actual speed (400 rpm/div)

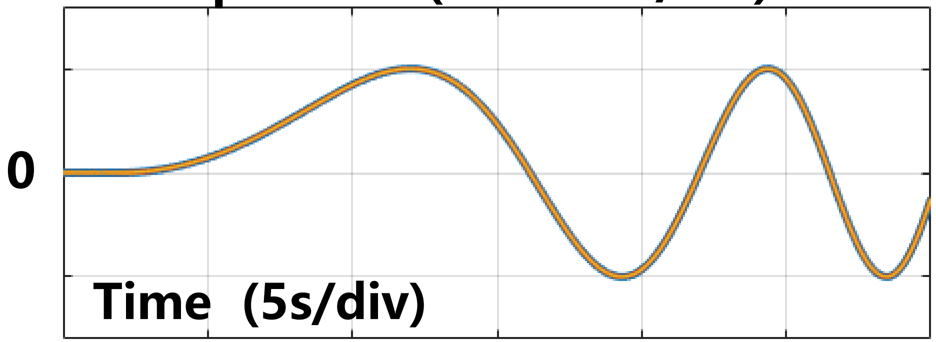


position estimation error(1°/div)
speed servo error (10 rpm/div)

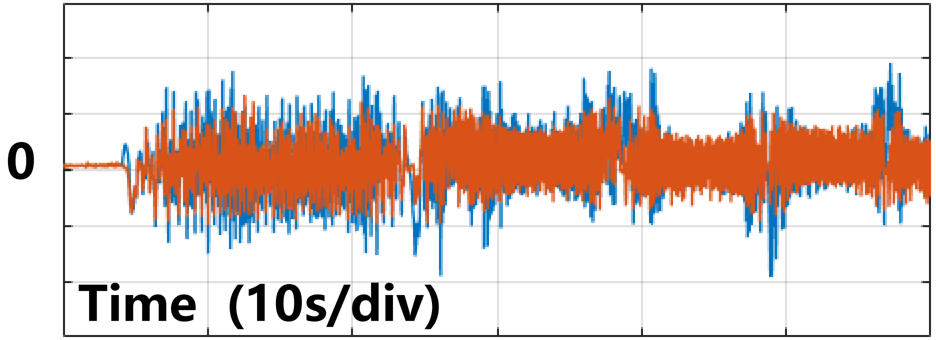


- Sensorless position servo control: Swept-frequency sinusoidal trajectory

reference & actual & estimated position (5 rounds/div)



position estimation error(1°/div)
position servo error (1°/div)



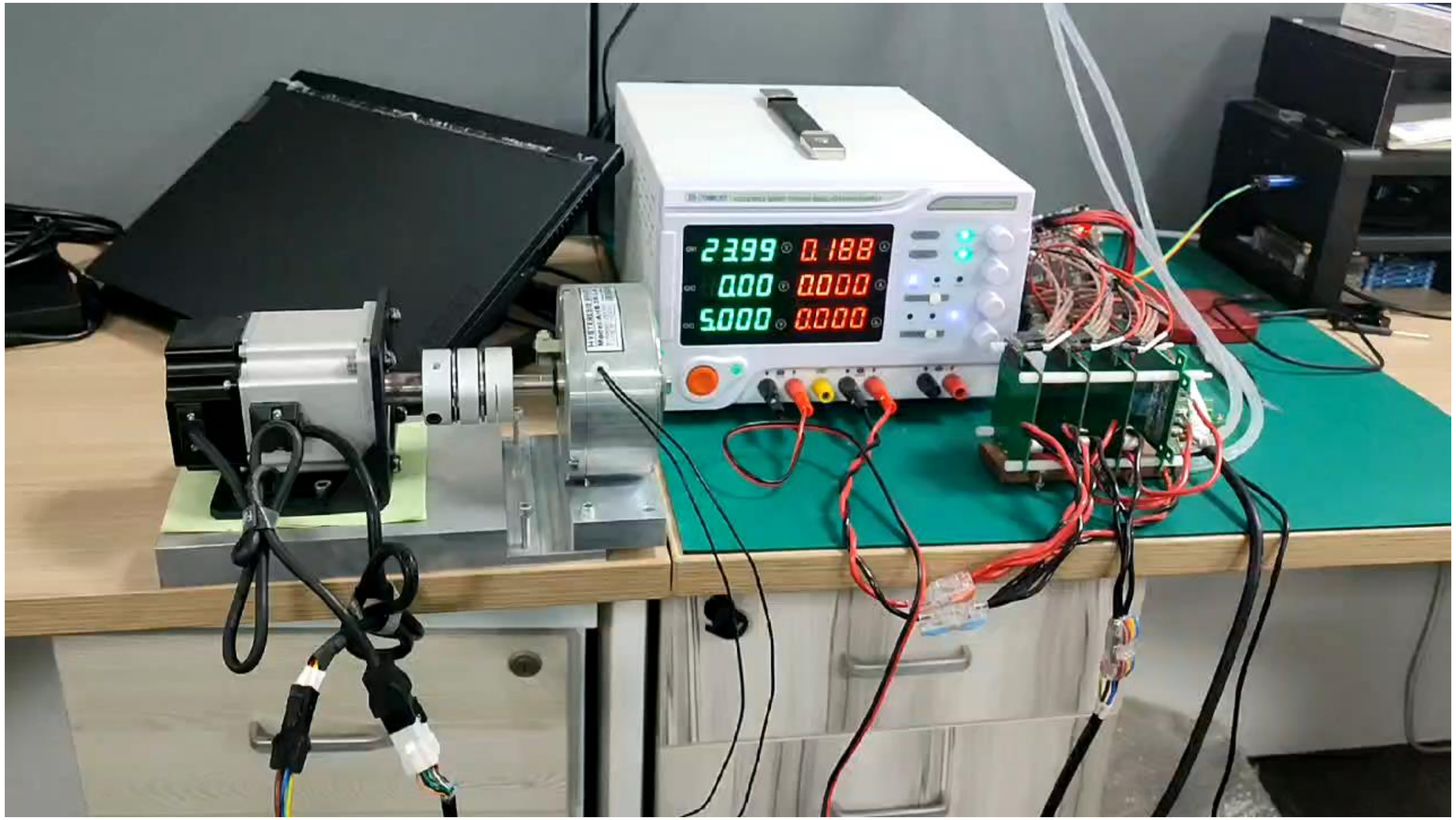
4.4 Experimental results

➢ experimental data

error	max err	rms err
position estimation	1.346°	0.335°
position servo	1.968°	0.534°
speed servo	19.94rpm	3.812rpm

➢ speed range comparison

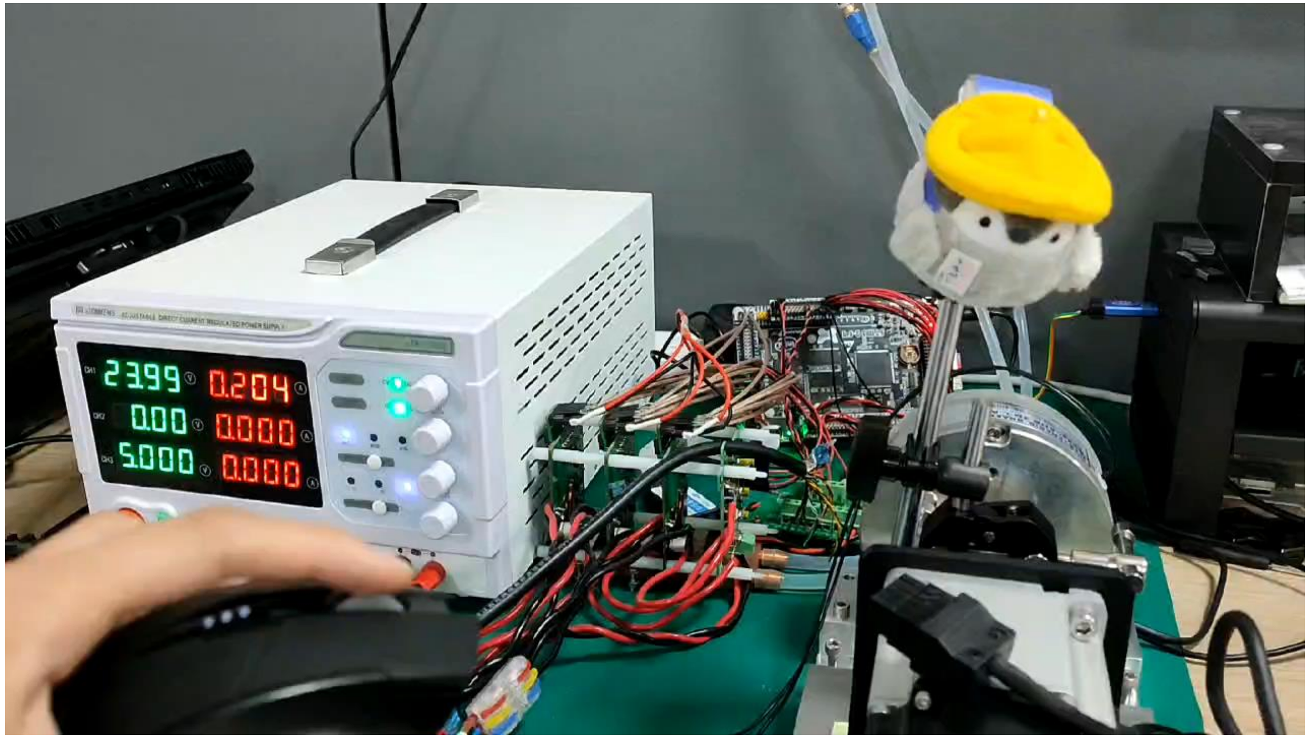
method	speed range
back EMF	200rpm~1200rpm
HF injection	0rpm~150rpm
proposed FPE	**0rpm~1200rpm**



Sensorless speed servo control

4.5 Experimental results

← **As sensorless elevator tractor**



↑ **As sensorless robot joint**

4.6 Conclusions

- We have proposed a novel nonlinear LS-based FPE position estimation method towards IPMSMs **perfect sensorless control.**
- The proposed method can achieve closed-loop control without a physical position sensor, having the potential to **save cost, increase reliability and power density**.
- Our goal is to provide general-proposed or specialized **servo drivers with perfect sensorless control technology.**

Thanks for your attention!

Q&A

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