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Intelligent fractional-order integral sliding mode control for PMSM based on an improved cascade observer

Key words: Permanent magnet synchronous motor; Fractional-order integral sliding mode; Optimization algorithm; Sensorless control; Observer

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Motivation

- Because of its high efficiency, high torque density, and good reliability, the permanent magnet synchronous motor (PMSM) has been used in many applications and has attracted much attention from researchers.
- The control effect is closely related to the rotor information. However, traditional position sensors cause many control system stability problems. Consequently, many scholars have focused on sensorless control research.
- With further study of the fractional calculus theory in recent years, fractional-order sliding mode control (SMC) has gradually become an important branch of SMC.
- Fractional-order integral SMC (FOISMC) strategy can effectively reduce chattering, but the number of adjustable parameters will increase. It is extremely difficult to manually adjust the controller parameters. Hence, several heuristic algorithms have been developed to overcome the above challenges.

Contributions

- An intelligent FOISMC strategy is designed that has good tracking performance and combines strong points of integral SMC (ISMC) in eliminating steady state tracking errors and the flexibility of fractional calculus.
- An improved cascade observer is proposed based on an adaptive SMO (ASMO) and extended high gain observer (EHGO), and is used to effectively observe the rotor information with a higher observation accuracy.
- The variable-speed GWO (VGWO) presented in this study, with high convergence speed, high solution accuracy, and strong global optimization ability, realizes parameter optimization of the controller.
- Considering both the model parameter and load torque changes, the strategy can achieve accurate rotor speed tracking.

Intelligent FOISMC design

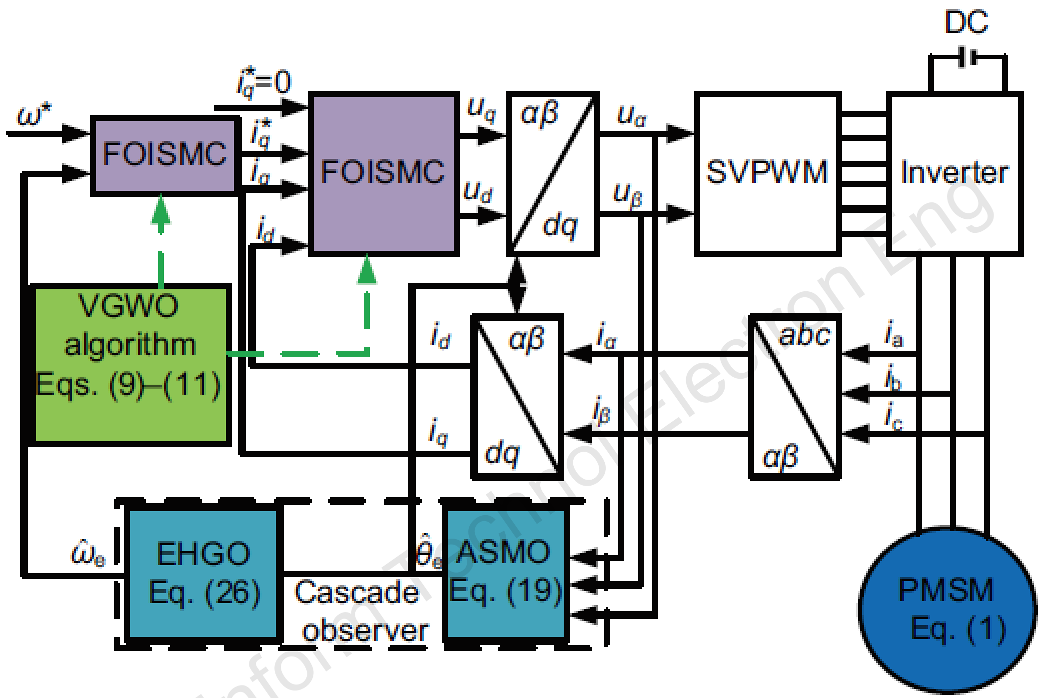


Fig. 1 The proposed control structure of PMSM (SVPWM: space vector pulse width modulation)

- The intelligent FOISMC is adopted in both the current loop and the voltage loop. An improved cascade observer based on ASMO and EHGO is designed to observer the rotor speed and position. The controller parameters are adjusted by VGWO.

Improved cascade observer design

- The observer consists of ASMO and EHGO.

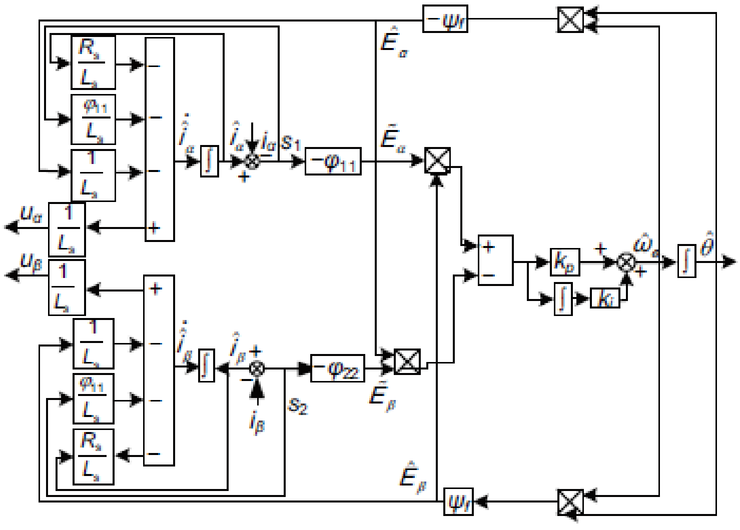
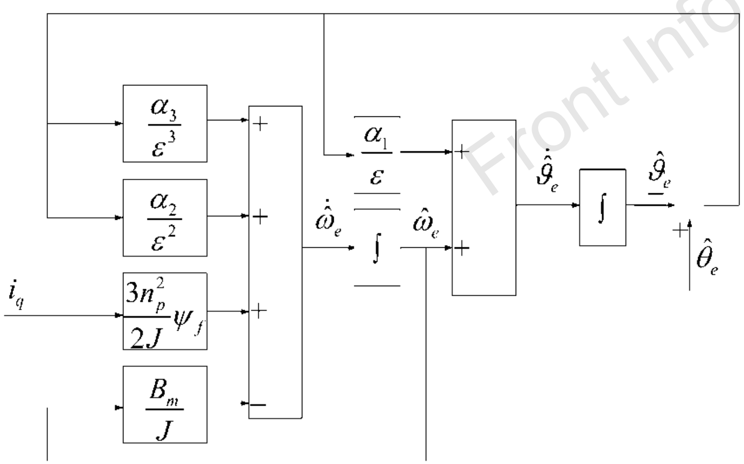


Fig. 2 Schematic of the ASMO

ASMO structure is as follows:

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\hat{i}_\alpha\\ \hat{i}_\beta\\ \hat{E}_\alpha\\ \hat{E}_\beta\end{bmatrix}=\begin{bmatrix}-\frac{R_s}{L_s} & 0 & -\frac{1}{L_s} & 0\\ 0 & -\frac{R_s}{L_s} & 0 & -\frac{1}{L_s}\\ 0 & 0 & 0 & -\hat{\omega}_e\\ 0 & 0 & \hat{\omega}_e & 0\end{bmatrix}\begin{bmatrix}\hat{i}_\alpha\\ \hat{i}_\beta\\ \hat{E}_\alpha\\ \hat{E}_\beta\end{bmatrix}+\begin{bmatrix}\frac{1}{L_s} & 0\\ 0 & \frac{1}{L_s}\\ 0 & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}u_\alpha\\ u_\beta\end{bmatrix}+\begin{bmatrix}-\frac{1}{L_s} & 0\\ 0 & -\frac{1}{L_s}\\ \xi & 0\\ 0 & \xi\end{bmatrix}\mathrm{sgn}(S).$$



Schematic diagram of EHGO

Based on mechanical motion, EHGO is taken as

$$\begin{cases}\dot{\hat{\vartheta}}_e=\hat{\omega}_e+\frac{\alpha_1}{\epsilon}(\hat{\theta}_e-\hat{\vartheta}_e),\\ \dot{\hat{\omega}}_e=\frac{3n_p^2}{2J}\psi_f i_q-\frac{B_m}{J}\hat{\omega}_e+\frac{\alpha_2}{\epsilon^2}(\hat{\theta}_e-\hat{\vartheta}_e)+\hat{\sigma},\\ \dot{\hat{\sigma}}=\frac{\alpha_3}{\epsilon^3}(\hat{\theta}_e-\hat{\vartheta}_e)\end{cases}.$$

Optimization of controller parameters

- The optimization value of the FOISMC-FOISMC method is smaller than those of the other control strategies. It not only shows the effectiveness of VGWO, but also proves that the ability of the FOISMC-FOISMC strategy is better than those of PID-PID and ISMC-ISMC.

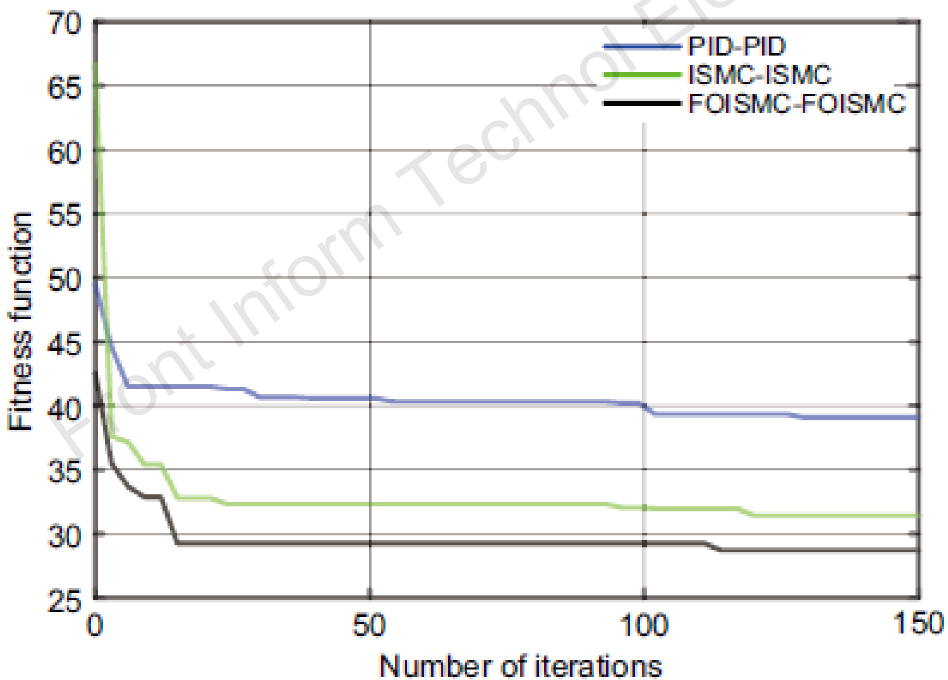


Fig. 3 Optimization results based on VGWO

Verification of the proposed cascade observer

- To demonstrate the superiority of the improved cascade observer (ASMO+EHGO), we compare it with a traditional cascade observer (SMO+EHGO).
- The figures show that the improved observer has the best observation accuracy and the strongest robustness. The maximum observation rotor speed error of the improved cascade observer is smaller than that of the traditional cascade observer.

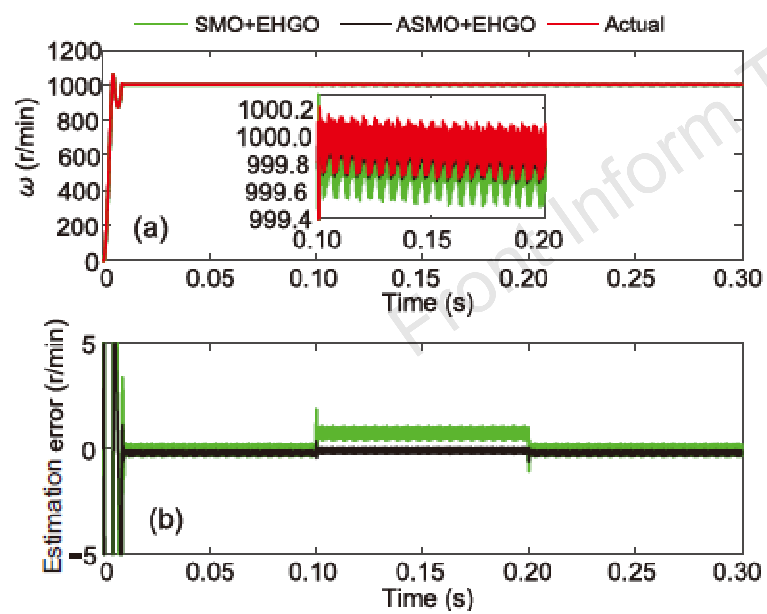


Fig. 4 Comparison of the rotor speed ω (a) and the estimation error (b)

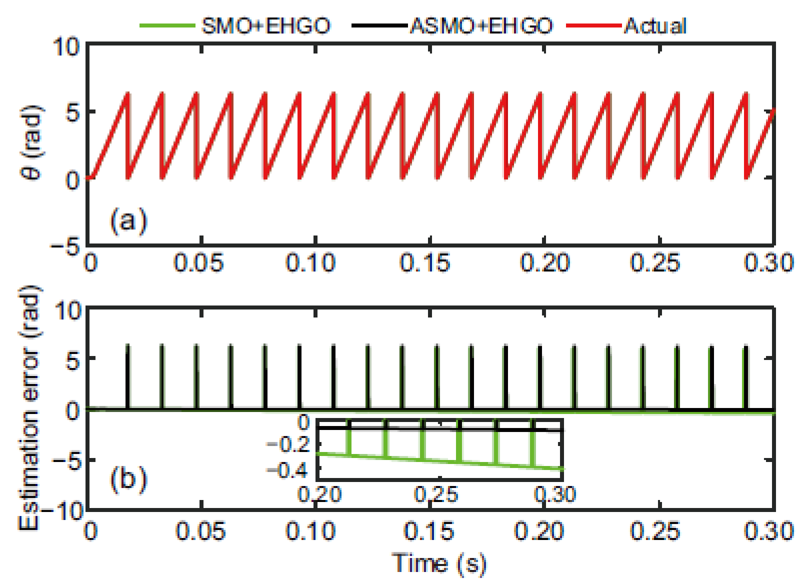


Fig. 5 Comparison of the rotor position θ (a) and the estimation error (b)

Tracking performance simulation

- The figure shows the effect of the employed scheme. The estimated rotor speed ω is obtained using the improved cascade observer (ASMO+EHGO) to estimate the actual ω.

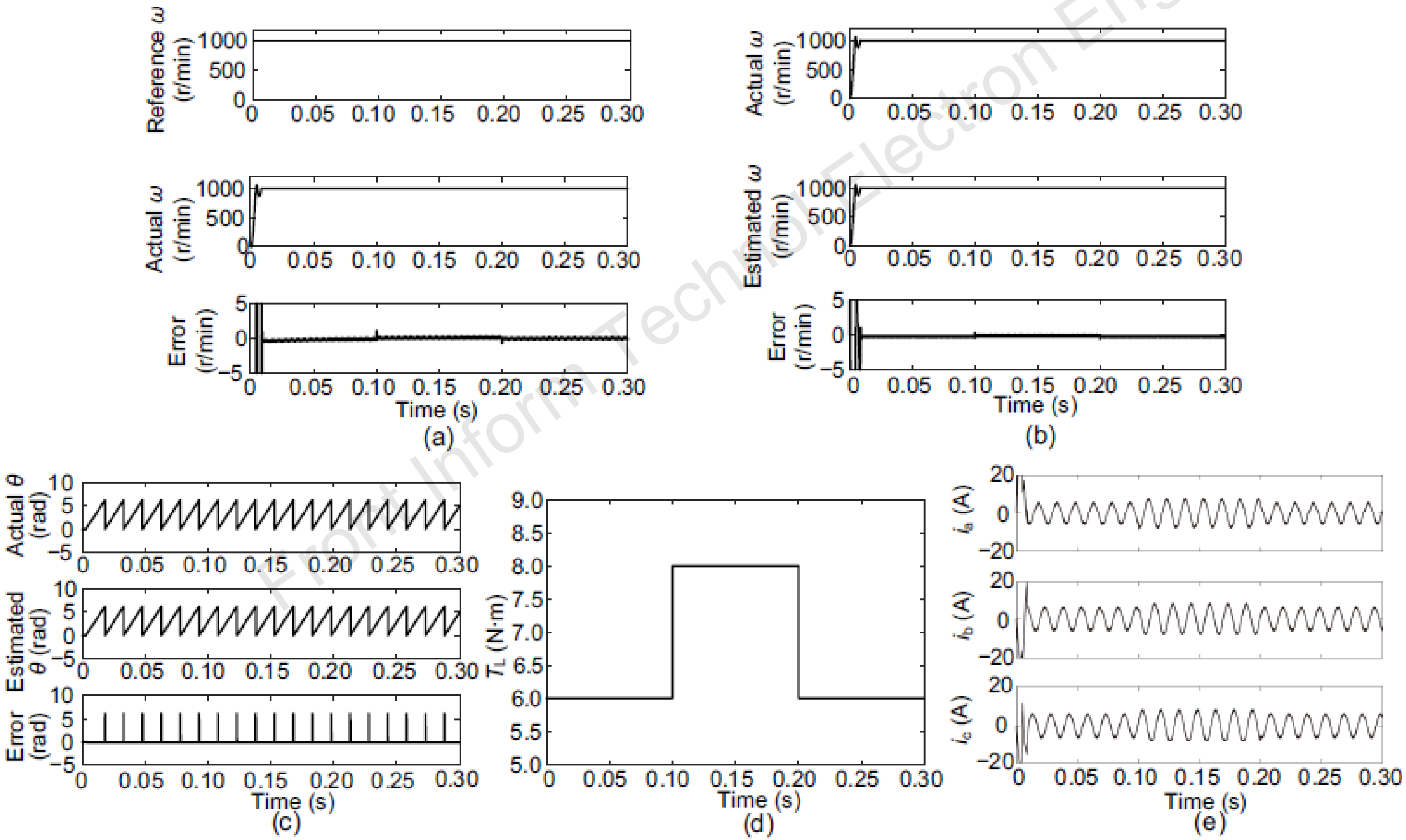


Fig. 6 Tracking performance simulation: (a) rotor speed responses and the tracking error; (b) rotor speed ω estimation and the error; (c) rotor position θ estimation and the error; (d) load torque T_L; (e) currents i_a, i_b, and i_c

Robustness simulation

- **Case 1**: $\Delta R_s = 0$, $\Delta L_s = 0$, $\Delta \psi_f = 0$.
- The figures show that the rotor speed of the FOISMC-FOISMC scheme has a high convergence speed and less chattering, and that the currents based on the FOISMC-FOISMC scheme have a smaller tracking error.

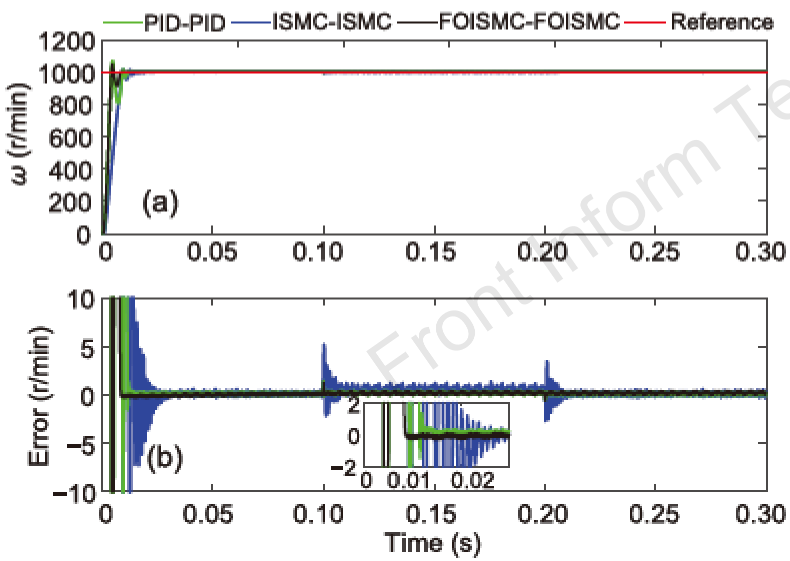


Fig. 7 Comparison of the rotor speed ω (a) and the tracking error (b) for case 1

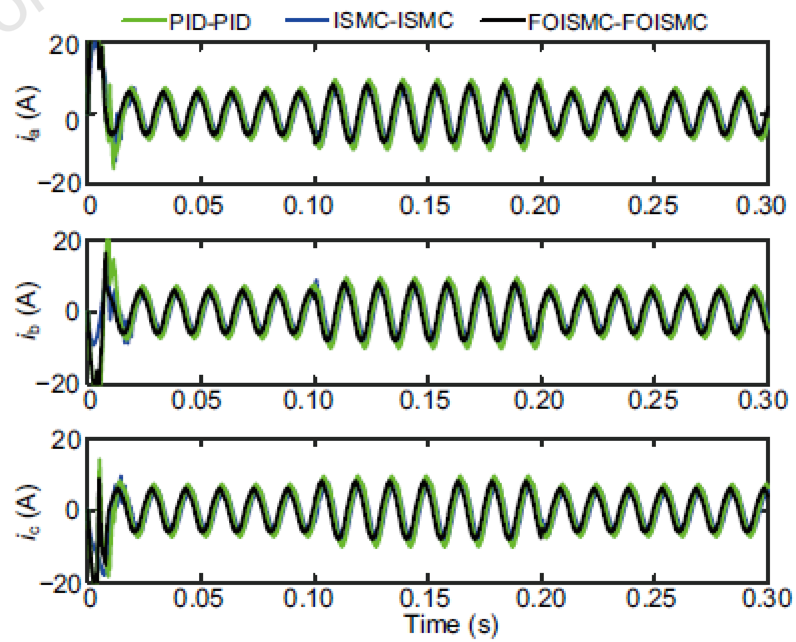


Fig. 8 Currents i_a, i_b, and i_c for case 1

Robustness simulation

- **Case 2**: $\Delta R_s = +15\% R_s$, $\Delta L_s = +15\% L_s$, $\Delta \psi_f = +15\% \psi_f$.
- The figures show that the control performance of PID-PID deteriorates significantly compared with those of the other schemes. These figures show that the robustness of PID-PID is poor, and that FOISMC-FOISMC can significantly reduce chattering and shorten the convergence time.

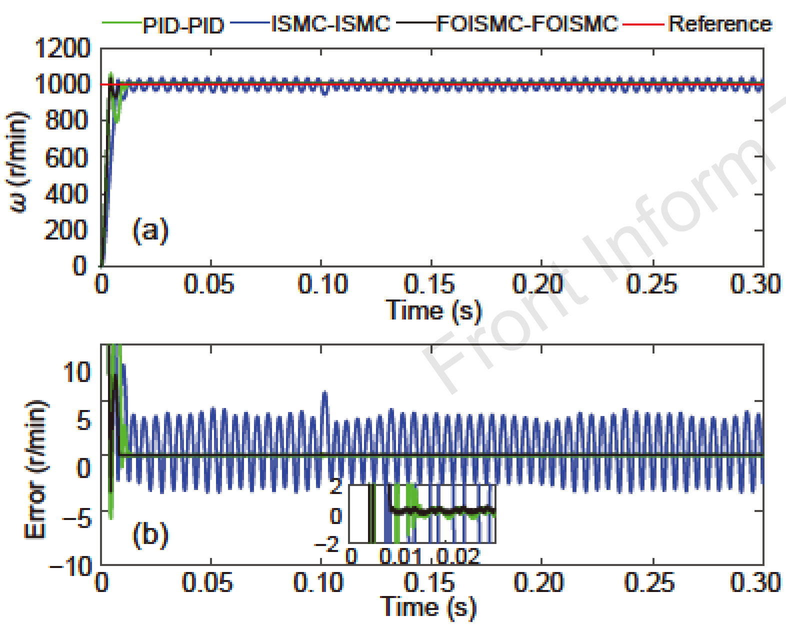


Fig. 9 Comparison of the rotor speed ω (a) and the tracking error (b) for case 2

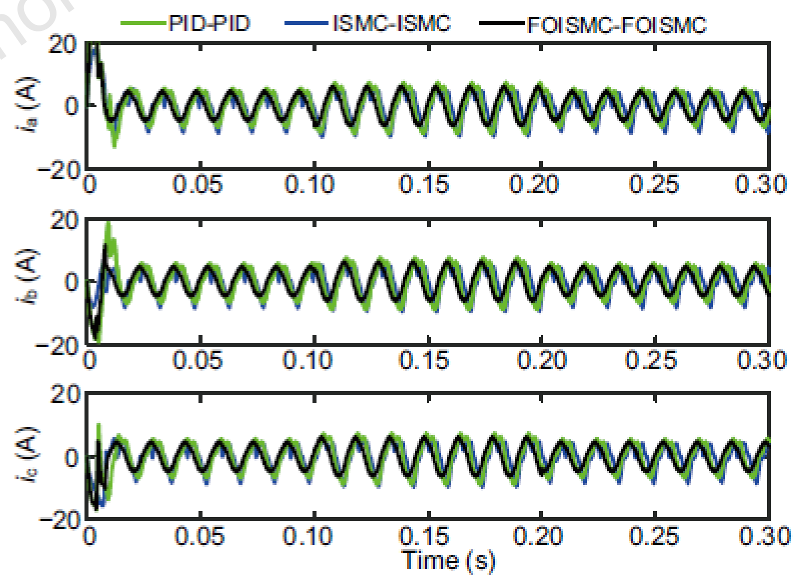


Fig. 10 Currents i_a, i_b, and i_c for case 2

Experimental results

- The experimental platform includes mainly personal computer (PC), data monitor and control interface (DMCI), dsPIC digital signal controller (dsPIC DSC), PMSM, and so on.
- The reference rotor speed of the PMSM is 1000 r/min.

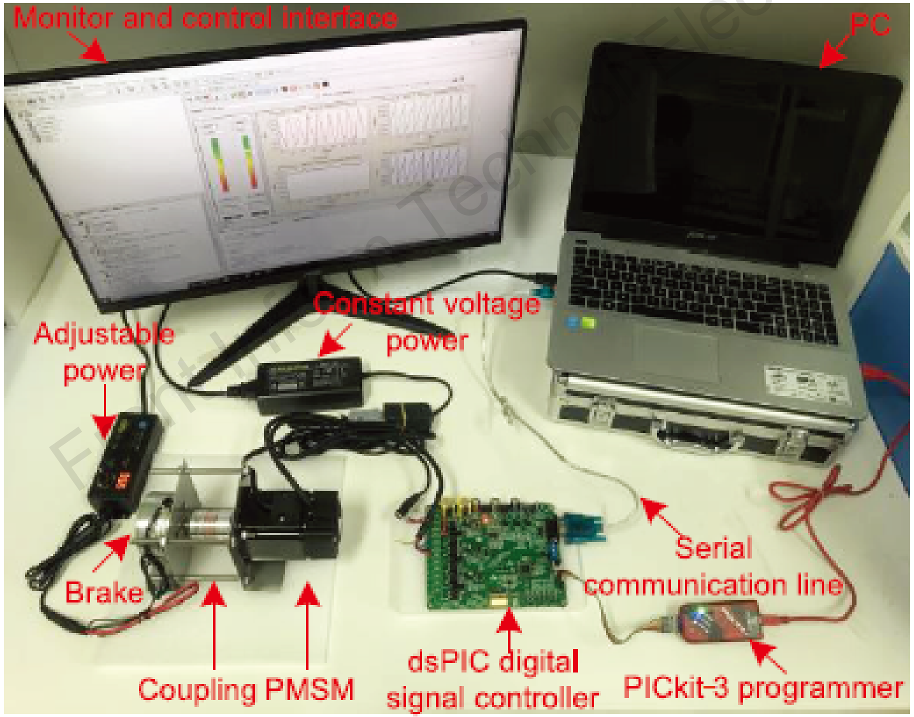


Fig. 11 Experimental platform

Experimental results

- The PID-PID controller has more fluctuation when the load torque suddenly changes. Fig. 13 shows that the FOISMC-FOISMC scheme can achieve better rotor speed tracking and stronger robustness.
- The current changes with the load torque change. Fig. 14 shows that the current response of the FOISMC-FOISMC scheme maintains a stable state and has less chattering.

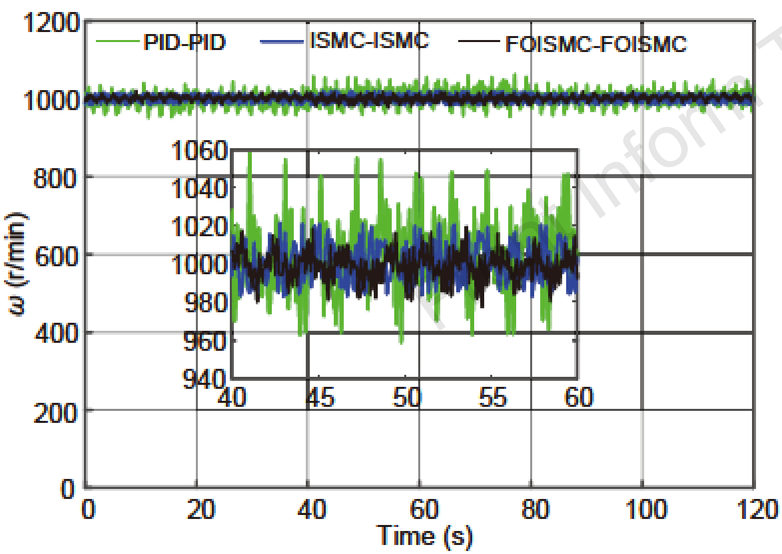


Fig. 13 Rotor speed ω in the experiment

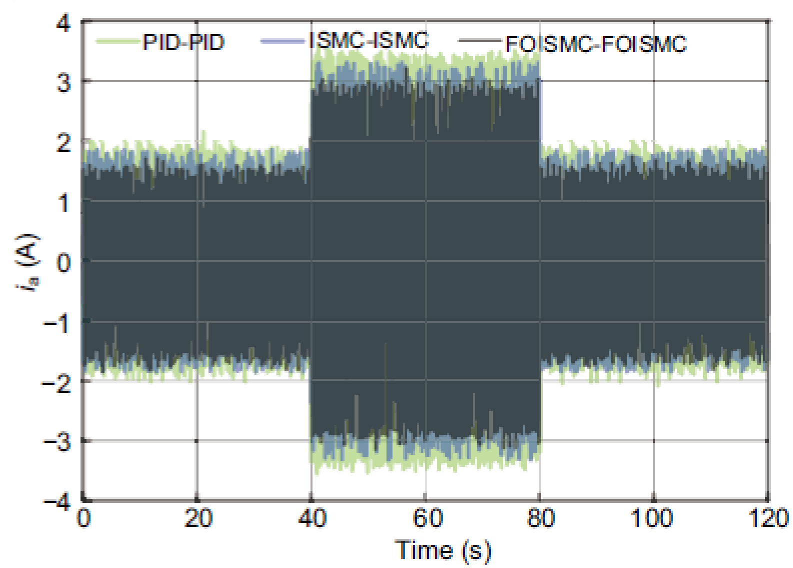


Fig. 14 Current i_a in the experiment

Conclusions

- Based on model uncertainty and external disturbance, a robust sensorless control scheme was employed. Results showed that the FOISMC-FOISMC strategy has better control performance compared with PID-PID and ISMC-ISMC.
- In addition, the proposed improved cascade observer has better observation effect, meeting the control requirements. The effectiveness of the strategy was tested by simulations and an experiment. The scheme can be applied to the field of wind power generation.
- However, the model parameter identification and an adaptive adjustment algorithm were not considered in the proposed control strategy. These issues will be addressed in further research, along with the consideration of actuator failures and fault tolerant control.

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