Composite fractional-order sliding mode controller for PMSM drives based on GPIO

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Abstract
In order to optimize the performance of permanent magnet synchronous motor (PMSM) drives, a fractional-order sliding mode (FOSM) control scheme combining generalized proportional integral observer (GPIO) is adopted in this paper. A FOSM controller is firstly employed to reduce the negative effects of the load torque and parameter variations in the PMSM system. However, the FOSM control method mostly needs high control gain to moderate the unfavorable effects of the total disturbance, which will inevitably lead to large chattering phenomenon. Therefore, the unknown lumped disturbance is effectively estimated by using a GPIO, and the estimated value is synchronously compensated to the FOSM speed controller. Even if a smaller control gain is chosen, the robustness of the proposed composite GPIO-based FOSM controller is better than that of the FOSM controller. Finally, the effectiveness of the proposed control strategy is verified by comprehensive simulation and experimental results.

Keywords
Fractional-order sliding mode control, generalized proportional integral observer, feedforward compensation, permanent magnet synchronous motor

Introduction
Attributing to the superior characteristics of high reliability, the lower acoustic noise and simple structure, permanent magnet synchronous motor (PMSM) has been widely used at home and abroad in the past few decades.1–4 Meanwhile, with these distinctive advantages, PMSM has been successfully used in various industrial fields, such as computer numerical control machines, feed drive systems, and autonomous guided vehicles, etc. However, in the presence of system parameter variations and unknown external interference, the traditional linear proportional integral (PI) controller can scarcely acquire the high-precision control requirements.5,6 In order to solve the problem of poor control performance, a variety of nonlinear control methods have been used to improve the control accuracy, such as fuzzy control,7,8 predictive control,9 robust control,10 and sliding mode control (SMC),11–14 etc.

Among these various nonlinear algorithms, the SMC is a simple and effective control method.15,16 Due to its insensitivity to system parameter variations and load torque, the tracking accuracy of PMSM drive system can be improved.17 A conventional first-order sliding mode control algorithm was designed in Lu et al.18 to optimize the operation of PMSM system. Unfortunately, parameter uncertainties and unmodeled dynamics of the PMSM system have not been fully considered, which limits the application of this kind of SMC method in practical engineering. In addition, linear sliding surface was constructed in Lu et al.,18 the speed error can only be asymptotically stable. The traditional terminal sliding mode control (TSMC) method was developed in Liu et al.19 to obtain the satisfactory convergence rate. However, even if the speed error can converge to the neighborhood of zero in finite time, it may cause singular problem in the closed-loop system.

It should be noted that the upper bound of the total disturbance is generally hard to be measured. To achieve good anti-disturbance performance, the control gain of SMC method is typically chosen to be large enough to suppress the external load torque, which may inevitably cause severe chattering phenomenon.20–22
further alleviate the inevitable chattering phenomenon, some optimization methods have been employed in previous literatures. By choosing a proper exponential term to construct a novel reaching law, the tough problems of large chattering phenomenon and long reaching time in conventional first-order SMC method were solved.\(^{23}\) Moreover, an adaptive TSMC controller was proposed in Shao et al.\(^ {24}\) to guarantee the system states converge to origin in a finite time. Adopting a brand-new adaptive law to adjust the value of the switching gain, the chattering caused by overestimated control gain can be further reduced. With the rapid exploitation of intelligent control technique, a brand-new SMC controller based on the neural network strategy is proposed in Jon et al.\(^ {25}\) Nevertheless, the industrial application of intelligent control usually needs strict hardware condition, which limits its large-scale industrial application. Fortunately, the fractional-order calculus technique with unique characteristics of attenuating old data and saving new data can solve these relatively aforementioned issues.\(^ {26,27}\)

As is known to all, exploiting the disturbance observer (DOB) to measure the total interference is one valid approach to avoid overestimated control gains. Compensating the estimated value to the feedback controller, the closed-loop system can achieve excellent tracking and strong robustness performance simultaneously without choosing a large control gain.\(^ {28,29}\) Hence, the exploitation of DOB has received much attention, and many novel kinds of DOBs have been used in PMSM systems. A full-dimensional DOB was constructed in Mohamed\(^ {30}\) to further optimize the anti-interference capability of PMSM system with rapidly changing external load torque. An extended state observer (ESO) without exact knowledge of the speed regulation system was developed in Zuo et al.\(^ {31}\) to avoid the performance deterioration of PMSM system under load torque and system uncertainties. Nevertheless, if a state feedback controller is constructed using only PI control approach, the anti-interference performance of PMSM system needs to be enhanced urgently. Later, a generalized proportional integral observer (GPIO) combined with SMC controller was presented in Huo and Ding,\(^ {32}\) which enhances the robustness.

In this paper, a fractional-order sliding mode (FOSM) controller combined with GPIO is constructed to improve the anti-interference capability of the PMSM system. First of all, a FOSM controller is proposed to ensure that the motor can track the desired speed. Secondly, to solve the tough issue of poor performance caused by high control gain, the unknown total disturbance is directly estimated by using a GPIO with simple structure, and the estimated value is synchronously compensated to the FOSM controller. Finally, the effectiveness and feasibility of the developed control approach will be proved through simulation and experimental results. The contribution of this paper could be summarized in the following two aspects:

1. By using the advantages of fractional-order calculus technique in the sliding mode controller, the chattering phenomenon can be reduced and the anti-interference property can be enhanced.
2. In order to avoid the unsatisfactory control performance caused by the high switching gain of the FOSM controller, a GPIO is employed to observe the total disturbance.

The remaining parts of the paper are arranged in the following manner. Section 2 describes the mathematical model of PMSM system in detail. The proposed GPIO-based FOSM control method is developed in Section 3. The simulation and experimental results are presented in Section 4. Finally, Section 5 draws the conclusion.

### Mathematical model of PMSM

Assuming that the motor is an ideal controlled object, the current and motion equations of PMSM in the synchronous \(d-q\) rotating frame are described as \(^ {32}\)

\[
\begin{align*}
\dot{i}_d &= -\frac{B}{L_s}i_d + n_p o i_q + \frac{v}{L_s} \\
\dot{i}_q &= -\frac{n_p o i_d - B}{L_s}i_q - \frac{n_p o}{L_s} \omega + \frac{u}{L_s} \\
\dot{\omega} &= \frac{1.5 n_p \phi_f}{J} i_q - \frac{B}{J} \omega - \frac{T_\text{f}}{J}
\end{align*}
\]

where \(i_d\) and \(i_q\) are the stator currents in the \(d-q\) axis, \(u_d\) and \(u_q\) are the stator voltages in the \(d-q\) axis, \(L_s\) is the stator inductance, \(B\) is the viscous friction coefficient, \(R_t\) is the stator resistance, \(n_p\) is the number of pole pairs, \(\omega\) is the rotor angular velocity, \(\phi_f\) is the flux linkage, \(J\) is the moment of inertia, and \(T_\text{f}\) is the load torque.

Now, the stator current \(i_q\) is replaced by the reference current \(i_q^*\), and then one has

\[
\dot{\omega} = \frac{1.5 n_p \phi_f}{J} i_q^* + d(t) = b i_q^* + d(t)
\]

where \(d(t) = -\frac{B}{J} \Delta \omega - \frac{T_\text{f}}{J} + b (i_q - i_q^*) - \frac{4J \dot{\omega}}{J} \) is the lumped disturbance and \(|d(t)| \leq D\), \(\Delta J\), and \(\Delta B\) are the parameters variations.

### Composite controller design

#### Design of GPIO

Assuming that the total disturbance \(d(t)\) is differentiable and \(\lim \dot{d}(t) = 0\), the GPIO constructed for (2) is given as follows

\[
\begin{align*}
\dot{Z}_1 &= Z_2 + h i_q^* + l_1 (\omega - Z_1) \\
\dot{Z}_2 &= Z_3 + l_2 (\omega - Z_1) \\
\dot{Z}_3 &= l_3 (\omega - Z_1)
\end{align*}
\]

where \(l_1\), \(l_2\), and \(l_3\) are parameters of GPIO, \(Z_1\), \(Z_2\), and \(Z_3\) are the estimated values of \(\omega\), \(d(t)\), and \(\dot{d}(t)\).
Figure 1 illustrates the structure diagram of the proposed GPIO.

Letting $E_1(t) = \omega - Z_1$, $E_2(t) = d(t) - Z_2$, $E_3(t) = \dot{d}(t) - Z_3$ and combining with equation (3), one has

$$\begin{align*}
\dot{E}_1(t) &= E_2 - l_1 E_1 \\
\dot{E}_2(t) &= E_3 - l_2 E_1 \\
\dot{E}_3(t) &= \dot{d}(t) - l_3 E_1,
\end{align*}$$

(4)

Then, equation (4) can also be rewritten as

$$\dot{W} = A \cdot W + B$$

(5)

where

$$A = \begin{bmatrix}
-l_1 & 1 & 0 \\
-l_2 & 0 & 1 \\
-l_3 & 0 & 0
\end{bmatrix},
B = \begin{bmatrix}
0 \\
0 \\
\dot{d}(t)
\end{bmatrix}.$$  

(6)

Since matrix $A$ is Hurwitz and $\lim \dot{d}(t) = 0$, system (4) is input-to-state stable. Hence, according to the Lemma 3.1 in Khalil, we have $\lim E_2(t) = 0$, that is, the disturbance estimation $Z_2$ can converge to $\dot{d}(t)$ asymptotically.

**Remark 1.** The estimation performance of GPIO can be improved by selecting larger parameters (e.g., $l_1$, $l_2$, and $l_3$), which means that the negative effects of lumped disturbance can be weakened. Nevertheless, the limitations of measurement noise and system stiffness always exist in practical applications, which indicates that the parameter values of GPIO cannot be selected too large. Therefore, the GPIO parameters should usually be selected in a compromise way. One effective strategy for choosing the appropriate parameters in GPIO is to adjust parameters from small values to larger values until the desired performance is acquired.

**Design of FOSM controller**

In this subsection, a FOSM is proposed for the PMSM speed regulation system. Using the unique advantages of fractional calculus, the chattering phenomenon existing in conventional SMC methods can be obviously eliminated. With the development of the fractional calculus theory, many different definition approaches for fractional calculus have emerged, such as Caputo definition, Grunwald-Letnikov definition, and Riemann-Liouville definition.22

Setting $\omega_2$ as the desired speed, the speed error $\omega_e$ can be written as

$$\omega_e = \omega - \omega_2$$

(7)

For equation (2), the PMSM speed regulation system can be represented as

$$\dot{\omega}_e = b_q \omega_e + d(t)$$

(8)

Firstly, we choose the FOSM surface as

$$s = k_p \omega_e(t) + k_d \Delta t^{-\alpha} \omega_e(t)$$

(9)

where $k_p$ and $k_d$ are positive constants, $\Delta t^{-\alpha}$ is the operator of fractional calculus, $0$ and $t$ are the limits of the operation, and $\alpha$ is the order of fractional calculus.

Differentiating the sliding variable $s$ in (9) gets

$$\dot{s} = k_p \omega_e(t) + k_d \Delta t^{-\alpha} \omega_e(t) = k_p [b_q \omega_e + d(t)] + k_d \Delta t^{-\alpha} \omega_e(t)$$

(10)

Selecting a rational reaching law can alleviate the chattering and improve the anti-interference property of the PMSM system. In this paper, an exponential reaching law is selected to construct the FOSM controller. Hence, we have

$$\dot{s} = -\varepsilon \text{sgn}(s) - qs$$

(11)

where $\varepsilon$ and $q$ are positive constants.

Therefore, the FOSM controller can be constructed as

$$\dot{\omega}_e = -\frac{1}{b} \left[ q s + \frac{k_d}{k_p} \Delta t^{-\alpha} \omega_e(t) \right]$$

(12)

In order to guarantee the stability of the PMSM speed regulation system, the reaching condition should be met. On this basis, the Lyapunov function should be used to complete the proof.

**Theorem 3.1.** Under the FOSM controller (12), if the parameter $k_p$ satisfies $k_p > \frac{\eta + \varepsilon}{b}$, $\eta > 0$, the speed error $\omega_e$ will convergence to zero in a finite time.

**Proof.** We select a Lyapunov function as

$$V(s) = \frac{1}{2} s^2.$$  

(13)
Evaluating the time derivative of $V$ along system (9) obtains

$$V'(s) = s V(s) = s[k_p \omega_c(t) + k_d 0 D_1^{-a} \omega_c(t)]$$

$$= s[k_p (b_i q + d(t)) + k_d 0 D_1^{-a} \omega_c(t)]$$

$$= s[k_p d(t) - e sgn(s) - q s]$$

$$= - q s^2 - e |s| + k_p d(t) s$$

Noting that $k_p > \frac{n + c}{D}$, we have

$$V'(s) \leq -e |s| + k_p D s$$

$$\leq (k_p D - e) |s|$$

$$= - \sqrt{2} \eta V^2(s)$$

In the light of the finite-time Lyapunov theory in Levant, one can conclude from (15) that the system states will reach the sliding surface in a finite time. Apparently, the system states reach the sliding surface (9), which means that the states asymptotically converge to the zero. This completes the proof.

Next, since the total disturbance $d(t)$ is precisely estimated by the aforementioned GPIO, the composite FOSM controller for speed loop can be constructed as follows

$$i_q = - \frac{1}{b} \left[ \frac{1}{k_p} e sgn(s) + q s + \frac{k_d}{k_p} b_i s + k_p D_1^{-a} \omega_c(t) - Z_2 \right]$$

Accordingly, the configuration of the presented FOSM + GPIO control framework is shown in Figure 2.

Remark 2. For a practical implementation, the control performance is compromised with peak value of the current, current ripple, and anti-disturbance property. First of all, a larger $k_p$ can increase the convergence rate of speed error $\omega_c$, but it will greatly increase the peak value of the current when the speed changes suddenly. Secondly, a larger $k_d$ can promote the convergence rate of $\omega_c$ and improve the anti-disturbance performance of the PMSM system. However, increasing the value of $k_d$ will increase the current ripple and affect the stable operation of the PMSM system. Finally, the smaller $\alpha$ means better anti-disturbance property, but it will also increase the peak value of the current when the speed changes suddenly.

Remark 3. In order to realize the complex fractional calculus, various strategies have been proposed in the past few decades. Among these methods, the most effective method is to approximate these operators with high order integer transfer functions. Fortunately, the “Ninteger” toolbox in MATLAB developed according to this method can easily implement the fractional-order derivatives and integrals, which greatly facilitates the simulation and experiment of this algorithm.

Simulation and experimental results

In order to verify the advantages of the control algorithm designed in this paper, the comparative analysis between the composite FOSM + GPIO and pure FOSM controllers are performed. The control algorithm is based on space vector pulse width modulation (SVPWM) control with $i_q = 0$. Decoupled PI regulators are adopted in the current loops, and these proposed controllers are applied in the speed loop. The nominal parameter values of the PMSM system are illustrated in Table 1.

Simulation results

When adjusting the parameters of these two control strategies, we will consider anti-interference ability and current ripple at the same time. The gains of FOSM
and FOSM + GPIO controllers are selected as follows:

\[ k_p = 500, \quad k_d = 5, \quad \alpha = 0.75, \quad q = 2200, \quad \varepsilon = 5000 \]

for FOSM controller, and

\[ k_p = 300, \quad k_d = 3, \quad \alpha = 0.75, \quad q = 2200, \quad \varepsilon = 5000, \quad l_1 = 90, \quad l_2 = 2700, \quad l_3 = 27000 \]

for FOSM + GPIO controller.

Figure 3 illustrates the step responses of the pure FOSM and composite FOSM + GPIO control methods at the desired speed of 800 rpm. The initial value of the load torque is set to zero, which means that the PMSM has no load at first. Figure 3 shows that the start-up performance under both controllers are satisfactory, while the overshoot of FOSM strategy is larger than FOSM + GPIO controller. In addition, compared to pure FOSM controller, the composite FOSM + GPIO controller can enable the PMSM speed regulation system to track the reference speed faster.

To demonstrate the estimation performance of the GPIO, a load torque is suddenly added to the PMSM system at 2.5 s. From Figure 4, we can find out that the GPIO can estimate the load torque in a short time, and its estimation accuracy is high. On this basis, the anti-load property of the designed controller is tested. The simulation results are depicted in Figure 5. When the load torque is suddenly added, the speed drop under FOSM controller is 14 rpm, which is larger than that under FOSM + GPIO method. Increasing the values of parameters \( k_p \) and \( k_d \) can enhance the disturbance rejection property, and the parameters \( k_p \) and \( k_d \) in FOSM + GPIO strategy is smaller than those in FOSM controller. It can be easily concluded that the anti-load performance of composite FOSM + GPIO controller is superior than pure FOSM controller.

### Experimental results

To further confirm the excellent performance of the developed FOSM + GPIO controller, an experiment bench based on ETL-PCI-662 DSP is built. A three-phase pulse width modulation (PWM) inverter with an intelligent power module (IPM) to drive the motor. The experimental equipment is shown in Figure 6. Two Teknic three-phase motors are utilized to implement the comparative experiments. The proposed control algorithm is tested on one test motor, and the load torque is obtained on another motor. The sample and control frequency are both selected as 10 kHz.
In order to acquire fair experimental results, we will adjust the parameters of pure FOSM and composite FOSM + GPIO controllers to achieve the best control capability. First of all, Figures 7 and 8 presents the step responses under pure FOSM controller and composite FOSM + GPIO controller respectively. The motor reference speed is set to 800 rpm without additional load torque. We can easily reveal that the speed response curve under the FOSM control has a larger overshoot and longer settling time compared with the proposed FOSM + GPIO control method. In addition, the peak values of the $q$-axis current and $a$-phase current under FOSM + GPIO control algorithm are smaller than those under FOSM control algorithm. Therefore, the control capability of the PMSM system is prominently optimized by adopting the composite FOSM + GPIO scheme rather than the pure FOSM method.

Next, when the motor is running in a stable state, we further test its ability to resist the change of load torque. Figures 9 and 10 presents the experimental results of PMSM speed regulation system under the condition of increasing full load. Compared with pure FOSM controller, the proposed composite FOSM + GPIO control method has better anti-interference property. Figures 9 and 10 display that the anti-interference capability of composite FOSM + GPIO controller is superior than pure FOSM approach. Although the values of control gains in FOSM + GPIO controller is smaller than those in FOSM controller, the quick compensation of the external interference by GPIO can further optimize the robustness. Moreover, large control parameters $k_p$ and $k_d$ may cause chattering phenomenon, the current ripple under composite FOSM + GPIO algorithm is smaller than pure FOSM method.

Due to the existence of dead time, turn-on/off delay and voltage drop across switches in PMSM system, the VSI nonlinearity phenomenon is inevitable. In addition, the VSI nonlinearity may cause the control performance degradation in low-speed range. Therefore, it is very important to show the comparison experimental results of the proposed two controllers at low speed region. Figures 11 and 12 show the response curves of speed, current $i_q$ and current $i_a$ in the presence of adding full load at 150 rpm. We can observe from Figures 11 and 12 that the anti-interference capability of FOSM + GPIO control law is still better than pure FOSM control law. Meanwhile, the ripples of speed and current $i_q$ under FOSM + GPIO control method is smaller than those under FOSM control scheme. Hence, the developed FOSM + GPIO control approach can control the PMSM system well under a wide operating speed.
In general, the above simulation results are consistent with the experimental results. Therefore, we can conclude that the performance of composite FOSM + GPIO control method is superior than pure FOSM control strategy.

Conclusions

In this paper, a GPIO-based composite FOSM control method has been designed to upgrade the control capability of the PMSM system with unknown external disturbance and load torque. Compared with pure FOSM control method, the proposed composite FOSM + GPIO controller can provide stronger anti-disturbance performance and produce less chattering. Intensive simulation and experimental results have demonstrated the effectiveness and robustness of the designed control scheme. Our future work will concentrate on solving the problems of input saturation, parameter uncertainties, and current-loop optimization.
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