

Research on SMC-ADRC Method of PMSM in Mine Ventilation System Based on ESO

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Recently, the energy saving control of mine ventilation system has gradually become a hot issue in mine technology research. On account of this, an extended state observer (ESO) based sliding mode speed control strategy of the permanent magnet synchronous motor (PMSM) speed regulation system is put forward. The thesis conduct an in-depth study of the frequency-control-based strategy for mine ventilation, and investigate how effective it can be in the experiment. Firstly, in consideration of the disturbance factors, the sliding mode speed controller is designed in the original mathematical model of the surface permanent magnet synchronous motor (SPMSM). Secondly, considering the time-varying and unknown upper bound of the disturbance term, ESO is designed to observe the disturbance term in real time and feed forward compensation. Then, on the basis of the dynamic mathematical model of the current loop, an active disturbance rejection current controller (ADRC) is designed. This is followed by the sliding mode speed control law of the PMSM speed regulation system for mine ventilation on the basis of ESO is obtained, which enhances the robustness, energy saving effect of the speed regulation system and dynamic quality, further improves the reliability of the mine ventilation system. Finally, when considering the effectiveness of the proposed control strategy, the research suggested it could be verified by hardware in the loop (HIL) simulation experiment.

Keywords: mine ventilation system; permanent magnet synchronous motor (PMSM); sliding mode control (SMC); extended state observer (ESO); active disturbance rejection control

1. PREFACE

As an indispensable part of mine production system, mine ventilation system plays an important role in the safety of production. To adapt to the situation of scene, some amendments of parameters are needed, including air quantity, air velocity and etc. However, the controlling methods, widely used today, are not convenient enough in terms of operation. Such methods include adjusting the position of air door flashboard, scooping leading device and adjusting the blade angle. Besides, the controlling methods mentioned above would limit the controlling area as well as the accuracy, and need the electric machine to operate in full speed. Such drawbacks lead to great waste of energy.

Worse still, the equipment loss is serious and the device span is shortened. Furthermore, when the asynchronous AC motor is driven directly, it would fail to have a good performance as a fan, owing to mechanical shock, excessive starting current, poor electrical protection performance and etc. With the development of power electronic technology, computer control technology and modern control theory, in both research and application, there is a tendency to use frequency conversion and speed regulation to make the fan drive. On the premise of ensuring the ventilation quality, this technology can save energy to the maximum extent [1].

Since the Permanent Magnet Synchronous Motor has some outstanding advantages, including the simple structure, high efficiency, energy saving and rapid response, applying PMSM to mine ventilation system can help solve some traditional

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problems, like low energy utilization and inconvenient operation. And in terms of the speed control of PMSM, the control system will be affected by various internal and external factors. On the one hand, the internal interference factors, which is specified as long-time operation will lead to temperature change, thus resulting in the perturbation of stator resistance and inductance. On the other hand, the external interference factors focus on the changes of underground personnel number, gas situation, tunnel resistance and other factors which will lead to the difference between the air supply volume and the actual demand[2]. Such interference factors will influence the robustness of the PMSM speed control system, thus deterring the mine ventilation system from operating properly. In order to ensure the stability and reliability of the mine ventilation system, it is of great importance to improve the controlling performance of the PMS, including its robustness and etc.

To achieve this goal, some advanced control strategies with great performance, like sliding mode control, auto disturbance rejection control, adaptive control and intelligent control should be applied to the speed control system of the PMSM, targeting at mine ventilation[3–5]. Among those strategies, the sliding mode control can overcome the uncertainties inside and outside of the system, and it has strong robustness to model changes and unknown disturbances, especially for nonlinear models, like the PMSM. However, when the upper limit is unknown, or the disturbance changes rapidly, the selection of the gain of sliding mode switch tends to be conservative, thus increasing the chattering of the sliding mode. To cope with the above problem, scholars have made lots of attempts, conducting further studies and then various improvement strategies have been put forward[6–7] supposed that the improved exponential approach law suppressed the chattering of sliding mode and improved the performance of the controller through proposing a new sliding mode control approach law.[8] suppressed sliding mode control chattering effectively and enhanced the dynamic performance of the speed control system.[9] have proposed a sliding mode controller based on the fast power approach law was proposed. Besides this law, the exponential terms and the system state variables were added to deal with the slow approach speed, when the power approach law is far away from the sliding surface. And it also helped overcoming the system chattering, caused by the exponential terms[10]. In reference, a nonlinear terminal sliding mode control strategy based on disturbance observer was put forward, which reduced the chattering of sliding mode in an indirect way, through observing and compensating the disturbance. And the convergence speed and tracking accuracy were also improved in this reference.[11] Have proposed an optimal speed control strategy based on terminal sliding mode observer was suggested. The observer can effectively estimate unknown disturbance and suppress system chattering. In addition to the sliding mode control mentioned above, as a disturbance compensation module, the extended state observer in ADRC tracks the comprehensive uncertainty composed of unknown part of the model and external disturbance, by the means of expanding a state quantity. Then the control quantity to compensate these uncertainties will

be given, therefore, the robustness of the system can be improved.[12] Have proposed in terms of the predictive function controller's failure of achieving satisfactory control effect with unknown disturbance, the extended state observer was used to observe the comprehensive disturbance in real time and carry out feedforward compensation, which improved the performance of the controller and enhanced the system robustness.[13] Have proposed the extended state observer is used to estimate and compensate the inductance parameters in actual time, which solved the problem of inductance parameter mismatch and improved the system robustness. Have proposed that the system robustness depended on the tracking performance of ESO. In other words, the higher the tracking accuracy is and the faster the speed is, the stronger the system robustness will be. In addition, ADRC is a nonlinear control strategy which is increasingly widely adopted in speed regulation system of permanent magnet synchronous motor (PMSM) in recent years. High performance PMSM servo system requires a fast response current inner ring to ensure high dynamic performance of the system, while the traditional PI regulator is prone to overshoot and oscillation adjustment process. To realize the exact control of the current loop of the high performance permanent magnet synchronous motor servo system, an ADRC is used to take the place of the traditional PI regulator to follow the current command more quickly and precisely [14]. Have proposed an ADRC is used to replace the traditional PI current controller in the speed regulation system of permanent magnet synchronous motor to realize fast tracking of the expected current of d and q axes, improving the dynamic quality of the speed regulation system. To sum up, on the basis of the excellent tracking performance of ESO to time-varying comprehensive disturbance and the strong robustness of sliding mode control, a sliding mode speed control strategy of the PMSM speed control system for mine ventilation based on ESO was proposed, which could enhance the robustness of the system and improve the control accuracy. At the same time, the adoption of the ADRC instead of the traditional PI current controller can enhance the response speed of the current loop, so as to further improve the dynamic quality of the governing system [15–16].

In this thesis, a sliding mode speed control strategy of the PMSM speed control system for mine ventilation based on ESO was put forward to solve the problems of low efficiency and poor reliability of traditional ventilation system. Firstly, the sliding mode speed controller was designed, based on the motion equation of the PMSM. Then the uncertainties inside and outside the system were regarded as the comprehensive interferences of the system. ESO was used for real-time observation and feedforward compensation, which indirectly reduced the chattering of the sliding mode, improved the control performance of the motor, furthermore, the ADRC controller is designed to improve the current tracking speed of d-q axes, and achieved the high-precision and strong robustness control of the speed regulating system of the PMSM for mine ventilation. To conclude, the feasibility of the scheme was proved by the semi physical experiment.

2. PMSM MATHEMATICAL MODEL

The equation of the motion of PMSM in d-q rotation coordinate system is as followed:

$$J \frac{d\omega_m}{dt} = -B_0\omega_m + \frac{3}{2} P_n \psi_f i_q - T_L \quad (1)$$

In this equation, ω_m refers to the mechanical angular velocity; i_q refers to the shaft current of q-axis; P_n refers to the polar logarithm; Ψ_f refers to the permanent magnet flux; B_0 and J refers to the friction coefficient and the moment of inertia; T_L refers to the load torque.

Considering the load disturbance and parameter perturbation, equation (1) is written as followed:

$$\frac{d\omega_m}{dt} = -\frac{B_0}{J}\omega_m + \frac{3P_n\psi_f}{2J}i_q + d \quad (2)$$

In this equation $d = -\Delta\left(\frac{B_0}{J}\right)\omega_m + \Delta\left(\frac{\psi_f}{J}\right)\frac{3P_n}{2}i_q - \left[\frac{1}{J} + \Delta\left(\frac{1}{J}\right)\right](T_L + \Delta T_L)$, and it is the comprehensive disturbance factor. $\Delta\left(\frac{B_0}{J}\right)$, $\Delta\left(\frac{1}{J}\right)$, $\Delta\left(\frac{\psi_f}{J}\right)$ and ΔT_L represent parameter perturbation and load disturbance.

The dynamic mathematical models of PMSM in d-q rotating coordinate system are as follows:

$$\frac{di_d}{dt} = \frac{1}{L}u_d - \frac{R_s}{L}i_d + P_n\omega_m i_q \quad (3)$$

$$\frac{di_q}{dt} = \frac{1}{L}u_q - \frac{R_s}{L}i_q - P_n\omega_m i_d - \frac{P_n}{L}\omega_m \psi_f \quad (4)$$

As followed: is the d, q axis current, d, q axis voltage, and stator resistance and inductance respectively.

3. THE DESIGN OF ESO SLIDING MODE SPEED CONTROL

3.1 Design of Sliding Mode Control

Based on Equation (2), the integral sliding surface is designed as followed:

$$S = x_1 + kx_2, k > 0 \quad (3)$$

$$\text{and, } \begin{cases} x_1 = \omega_m^* - \omega_m \\ x_2 = \int x_1 dt \end{cases}$$

The advantage of designing integral sliding mode surface is that the initial value of integral can be chosen in advance, so that the system state is on the switching surface at the initial moment, that is, the system moves on the sliding mode surface at the beginning, making the system have global robustness. Furthermore, the integral action can also eliminate the steady-state error.

In equation (5), let and derivative with respect to time, can be obtained, which indicates that the velocity error approaches to zero exponentially with time constant. Therefore, the dynamic characteristics of sliding mode motion can be predetermined by the selection coefficient.

The controlling formula is as followed:

$$u = i_q^* = \frac{2J}{3P_n\psi_f} \left(\eta \text{sign}(s) + ms + \dot{\omega}_m^* + kx_1 + \frac{B_0}{J}\omega_m \right) \\ \eta \geq d, m > 0 \quad (5)$$

The verification of stability:

The Lyapunov function is constructed as followed:

$$V = \frac{1}{2}S^2 \quad (6)$$

So,

$$\dot{V} = s\dot{s} \quad (7)$$

According equation (2),

$$\begin{aligned} \dot{V} &= s\dot{s} \\ &= s(\dot{x}_1 + kx_1) \\ &= s[\dot{\omega}_m^* - \dot{\omega}_m + kx_1] \\ &= s\left[\dot{\omega}_m^* + kx_1 - \frac{3P_n\psi_f}{2J}i_q + \frac{B_0}{J}\omega_m - d\right] \end{aligned} \quad (8)$$

So, in equitation (4),

$$\begin{aligned} \dot{V} &= s - \eta \text{sign}(s) - ms - d \\ &= -ms^2 - \eta|s| - ds \\ &\leq 0 \end{aligned} \quad (9)$$

The equals sign only holds, when $S = 0$

Furthermore, an ADRC is designed to improve the tracking speed of d and q axis current. In actual control, high frequency buffeting exists in sliding mode control. Reasonable buffeting suppression is the key to designing sliding mode controller. The exponential approach law adopted in this design can better attenuate the buffeting of sliding mode. A reasonable approach law design can increase the speed of motor point approaching the switching surface when it is far away from the switching surface, thus accelerating the dynamic response of the system. When approaching the switching surface, its speed is asymptotically zero to reduce chattering. In addition, using the saturation function to substitute the sign function in the control law can further solve the problem.

The expression of the saturation function is:

$$\text{sat}(s, \delta) = \begin{cases} 1, & s > \delta \\ s/\delta, & |s| < \delta \\ -1, & s < -\delta \end{cases}$$

In addition, the sliding mode chattering can be improved indirectly by designing a disturbance observer to compensate the system disturbance.

3.2 The Design of ESO Disturbance Observer

ESO is an observer that can not only correctly estimate the system state, but the unmodeled links and external disturbances as well, which is equivalent to expanding the state of the system. The observer transforms the controlled objects

with unknown disturbance and nonlinear characteristics into integral series with nonlinear state feedback, which is a feedback structure that linearizes the nonlinear unknown objects. The observed results here are fed back to the sliding mode controller, which can indirectly suppress the sliding mode chattering.

Based on equation (2), the ESO Model is established.

$$\begin{cases} \frac{d\omega_m}{dt} = \frac{3P_n\psi_f}{2J}i_q - \frac{B_0}{J}\omega_m + d \\ y = \omega_m \end{cases} \quad (10)$$

The second-order ESO of the velocity loop of SPMSM is as followed:

$$\begin{cases} \varepsilon = z_1 - y \\ \dot{z}_1 = z_2 - \beta_1 \text{fal}(\varepsilon, \tau, \delta) + \frac{3P_n\psi_f}{2J}i_q - \frac{B_0}{J}\omega_m \\ \dot{z}_2 = -\beta_2 \text{fal}(\varepsilon, \tau, \delta) \end{cases} \quad (11)$$

$$\text{fal}(\varepsilon, \tau, \delta) = \begin{cases} \frac{\varepsilon}{\delta^{1-\tau}}, & |\varepsilon| \leq \delta \\ \text{sign}(\varepsilon) \cdot |\varepsilon|^\tau, & |\varepsilon| > \delta \end{cases} \quad (12)$$

In this equation, δ refers to the filter coefficient; τ refers to the nonlinear factor; z_1 tracks ω_m ; z_2 observes the comprehensive interference term of velocity loop, \hat{d} . Choosing proper β_1, β_2 can predict \hat{d} .

Finally, based on ESO, the sliding mode speed control law based on ESO is obtained as followed:

$$u = i_q^* = \frac{2J}{3P_n\psi_f} \left(\eta \text{sign}(s) + ms + \dot{\omega}_m^* + kx_1 + \frac{B_0}{J}\omega_m - d \right) \quad (13)$$

4. 4DESIGN OF ADRC CONTROLLER

ADRC includes tracking differentiator, extended state observer, nonlinear state feedback, etc., among which, tracking differentiator is a nonlinear dynamic link that can reasonably extract differential signals, and its tracking signals and differential signals will be generated for input signals. The extended state observer is a kind of real-time tracking system state, at the same time, it is also the link to observe and compensate the integrated disturbance. The nonlinear state error feedback control law can enormously enhance the efficiency of information processing by replacing the classical linear weighted sum form with the nonlinear feedback structure of past, present and future information of errors. The control quantity of the system can be constituted to use the feedback state of the above extended state observer and the error of the system state output by the tracking differentiator, as well as the adoption of the appropriate nonlinear combination and compensation of the model and external disturbance.

The d-axis current control of PMSM is generated by ADRC, so that the integrated disturbance term and parameter term in formula (3) are:

$$a(t) = -\frac{R_s}{L}i_d + P_n\omega_m i_q, b = \frac{1}{L} \quad (14)$$

From equations (3) and (16):

$$\dot{i}_d = a(t) + bu_d \quad (15)$$

On the grounds of the design principle of ADRC, a first-order ADRC can be used to generate the d-axis current controller. Since the control strategy is adopted, its expression is:

First order tracking differentiator:

$$\begin{cases} \varepsilon_0 = r_1 \\ \dot{r}_1 = -\lambda \text{fal}(\varepsilon_0, \alpha_0, \delta_0) \end{cases} \quad (16)$$

Second order extended state observer:

$$\begin{cases} \varepsilon_d = z_1 - i_d \\ \dot{z}_1 = z_2 - \beta_1 \text{fal}(\varepsilon_d, \alpha, \delta_d) + bu_d \\ \dot{z}_2 = -\beta_2 \text{fal}(\varepsilon_d, \alpha, \delta_d) \end{cases} \quad (17)$$

Nonlinear feedback control law:

$$\begin{cases} \varepsilon_1 = r_1 - z_1 \\ u_{d0} = \beta_3 \text{fal}(\varepsilon_1, \alpha_1, \delta_1) \\ u_d = u_{d0} - z_2/b \end{cases} \quad (18)$$

At this point, the d-axis current control law can be obtained u_d .

In the same way, the q-axis current control of PMSM is generated by ADRC, so that the integrated disturbance term and parameter term in equation (4) are respectively:

$$\begin{aligned} a(t) &= -\frac{R_s}{L}i_q - P_n\omega_m i_d - \frac{P_n}{L}\omega_m\psi_f, \\ b &= \frac{1}{L} \end{aligned} \quad (19)$$

From(4) and (21):

$$\dot{i}_q = a(t) + bu_q \quad (20)$$

Then the ADRC expression:

First order tracking differentiator:

$$\begin{cases} \varepsilon_0 = r_1 - i_q^* \\ \dot{r}_1 = -\lambda \text{fal}(\varepsilon_0, \alpha_0, \delta_0) \end{cases} \quad (21)$$

Second order extended state observer:

$$\begin{cases} \varepsilon_q = z_1 - i_q \\ \dot{z}_1 = z_2 - \beta_1 \text{fal}(\varepsilon_q, \alpha, \delta_q) + bu_q \\ \dot{z}_2 = -\beta_2 \text{fal}(\varepsilon_q, \alpha, \delta_q) \end{cases} \quad (22)$$

Nonlinear feedback control law:

$$\begin{cases} \varepsilon_1 = r_1 - z_1 \\ u_{q0} = \beta_3 \text{fal}(\varepsilon_1, \alpha_1, \delta_1) \\ u_q = u_{q0} - z_2/b \end{cases} \quad (23)$$

So far, the q-axis current control law can be obtained u_q .

5. THE VERIFICATION OF HARDWARE IN THE LOOP SIMULATION EXPERIMENT

In order to achieve the goal of verifying the effectiveness of the designed control law, the hardware in the loop simulation

Table 1 Parameters of PMSM.

Physical quantity	Value
Stator resistance R_s	0.346ω
Wound inductance L	0.0078 H
Friction coefficient B_0	$0.005N \cdot m \cdot s$
Moment of inertia J	$0.089 kg \cdot m^2$
Flux linkage ψ_f	$0.51825V \cdot s$
Polar logarithm P_n	2
Rated power	10kW
Rated voltage	260V
Rated speed	1500 r/min

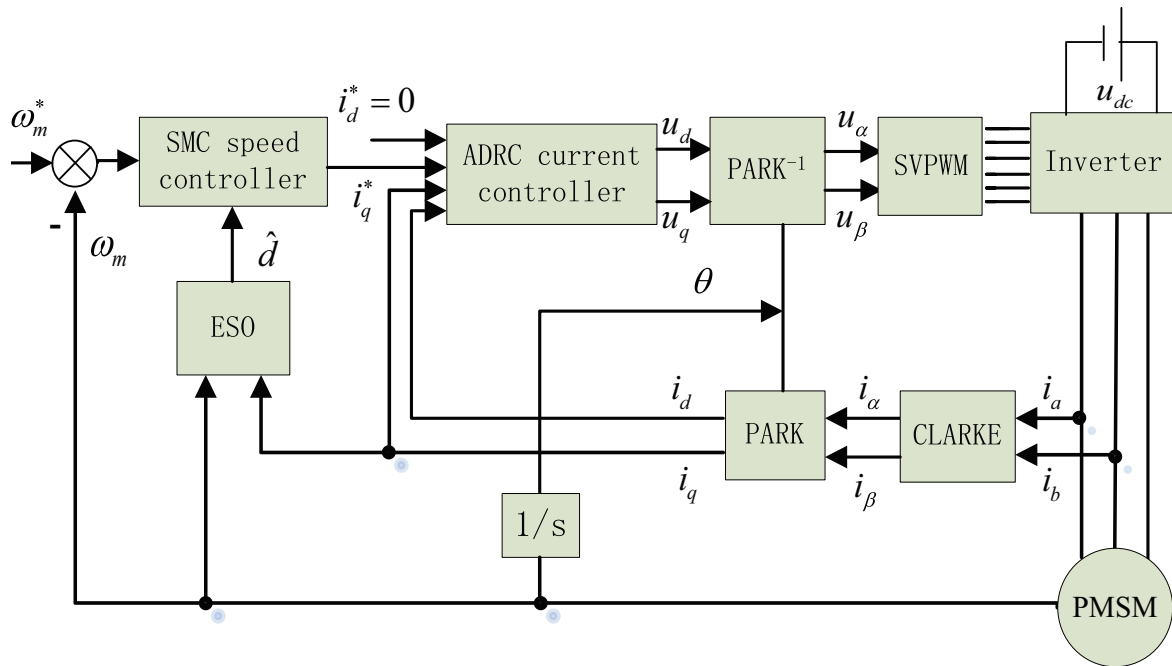


Figure 1 The Principle diagram of PMSM speed regulation System

platform is used. The platform includes PWM frequency converter, NI virtual controller, PMSM speed regulating and loading platform (PMSM, magnetic powder braking device and torque and speed measuring instrument), power distribution line and monitoring PC upper computer. The parameters used are shown in Table 1.

In response to this problem, since the simulation running time depends on the performance of the simulator and the algorithm complexity, etc, high performance emulator can be selected to improve the real-time performance of the system for the same control algorithm. The adopted NI simulation controller is composed of PXI1071 baseplate, PXI8840 controller and PXIe-7846R FPGA.

As it can be shown from figure 1, the PMSM speed regulation system is a double-closed-loop control structure is composed of two parts: the inner current loop and the outer speed loop. In the latter one, the ADRC replaces the traditional PI current controller and realizes the rapid tracking of the d and q axis current. Sliding mode speed controller with ESO achieves strong robustness and excellent dynamic quality of the speed governing system. The design of ESO not only effectively suppresses the integrated

interference term of velocity loop including load disturbance, but also reduces the sliding mode buffeting to some extent.

The verification process is carried out under three different working conditions: loading and unloading, speed up and down, forward and reverse.

5.1 The Hardware in the Loop Simulation Experiment of Loading and Unloading

The given speed was 300r/min, and after 20s, 5N* m load suddenly was added. And 20s later, it was unloaded the loaded suddenly. When the motor was loaded or unloaded, the loop simulation curve of n , i_d , i_q and i_{abc} is shown in Figure 2.

According to Figure 2 (a), the motor has fast convergence speed and smooth transition in the starting phase. The small fluctuation of speed during loading and unloading reflects the strong robustness of the proposed control strategy. It can be seen from Figure 2 (b) and Figure 2 (c) that the starting current was less than 20A, and the current curve was smoothly transited during loading and unloading.

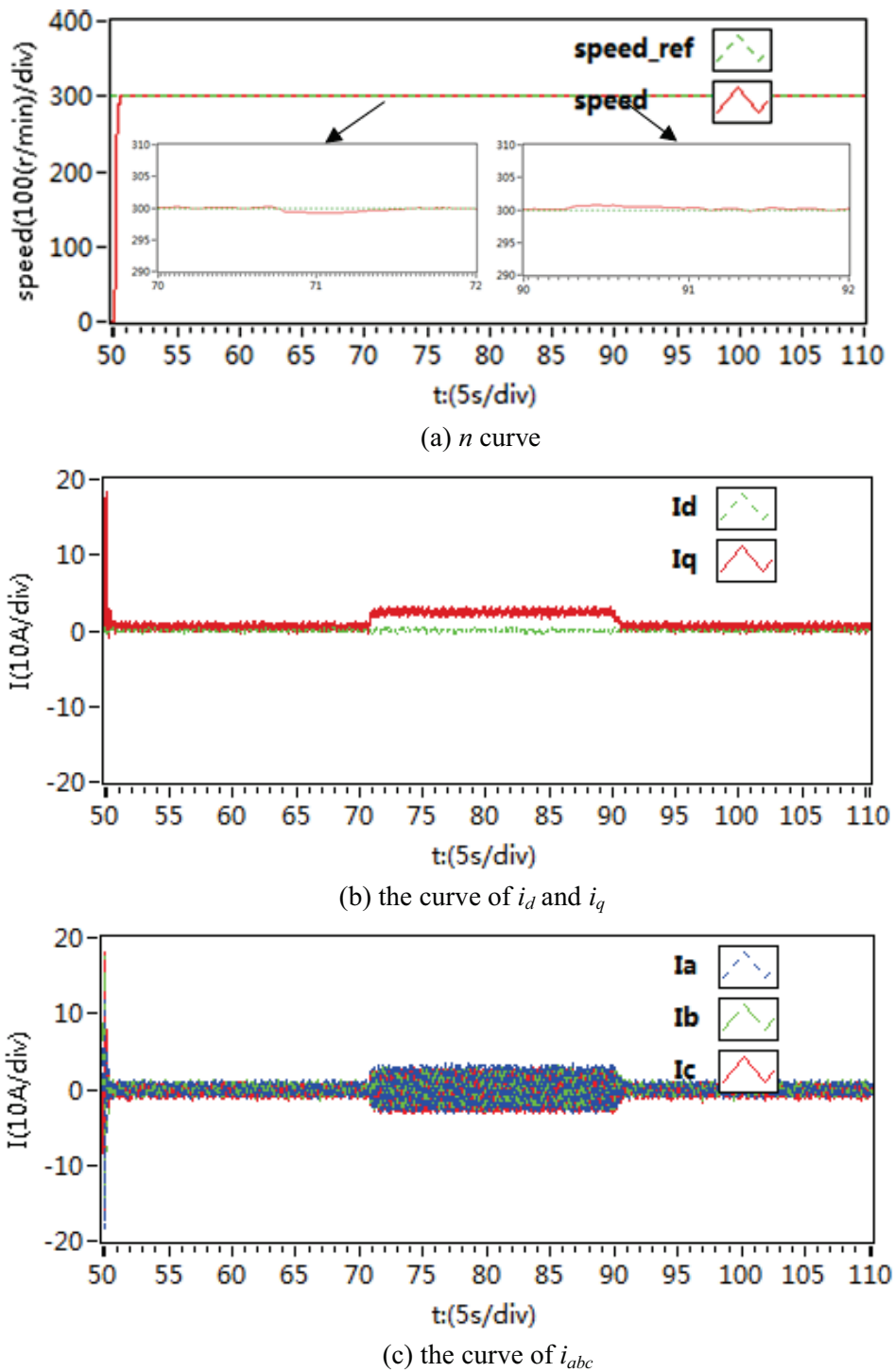


Figure 2 HIL simulation curves of motor with loading and unloading

1) Hardware in the Loop Simulation Experiment of up and Down Speed

The initial given speed was 300r/min. After 20s, the given speed was increased to 500r/min, and then it was changed to 300r/min 20s later. The hardware in the loop simulation curve of motor speed of n , i_d , i_q and i_{abc} is shown in Figure 3.

2) According to Figure 3 (a), because the sliding mode speed control strategy with ESO designed in this paper has high tracking performance to the given speed, the

speed regulation system has the features of fast response speed and smooth tracking curve, reflecting the excellent dynamic quality of the proposed control strategy. It can be seen from figure 3 (b) and (c) that the starting current is all less than 20A. At the moment when the speed control changes at a theoretic speed, there is a certain degree of current fluctuation in Figure 3 (b) and (c), but this fluctuation is within the allowed range of current variation and quickly returns to the stable value, which shows the excellent current tracking characteristics of ADRC.

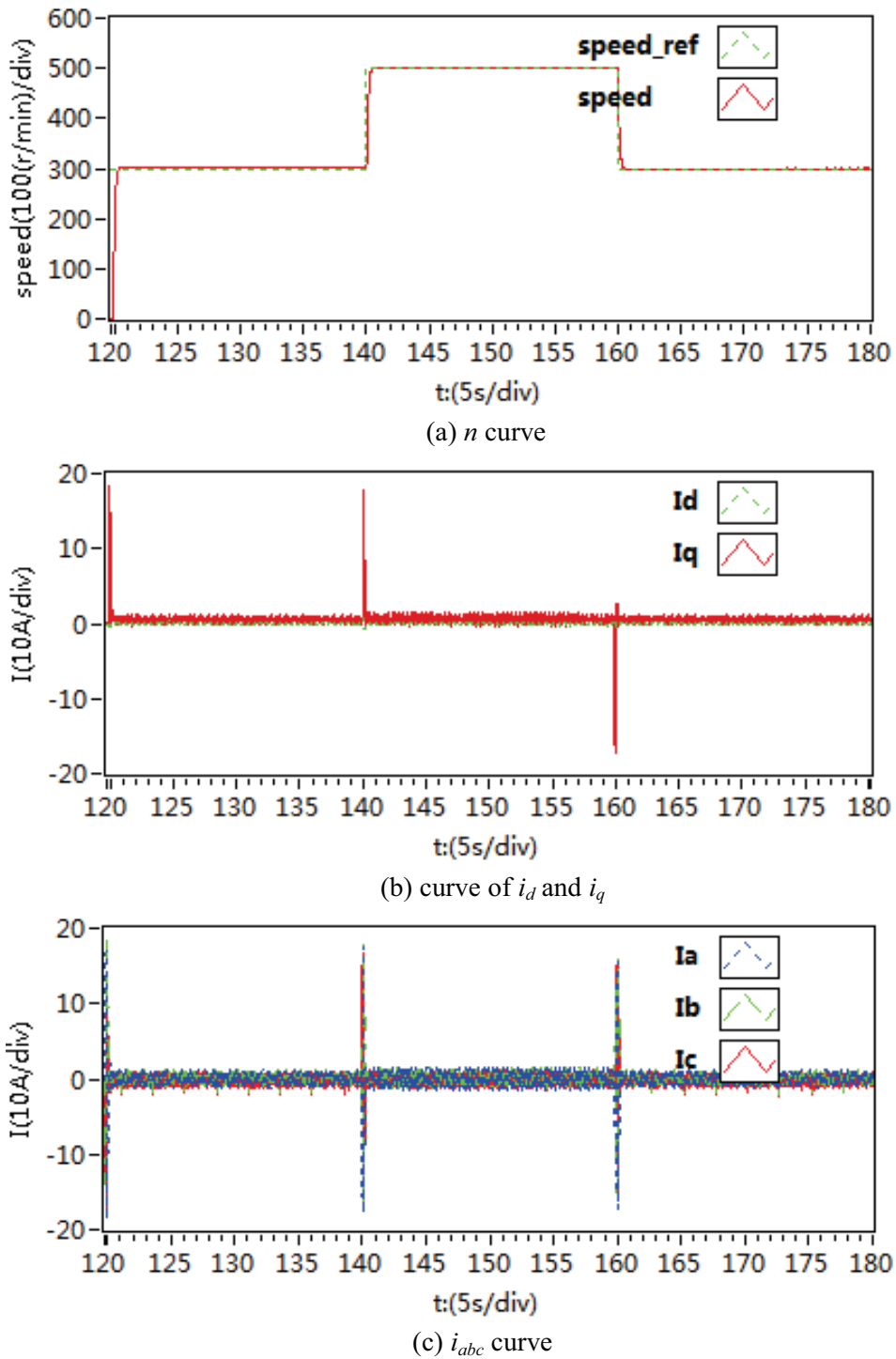


Figure 3 HIL simulation curves of motor speed up and down

3) The HIL simulation experiment

The given speed was 300r/min, and it was reduced to 300r/min, 30s later. The HIL simulation curve of n , i_d , i_q and i_{abc} is shown in Figure 4.

According to Fig. 4 (a), the dynamic response performance was good in the starting stage. Although there was a slight overshoot in the reverse moment, it was within the error tolerance range. It can also beshown clearly from Fig. 4 (b) and (c) that the starting current was less than 20A. At the moment of positive and negative rotation of a given

speed, figure 4 (b) and (c) show current fluctuation within the allowable range, and then quickly stabilize, reflecting the excellent current control performance of ADRC.

6. CONCLUSION

Based on the traditional vector control, this thesis proposed a sliding mode speed control strategy of PMSM speed control system for mine ventilation on the basis of the comprehensive disturbance observation of ESO. Firstly, the

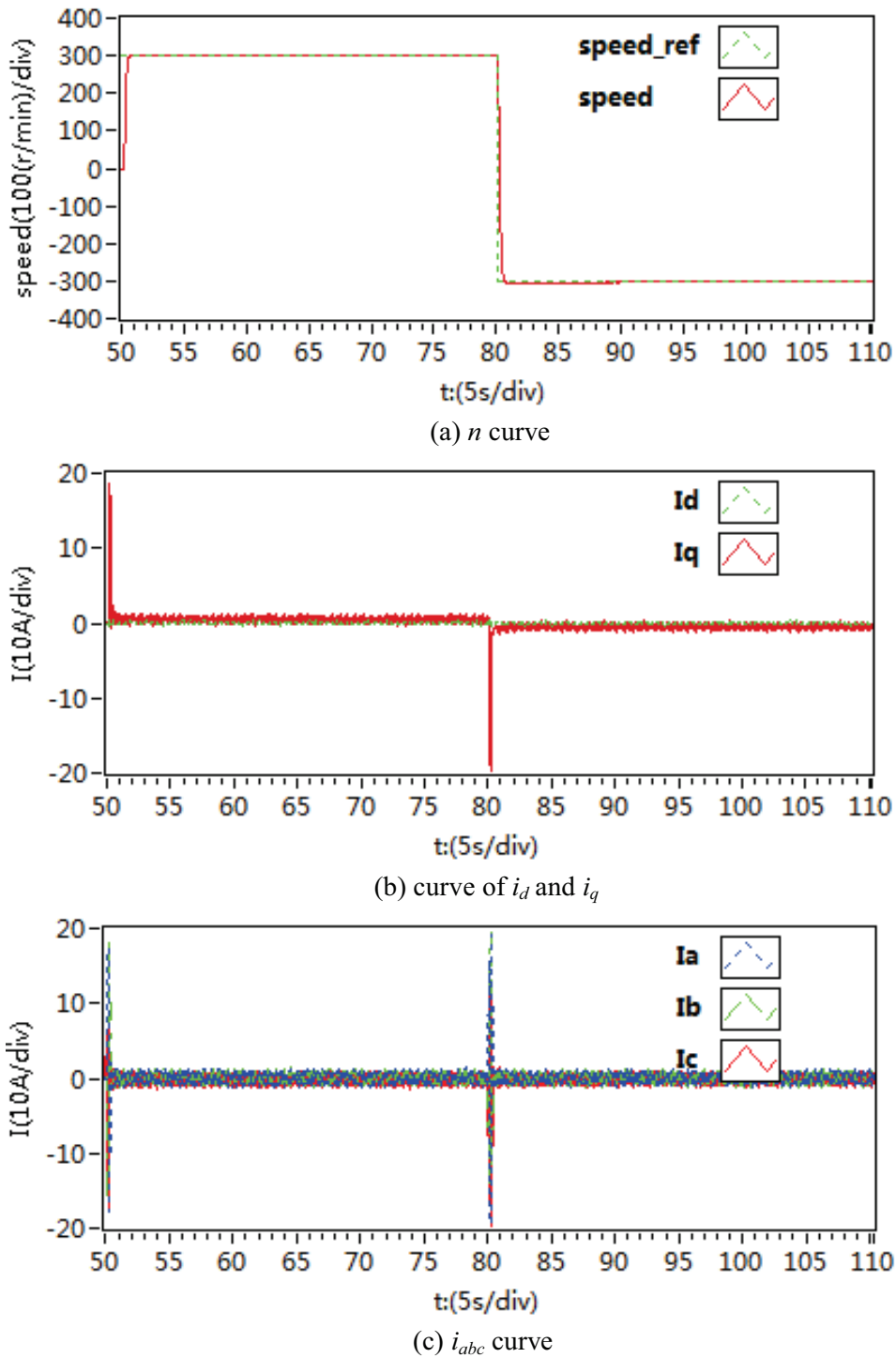


Figure 4 HIL simulation curves of motor speed forward and reverse

sliding mode speed controller was designed under the original PMSM mathematical model. Then the internal and external disturbances of the mine ventilation system were regarded as the comprehensive interferences of the motor speed control system. Thus, the sliding mode speed control law of the PMSM speed control system for mine ventilation based on ESO was obtained, which made the speed control system have better robustness and energy saving effect, and improved the mine ventilation system Energy efficiency and reliability. Finally, the effectiveness of the proposed control scheme was verified by the HIL simulation.

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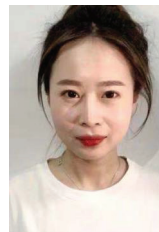
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