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# Speed Regulation for PMSM Drives Based on a Novel Sliding Mode Controller

**LI FENG[1], MENG DENG[1], SHUIQING XU[2], AND DARONG HUANG[3]**
[1]College of Traffic and Transportation, Chongqing Jiaotong University, Chongqing 400074, China
[2]College of Electrical and Automation Engineering, Hefei University of Technology, Hefei 230009, China
[3]College of Information Science and Engineering, Chongqing Jiaotong University, Chongqing 400074, China

Corresponding authors: Li Feng (fengli_cqu@126.com) and Shuiqing Xu (xsqanhui91@gmail.com)

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**ABSTRACT** This paper develops a novel sliding mode control technology and a comprehensive evaluation methodology for speed control of permanent magnet synchronous motor (PMSM). In most of the existing literature, only control precision of the speed corrector is investigated. However, the control strategy should be stable to the noise and disturbance caused by the environment and parameter uncertainties. In order to possessing faster dynamic response, stronger anti-interference ability and high stability of input, a highly stable sliding surface is proposed for siding mode control. Unlike most of reaching laws that requires the variation of designed sliding surfaces, this method takes state vectors in consideration. In addition, a comprehensive evaluation algorithm is presented to obtain reasonable assessment on speed control for synchronous PMSMs in different operating phases (starting, transient, steady-state rating). Finally, the simulation results verify the effectiveness and validity of the proposed sliding mode speed controller.

**INDEX TERMS** Comprehensive evaluation, PMSM, sliding mode control, torque ripple suppression.

## I. INTRODUCTION

Due to the advantages of reliable operation, high efficiency and low loss, permanent magnet synchronous motor plays a crucial role in many industrial applications, such as aerospace industry, robot industry, petroleum industry and metallurgical industry, especially in the field of electric vehicles. The system of PMSM is easily affected by parameter variations, load disturbance and nonlinear dynamics during operation if the control performance is degeneration. Therefore, more and more scholars pay attention to the control strategies design of performance of PMSM.

In recent decades, a large number of literatures have conducted the PMSM control. So far the methods to control PMSM can be categorized into several types such as vector control [1], direct torque control [2] and adaptive control [3]. Among them, vector control (also called magnetic field orientated control (FOC)) uses coordinate transformation to realize the performance of alternating-current (AC) motor similar to direct-current (DC) motor. In such applications, it is crucial to regulate speed for guaranteeing high performance applications of PMSMs, whether response speed when just starting the motor, or response speed when load changes. The methods of existing speed control mainly can be summarized in two categories. The first type is the traditional linear control approach, such as proportional-integral-derivative (PID) [4]–[6]. The traditional PI regulator is widely used in the AC speed regulating vector control system of the three-phase permanent magnet. Its algorithm has the advantages of simplicity, high reliability and convenient parameter setting. However, the three-phase PMSM is a nonlinear, strongly coupled and multivariable system. The traditional PI control method cannot achieve the actual requirements when the control system is affected by external disturbances or the change of internal parameters of the motor.

In addition, another type is nonlinear control theories, for instance neural network control [7], fuzzy control [8] and slide mode control (SMC) [9], [10]. SMC is insensitive to disturbances and parameters and has fast response speed, which can improve the dynamic quality of the speed control system of the three-phase PMSM. Therefore, many literatures apply it to speed control and propose various methods to enhance

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its control efficiency. Under the conventional sliding mode control, the speed controller has better dynamic performance, but the overshoot is large and the anti-disturbance capability needs to be strengthened [11]. Consequently, it is necessary to propose a novel sliding mode control technique to tackle these disadvantages.

It is worth mentioning that, reference [12] proposes an effective approach to deal with the constraint problem for a class of underactuated systems. It can handle different kinds of state constrains, whether actuated state constraints or unactuated ones, even or the constraints with some specific composite variables. The control strategy performs well in underactuated system. In view of which the model considered in the control method proposed in this paper is ideal, future work can be carried out in this direction of underactuated systems.

Motivated by the above reasons, this paper proposes a novel SMC method combining the optimized exponential reaching law with a designed sliding mode surface function. The novel sliding mode controller can improve the response speed and accuracy. Besides, this paper proposed a comprehensive evaluation algorithm to evaluate the control effect of various speed regulation strategies. The main contributions of the proposed method are as follows:

1. Compared with conventional sliding mode control, the method proposed in this paper greatly reduces the maximum overshoot of speed after the PMSM just started, and improves the anti-interference ability of the motor when its load changes.
2. Compared to the existing literature about speed regulation of PMSMs, this paper proposes a comprehensive evaluation scheme, which can assess speed control methods of PMSMs comprehensively and show its advantages and disadvantages clearly.
3. The method proposed in this paper not only has high precision, but also possesses high respond speed.

The rest of the paper is organized as follows: the part two introduces mathematical model of PMSM. The section three designs speed controllers based on various control methods and part four simulates these control algorithms. Finally, this article summarizes in the fifth part.

## II. MATHEMATICAL MODEL OF THREE-PHASE PMSM

This section presents the analytic models for a three-phase PMSM. The PMSM closed-loop speed regulation system is usually composed of double-loop structure: current loop and speed loop. In the PMSM, the rotor is comprised of permanent magnet and has fixed amplitude of the flux linkage.

In order to simplify the analysis, the following assumptions are first addressed:

*Assumption 1:* The saturation of the stator core is ignored.

*Assumption 2:* Regardless of eddy current and hysteresis loss in the motor.

*Assumption 3:* The magnetic field of the rotor is distributed as sinusoidal in the air gap space.

For the convenience of derivation, the mathematical model of surface mounted PMSM motor in *d-q* axes rotational reference frame is established as follows.

$$\begin{cases} u_d = Ri_d + L_s\dfrac{di_d}{dt} - p_n\omega_m L_s i_q \\ u_q = Ri_q + L_s\dfrac{di_q}{dt} + p_n\omega_m L_s i_d + p_{\mathrm{n}}\omega_m\psi_f \\ J\dfrac{d\omega_m}{dt} = \dfrac{3}{2}p_n\psi_f i_q - T_L \end{cases} \tag{1}$$

where $u_d$ and $u_q$ are the stator voltages of $d$-axis and $q$-axis, respectively; $i_d$ and $i_q$ are the currents of $d$ and $q$ axes; $R$ and $L_s$ are the resistance of three-phase winding and stator inductance, respectively; $p_n$ is the number of pole pairs; $\omega_m$ is the mechanical angular velocity of motor; $\psi_f$ is the permanent magnet flux linkage; $J$, $T_L$ and $B$ are the moment of inertia, load torque and damping coefficient, respectively.

For surface mounted PMSM, better control performance can be obtained by setting $i_d^* = 0$, where $i_d^*$ is the $d$-axis reference current. Thus the mathematical model can be expressed by:

$$\begin{cases} \dfrac{di_q}{dt} = \dfrac{1}{L_s}\left(-Ri_q - p_n\omega_m\psi_f + u_q\right) \\ \dfrac{d\omega_m}{dt} = \dfrac{1}{J}\left(-T_L + \dfrac{3}{2}p_n\psi_f i_q\right) \end{cases} \tag{2}$$

Define that the state variables of PMSM system are:

$$\begin{cases} x_1 = \omega_{ref} - \omega_m \\ x_2 = \dot{x}_1 = -\dot{\omega}_m \end{cases} \tag{3}$$

where $\omega_{ref}$ is the desired motor speed, and $\omega_m$ is the actual motor speed. According to (2) and (3), the mathematical model of the PMSM can be expressed by the differential equations as

$$\begin{cases} \dot{x}_1 = -\dot{\omega}_m = \dfrac{1}{J}\left(T_L - \dfrac{3p_n\psi_f}{2}\right)i_q \\ \dot{x}_2 = -\ddot{\omega}_m = -\dfrac{3p_n\psi_f}{2J}\dot{i}_q \end{cases} \tag{4}$$

Based on (4), the state equation using stator current as the state variables is given by:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -D \end{bmatrix}u \tag{5}$$

In which, the input vector is $u = \dot{i}_q$ and the parameter is $D = \frac{3p_n\psi_f}{2J}$. Then the consistent description of state equations can get:

$$\dot{x} = Ax + Bu \tag{6}$$

where the state vector is $x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$, the parameter matrices are $A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ -D \end{bmatrix}$, respectively.

## III. DESIGN OF SPEED CONTROLLER

From the above analysis, it can be seen that the state model is the foundation of control design. This section presents a novel sliding mode control to realize the effective suppression of the speed fluctuation and improve the response speed.

### A. CONVENTIONAL SLIDING MODE CONTROLLER ANALYSIS

The conventional sliding surface [13] can be defined as follows:

$$s_1 = cx_1 + x_2 \tag{7}$$

And the integral sliding surface [10] can be defined as follows:

$$s_2 = x_1 + c\int_0^t x_1 dt \tag{8}$$

In (7) and (8), $c > 0$, is constant quantity.

As for the conventional sliding surface, the asymptotic stability of the sliding mode is ensured with convergence rate depending on the value of $c$. However, the traditional sliding mode surface is susceptible to external interference, which is likely to lead to steady-state error and degradation of control performance. In terms of the integral sliding surface, it can reduce the steady-state error of the system while the performance of it is proven to be less satisfactory in terms of convergence rate and settling time.

Sliding mode controller can resort to design various reaching law functions to ensure the quality of normal motion stage. There are three kinds of common sliding surface functions [14]. The constant velocity reaching law can be defined as follows:

$$\dot{s}_1 = -\varepsilon \mathrm{sgn}(s) \quad \varepsilon > 0 \tag{9}$$

The constant $\varepsilon$ indicates the rate at which the moving point of the system approaches the switching point s = 0. When $\varepsilon$ is too small, the reaching speed is slow. And when $\varepsilon$ is too large, the approaching speed is quicker but the resulting jitter is large, simultaneously.

The exponential reaching law can be can be described as

$$\dot{s}_2 = -\varepsilon \mathrm{sgn}(s) - qs \quad \varepsilon, q > 0 \tag{10}$$

where, $s = s(0)^{-ek}$ is the solution of the exponential approach term $\dot{s} = -ks$. The exponential term $-ks$ can ensure that the state of the system can approach the sliding mode at a larger speed when $s$ is large.

The power reaching law can be defined as follows:

$$\dot{s}_3 = -q|s|^{\alpha}\mathrm{sgn}(s) \quad q > 0, 1 > \alpha > 0 \tag{11}$$

The small control gain can be guaranteed to reduce buffeting by adjusting the value of $\alpha$ when the state of the system is far from the sliding mode, i.e. $s$ is large.

According to reference [10], a novel exponential reaching law is proposed:

$$\dot{s}_4 = -\varepsilon|s|\,\mathrm{sigmod}(s) - q|s|s \quad \varepsilon, q > 0 \tag{12}$$

The reaching law results in the convergence speed related to the system state in the approaching phase with introducing the system state variable $|s|$. The reaching law can suppress some chattering and improve the dynamic performance of the system due to the continuous function sigmod $(s)$ replaces the sign function sgn $(s)$.

### B. A NOVEL DESIGN OF SMC SPEED CONTROLLER

In order to achieve fast convergence and strong robustness, a novel sliding mode surface is designed as:

$$s = c_1x_1 + c_2x_2 + c_3\int_0^t x_1 d\tau \tag{13}$$

where $\mathrm{c}_1, c_2, c_3 > 0$. Differentiating $s$ with respect to time gives

$$\dot{s} = c_1\dot{x}_1 + c_2\dot{x}_2 + c_3x_1 = c_1\dot{x}_1 - c_2D\dot{i}_q + c_3x_1 \tag{14}$$

To design the sliding mode controller to ensure better dynamic character and track capability, the exponential reaching law as (10) is adopted. Based on the novel sliding mode surface as (13), $q$-axis reference current can be described as

$$i_q = \frac{1}{D}\int_0^t \left[\frac{c_1}{c_2}x_2 + \frac{c_3}{c_2}x_1 + \frac{\varepsilon}{c_2}\mathrm{sgn}(s) + \frac{q}{c_2}\mathrm{s}\right]d\tau \tag{15}$$

For consistent description, define that $\frac{c_1}{c_2} = k_1$, $\frac{c_3}{c_2} = k_2$, $\frac{\varepsilon}{c_2} = k_3$, $\frac{q}{c_2} = k_4$, then it can be obtained that

$$i_q = \frac{1}{D}\int_0^t (k_1x_2 + k_2x_1 + k_3\mathrm{sgn}(s) + k_4s)d\tau \tag{16}$$

According to reference [15], the design reaching law is as follows.

$$\dot{s} = -\varepsilon \cdot \lambda(|x_1|)\,\mathrm{sgn}(s) - qs \quad \varepsilon, q > 0 \tag{17}$$

where $\lambda(|x_1|)$ is a variable. In order to suppress sliding mode chatter, the design variable is as follows:

$$\lambda(|x_1|) = \frac{|x_1|}{|x_1| + \lambda} \quad \lambda > 0 \tag{18}$$

It can be seen from (18) that $\varepsilon \cdot \lambda(|x_1|)$ is approximately equal to the original switching gain $\varepsilon$ when the system state trajectory is relatively far from the sliding mode surface, i.e., $|x_1|$ is larger. In addition, $\varepsilon \cdot \lambda(|x_1|)$ is much smaller than the original switching gain $\varepsilon$ when the state trajectory of the system approaches the sliding surface. It is conducive to the sliding mode switching gain to dynamically adapt to the changes of the system state. Therefore, effective inhibition of the sliding mode chattering phenomenon can be realized by the addition of variable term $\lambda(|x_1|)$.

In what follows, the reachability condition of sliding motion is proved, i.e., the state trajectories of the closed-loop systems will be globally driven onto a sliding surface in finite time. The Lyapunov function candidate is used to testify that the system state of this sliding mode control can reach the sliding mode surface form arbitrary initial state in limited time, and it is defined as

$$V = \frac{1}{2}s^2 \tag{19}$$

Then substituting (10) into (19) and taking the derivative of (19) with

$$\dot{V} = s\dot{s} = s\left[-\varepsilon\,\mathrm{sgn}(s) - qs\right] = -\varepsilon s\,\mathrm{sgn}(s) - qs^2 \leq 0 \tag{20}$$

In (20), owing to $\varepsilon > 0$ and $q > 0$, it is obvious that $\dot{V} \leq 0$ can be established. Therefore, according to Lyapunov theory, the speed for (3) can converge to zero in limited time by designing the sliding mode surface of (13) and control law of (10).

And substituting (17) into (20)

$$\begin{aligned} \dot{V} &= s\dot{s} = s\left(-\varepsilon \cdot \lambda\left(|x_1|\right) \operatorname{sgn}(s) - qs\right) \\ &= -\varepsilon s \cdot \lambda\left(|x_1|\right) \operatorname{sgn}(s) - qs^2 \leq 0 \end{aligned} \tag{21}$$

In (21), due to $\lambda(x_1) > 0$, $\varepsilon > 0$ and $q > 0$, $\dot{V} \leq 0$ can be established. Consequently, according to the Lyapunov stability theory, the optimization controller is asymptotically stable, and it can guarantee the system reaching the sliding mode surface.

### C. A COMPREHENSIVE EVALUATION METHOD FOR SPEED CONTROLLERS

Based on the reference [16], a comprehensive evaluation method is designed on account of objectively judging the effectiveness of control strategy and fully comparing the performance of various controllers.

The evaluation system adopts four representative evaluation indexes, namely, steady state error, convergence speed, speed overshoot immediately after the motor is started (to be replaced by overshoot later) and anti-interference capability when the motor torque changes (to be replaced by anti-interference capability later) The evaluation method also resorts to a scoring system, whose highest score is n when assessing n controllers, and n was scored to which control strategy performed best, the second highest scoring n-1, until the worst one possessing 1 point.

The scoring results are summarized in a table, and then the corresponding radar chart is drawn according to it. Through the radar chart, the advantages and disadvantages of the control method and the comprehensive control effect can be clearly reflected.

## IV. SIMULATION

The simulation model of three-phase PMSM vector control based on sliding mode speed controller is established in the simulation environment of Matlab/Simulink, and the simulation block diagram is shown in Fig. 1. It can be seen from the figure, the current loop and speed loop are adopted in the control system. Speed error is the input of the speed controller, and q-axis reference current is the output of it. The schematic illustration for the SMC system is shown in Fig. 2.

### A. PARAMETER SETTINGS OF THE PMSM

In order to verify the effectiveness of the sliding mode speed control method, the rated parameter settings of the PMSM adopted in the simulation are shown in Table 1 and the values of simulation condition are set as shown in Table 2. Sampling cycle time is set to $T_s = 10\ \mu$s and relative tolerance of system is set to 0.0001. Setting simulation time to 0.4 seconds, load torque at initial moment and at 0.2 seconds are set to $0\ \mathrm{N \cdot m}$ and $10\ \mathrm{N \cdot m}$, respectively.

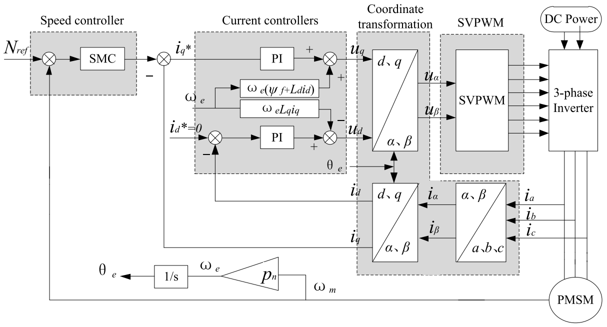

**FIGURE 1.** Three-phase PMSM vector control simulation block diagram.

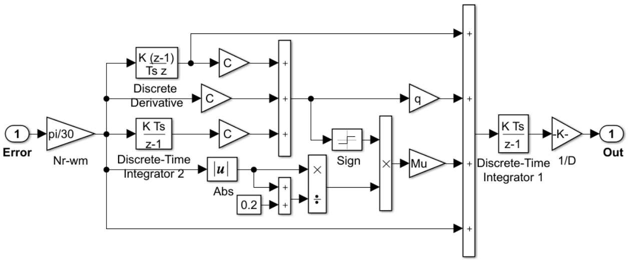

**FIGURE 2.** Simulation model of novel SMC speed control system.

**TABLE 1.** Rated parameters of the PMSM.

| Parameter | Value/Unit |
|---|---|
| Stator resistance, $R$ | 2.875 / Ω |
| Stator inductance, $L_s$ | 8.5/mH |
| Pole pair, $p_n$ | 4 |
| Flux linkage, $\psi_f$ | 0.175 / Wb |
| Moment of inertia, $J$ | 0.003 / Kg•m$^2$ |
| Damping coefficient, $B$ | 0.008 / N•m•s |
| DC side voltage, $U_{dc}$ | 311/V |
| Reference speed, $N_{ref}$ | 1000 / r•min$^{-1}$ |

**TABLE 2.** Simulation condition setting parameters.

| Parameter | Value/Unit |
|---|---|
| Sliding mode surface gain, $c = c_1 = c_2 = c_3$ | 60 |
| Reaching law gain, $\varepsilon$ and $k_3$ | 200 |
| Reaching law gain, $q$ and $k_4$ | 300 |
| The gain of controller, $\lambda$ | 1 |
| Power reaching law gain, $\alpha$ | 0.5 |

### B. SIMULATION AND COMPARISON BASED ON VARIOUS SLIDING MODE SURFACE

#### 1) THE DYNAMIC PERFORMANCE BASED ON CONVENTIONAL SLIDING MODE SURFACE

This part shows the comparison of the dynamic performance of PMSM for speed reference of 1000 rpm when controlled with constant velocity reaching law, exponential reaching law and power reaching law based on the conventional sliding mode surface.

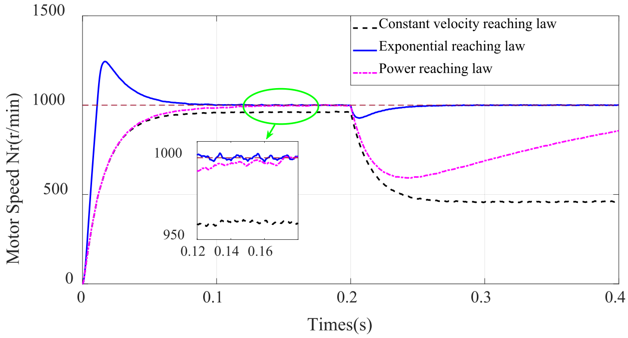

**FIGURE 3.** Simulation results based on the conventional sliding mode surface.

Results in Fig.3 shows that the convergence speed of system based on conventional sliding mode surface incorporated into constant velocity reaching law and power reaching law is slow and the anti-torque interference ability of those is poor. And the controller of conventional sliding mode surface combined with exponential reaching law has relatively better dynamic performance. Nevertheless, it tracks reference speed of 1000 rpm with about 24.43% maximum overshoot.

In order to compare the performance of controllers fully, the comprehensive evaluation method is adopted. Its highest score is 3. On the basis of simulation results, the comprehensive evaluation scheme of speed controllers based on the conventional sliding mode surface are shown in Table 3 and Fig.4.

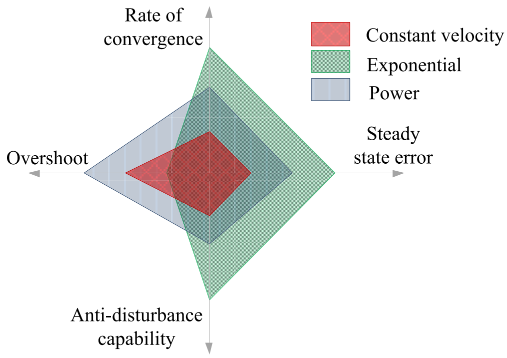

**FIGURE 4.** Radar chart of evaluation of controllers based on the conventional sliding mode surface.

**TABLE 3.** Evaluation of controllers based on the conventional sliding mode Surface.

| Reaching Law | Steady state error | Rate of convergence | Overshoot | Anti-disturbance capability |
|---|---|---|---|---|
| Constant | 1 | 1 | 2 | 1 |
| Exponential | 3 | 3 | 1 | 3 |
| Power | 2 | 2 | 3 | 2 |

As can be found out from the above, in terms of overshoot of system, the controller of power reaching law combined with the conventional sliding mode surface is the relatively better controller. Considering the convergence speed, steady state error or anti-interference ability of the system, the controller with the best performance is the controller of exponential reaching law combined with the conventional sliding mode surface. With regard to the controller of constant velocity reaching law, its performance is poor from four dimensions. In addition, as far as whole is concerned, the sliding mode controller of exponential reaching law combined with the conventional sliding mode surface has the better performance owing to its performance represented by green frame occupies the largest area in the radar chart. The power law of approach is the second and the law of isokinetic approach ranks the last according to their area.

### 2) THE DYNAMIC PERFORMANCE BASED ON THE INTEGRAL SLIDING MODE SURFACE

This part shows the comparison of the dynamic performance of system controlled with constant velocity reaching law, exponential reaching law and power reaching law based on the integral sliding mode surface.

As shown in Fig. 5, the control performance of the controller combining the integral sliding mode surface and constant velocity reaching law or exponential reaching law is similar to the simulation result of Fig. 3. The speed control effect of system with control method of combining integral sliding mode surface with power reaching law lies between other two controllers with its performance of response speed improving. The SMC controller combing the law of convergence of quotation with integral sliding mode surface possesses a 2.46 percent maximum volume of speed drop but a 31.07 percent maximum overshoot.

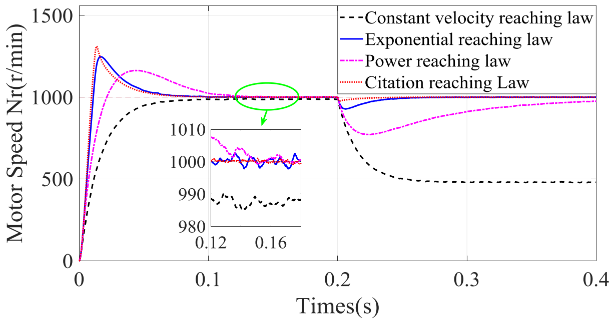

**FIGURE 5.** Simulation results based on the integral sliding mode surface.

The control performance of the three kinds of speed robust controllers is evaluated and compared as shown in Table 4 and Fig.6, using the comprehensive evaluation method with four points for the highest score. From the perspective of overshoot, the power reaching law performs well. As for the convergence speed, steady state error or anti-interference ability, the referenced reaching law has the absolute advantage. From the whole, the top one is the controller of the cited reaching law combining with the integral sliding mode surface owing to its biggest area. Law of exponential approach, law of power

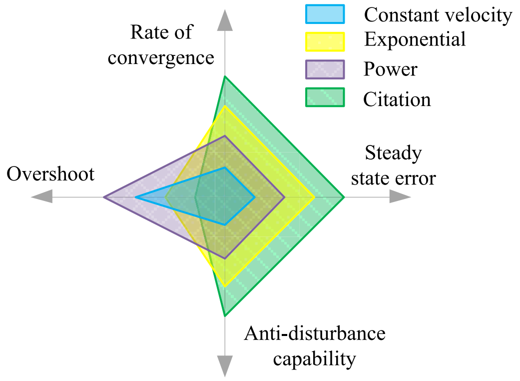

**FIGURE 6.** Radar chart of evaluation of controllers based on the integral sliding mode surface.

**TABLE 4.** Evaluation of controllers based on the integral sliding mode surface.

| Reaching Law | Steady state error | Rate of convergence | Overshoot | Anti-disturbance capability |
|---|---|---|---|---|
| Constant | 1 | 1 | 3 | 1 |
| Exponential | 3 | 3 | 2 | 3 |
| Power | 2 | 2 | 4 | 2 |
| Citation | 4 | 4 | 1 | 4 |

approach and law of isokinetic approach obtain second, third and last place respectively.

*Remark 1:* Above all, whether traditional sliding mode surface function or integral sliding mode surface function, the simulation speed curve of speed sliding mode controller combined with exponential reaching law is relatively ideal with relatively good dynamic performance and anti-disturbance capability regardless of the reaching law cited. In addition, the above two parts also prove that the evaluation method is applicable to the comparative evaluation of all control methods by being consistent with the simulation results.

### 3) THE DYNAMIC PERFORMANCE BASED ON THE NOVEL SLIDING MODE SURFACE

This part shows the comparison of the dynamic performance of system controlled with constant velocity reaching law, exponential reaching law and power reaching law based on the novel sliding mode surface.

Fig.7 shows the comparison of different speed responses based on a novel sliding mode surface function incorporated into constant speed reaching law, exponential reaching law and power reaching law function. The robust speed controller based on the novel sliding mode surface function and exponential reaching law function has much better dynamic performance with maximum overshoot of only 7.44% and anti-disturbance capability with settling back to its reference speed after less than 0.005 seconds when disturbed by load.

Results in Table 5 and Fig.8 based on the same comprehensive evaluation method to the first part show that the exponential reaching law based on the novel sliding mode has better dynamic performance in terms of rate of convergence, steady state error and anti-disturbance capability. Nevertheless, its maximum overshoot is largest, which means that it is the worst in the evaluation index of overshoot.

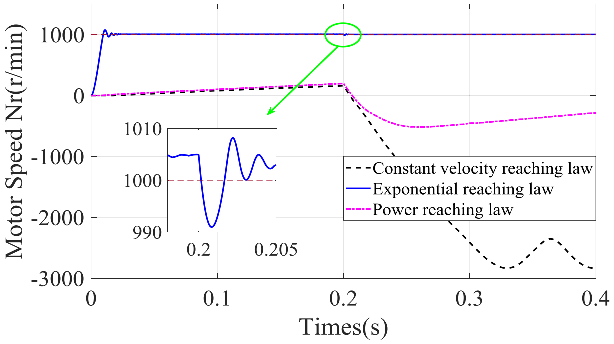

**FIGURE 7.** Simulation results based on a novel sliding mode surface.

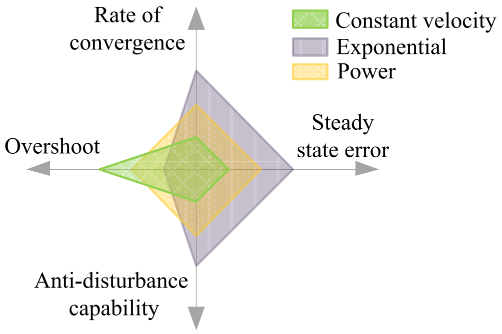

**FIGURE 8.** Radar chart of evaluation of controllers based on the novel sliding mode surface.

**TABLE 5.** Evaluation of controllers based on the novel sliding mode surface.

| Reaching Law | Steady state error | Rate of convergence | Overshoot | Anti-disturbance capability |
|---|---|---|---|---|
| Constant | 1 | 1 | 3 | 1 |
| Exponential | 3 | 3 | 1 | 3 |
| Power | 2 | 2 | 2 | 2 |

### 4) THE RESPONSE PERFORMANCE BASED ON DIFFERENT METHODS

The comparison of the dynamic performance of system controlled based on the conventional SMC, the integral SMC, the citation SMC, the novel SMC proposed in this paper and the PI control are presented in the fourth section, in view of their relatively better performance.

Fig.9 shows the response speed of novel SMC and cited SMC when starting up the motor is faster than conventional SMC and PI control while the maximum overshoot of the novel SMC is less than the cited SMC. And the response speed of the novel sliding mode control when load changes also faster than referenced SMC, PI control and conventional SMC. The disadvantage of the novel SMC is that the steady

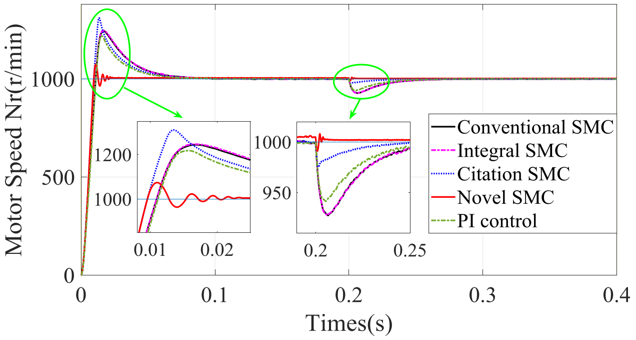

**FIGURE 9.** Simulation results based on several controllers with better control performance.

speed of the system is about 5.2 rpm higher than the rated speed of 1000 rpm.

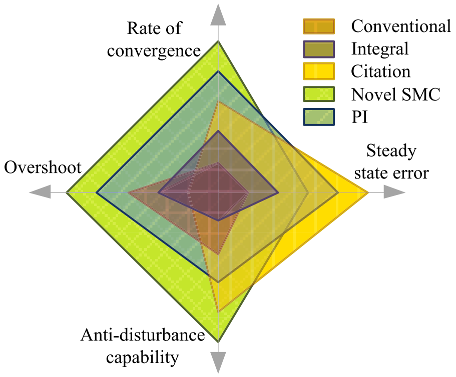

**FIGURE 10.** Radar chart of evaluation of several controllers with better control performance.

**TABLE 6.** Evaluation of several controllers with better control performance.

| Reaching Law | Steady state error | Rate of convergence | Overshoot | Anti-disturbance capability |
|---|---|---|---|---|
| Conventional | 1 | 1 | 3 | 2 |
| Integral | 2 | 2 | 2 | 1 |
| Citation | 5 | 3 | 1 | 4 |
| Novel | 3 | 5 | 5 | 5 |
| PI | 4 | 4 | 4 | 3 |

For a comprehensive comparison, Table 6 and Fig. 10 use the similar evaluation of the second section. In terms of the evaluation indices of rate of convergence, overshoot and anti-disturbance capability, novel SMC performs better. With regard to steady state error of speed control system, the novel SMC has relatively worst performance attributed to its steady speed being higher than the rated speed while the reference SMC performs well. On the whole, the novel SMC has the better property of velocity of dynamic response as the result of the assessment of the novel SMC represented by green frame occupying the larger area in the radar chart.

### 5) THE RESPONSE PERFORMANCE BASED ON NOVEL SMC AND OPTIMIZED SMC

This section shows the simulation results of novel SMC and optimized SMC. The speed curve, output curve and torque curve of comparison of novel SMC and optimized novel SMC are shown in Figs. 11, 12 and 13 respectively.

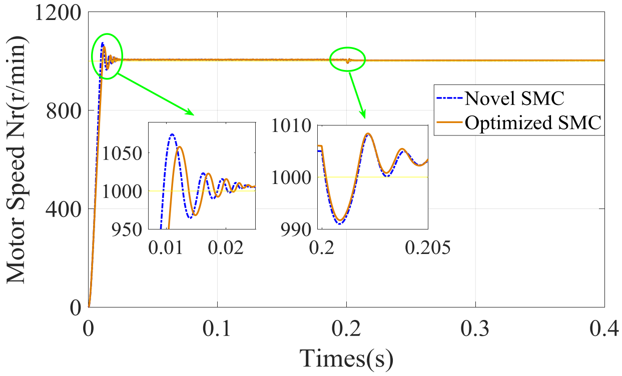

**FIGURE 11.** Motor speed of novel SMC and optimized SMC.

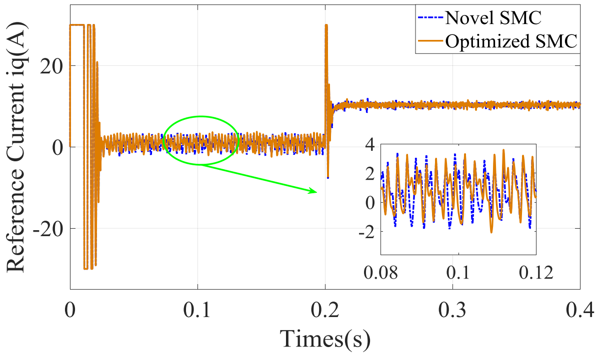

**FIGURE 12.** Reference current of novel SMC and optimized SMC.

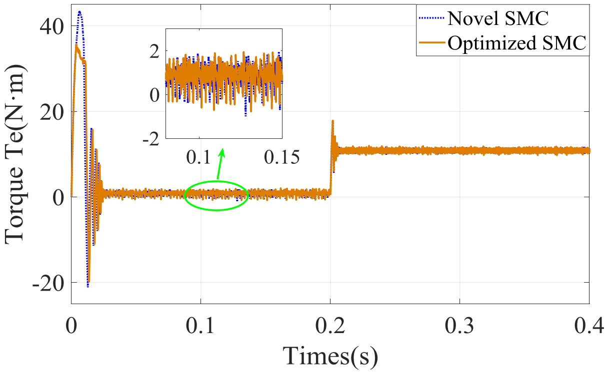

**FIGURE 13.** Torque of novel SMC and optimized SMC.

The simulation result of motor speed shows that compared with the novel SMC, speed of the optimized SMC takes 0.0006 seconds more to reach the stable speed, which is 0.0243 seconds. And the maximum overshoot of optimized

SMC speed decreases by 1.6% to 5.8%. When the torque is changed, the maximum volume of speed drop increases by 0.07% to 8.29%, and it takes 0.0008 seconds to return to the stable speed, which is 0.0056 seconds. In terms of output characteristics of speed controller, the amplitude of oscillation of optimized SMC decreases as shown in Fig.13. As for electromagnetic torque, the optimized SMC decreases maximum torque from 43.51 N · m to 32.67 N · m and suppresses some torque ripple.

## V. CONCLUSION

This paper proposes an optimized novel sliding mode speed controller for PMSM in terms of improving speed tracking ability and anti-disturbance properties. And a comprehensive evaluation methodology for better comparison and analysis is presented to verify the effectiveness of the proposed method. Through simulation, it is verified that the optimized novel SMC proposed in this paper can not only achieves the dynamic quality of high performance, but also ensures strong anti-interference ability and suppresses some torque jitter. In addition, the comprehensive evaluation method proposed in this paper is also proved to be suitable for simulation comparison evaluation. Reducing the steady state error under this speed control method, designing more advanced sliding mode controller, conducting experiments and applying it to PMSM vector control system to improve the dynamic quality can be finished with future works.

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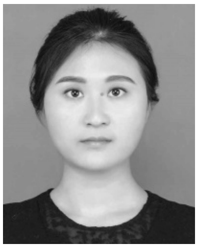

**LI FENG** received the Ph.D. degree from Chongqing University, Chongqing, China, in 2017. She is currently an Associate Professor with the College of Traffic and Transportation, Chongqing Jiaotong University.

Her research interests include iterative learning control, fault estimation, and fault-tolerant control for linear and nonlinear systems and their applications.

**MENG DENG** is currently pursuing the master's degree with the College of Traffic and Transportation, Chongqing Jiaotong University.

Her research interests include sliding mode control, fault estimation, and fault-tolerant control for linear and nonlinear systems and their applications.

**SHUIQING XU** received the Ph.D. degree from Chongqing University, Chongqing, China, in 2016.

Since 2017, he has been a Lecturer with the Hefei University of Technology. His research interests include sliding mode control, signal processing, fault diagnosis, and fault-tolerant control for linear and nonlinear systems and their applications.

**DARONG HUANG** received the Ph.D. degree from Chongqing University, Chongqing, China, in 2006. He is currently a Professor with the College of Information Science and Engineering, Chongqing Jiaotong University.

His research interests include sliding mode control, big data, deep learning theory, fault diagnosis and prediction, and fault tolerant control and their applications.

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