Current Sliding Mode Control with Gain-Scheduled Parameters for Permanent Magnet Synchronous Machines

Ningzhi Jin and Xudong Wang

***Abstract*—The structures and parameters of a sliding mode controller are required to change with the operating conditions and external disturbances in order to obtain satisfactory control performances in the global operation range. To solve this problem, a novel current sliding mode control (SMC) method with gain-scheduled parameters is proposed for permanent magnet synchronous machines (PMSM) in this paper. On the basis of the construction of the current sliding mode controller, the boundary layers of the switching gains are adjusted on-line with an adaptive method, and the controller coefficients the switching gains and the sliding surfaces are gain-scheduled in real time within the allowed boundary layers with the sliding surfaces as scheduling variables. The designed method not only ensures the system robustness, but also alleviates the system chattering and improves the control performances.**

***Index Terms*—Sliding mode control, gain-scheduled, permanent magnet synchronous machine.**

I. Introduction

Sliding mode control (SMC) is a special non-linear control method with advantages such as fast response, strong robustness and simple realization [1-3]. However, the sliding mode control will bring in inevitable system chattering, which makes the present-day research on the application of sliding mode control to the actual motor drive system focused on how to alleviate the chattering [4]-[8].

In the real system, the structures and parameters of the sliding mode controller are required to change with the operating conditions and external environment in order to obtain satisfactory control performances in the global operation range. Gain-scheduled control is an effective method to solve the control problems for nonlinear systems. In this method, a nonlinear task is divided into several subtasks, and the relationships between these subtasks are established through scheduling variables so as to construct a nonlinear controller satisfying the global performance requirements [9]-[12]. The design idea has been approved by the designers in flight control systems at first, and applied in industrial control systems such as turbine and boiler and wind power generation [13]-[16].

This paper presents an adaptive and gain-scheduled hybrid method to set the parameters of the current sliding mode controller. In this method, according to the real speed and torque, the boundaries of the switching gains are adjusted on-line with the adaptive method in order to ensure the system robustness. And with integral sliding surfaces with regard to d-q axis currents as scheduling variables, the controller coefficients of the switching gains and the sliding surfaces are tuned with gain-scheduled method so as to obtain optimal system performances.

Manuscript received April 4, 2014; revised June 6, 2014. This work was supported in part by the Science and Technology Research Projects of Heilongjiang Provincial Department of Education of China (No. 12541158).

Ningzhi Jin is with Department of Electrical Engineering, Harbin University of Science and Technology, Harbin, 150080 China (e-mail: sharon0716@126.com).

Xudong Wang is with the Engineering Research Center of the Automotive Electronic Drive Control and System Integration of the Ministry of Education, Harbin, 150080 China (e-mail: wxd6158@163.com).

II. Mathematical Model of PMSM

The stator voltage of PMSM in the d–q synchronous rotating reference frame can be expressed as

$$\begin{cases} u_{\mathrm{d}} = R_{\mathrm{s}} i_{\mathrm{d}} + L_{\mathrm{d}} \dfrac{\mathrm{d}i_{\mathrm{d}}}{\mathrm{d}t} - L_{\mathrm{q}} \omega_{\mathrm{e}} i_{\mathrm{q}} \\ u_{\mathrm{q}} = R_{\mathrm{s}} i_{\mathrm{q}} + L_{\mathrm{q}} \dfrac{\mathrm{d}i_{\mathrm{q}}}{\mathrm{d}t} + L_{\mathrm{d}} \omega_{\mathrm{e}} i_{\mathrm{d}} + \omega_{\mathrm{e}} \psi_{\mathrm{f}} \end{cases} . \tag{1}$$

where u_{d} and u_{q} are the d–q axis stator voltages, i_{d} and i_{q} are the d–q axis stator currents, L_{d} and L_{q} are the d–q axis inductances, R_{s} is the stator phase resistance, ψ_{f} is the rotor flux linkage, and ω_{e} is the rotor electrical angular speed.

The corresponding electromagnetic torque is

$$T_{\mathrm{e}} = 1.5 p(\psi_{\mathrm{f}} i_{\mathrm{q}} + (L_{\mathrm{d}} - L_{\mathrm{q}}) i_{\mathrm{d}} i_{\mathrm{q}}) . \tag{2}$$

The associated electromechanical equation is as follows:

$$T_{\mathrm{e}} - T_{\mathrm{L}} = J \frac{\mathrm{d}\omega_{\mathrm{m}}}{\mathrm{d}t} + B_{\mathrm{m}} \omega_{\mathrm{m}} . \tag{3}$$

where T_{L} is the load torque, p is the number of pole pairs, J is the moment of inertia, B_{m} is the friction coefficient, and ω_{m} is the rotor mechanical angular speed.

III. Design of Current Sliding Mode Controller

A. State Space Equation

In a current control system, the state variables are d–q axis current errors e_{d} and e_{q}, and the control inputs are d–q axis voltages u_{d} and u_{q}. Thus,

$$\begin{cases} \boldsymbol{x} = \begin{bmatrix} e_{\mathrm{d}} & e_{\mathrm{q}} \end{bmatrix}^{\mathrm{T}} = \begin{bmatrix} i_{\mathrm{dr}} - i_{\mathrm{d}} & i_{\mathrm{qr}} - i_{\mathrm{q}} \end{bmatrix}^{\mathrm{T}} \\ \boldsymbol{u} = \begin{bmatrix} u_{\mathrm{d}} & u_{\mathrm{q}} \end{bmatrix}^{\mathrm{T}} \end{cases} . \tag{4}$$

DOI: 10.7763/IJIEE.2014.V4.482

where i_{dr} and i_{qr} are the reference commands of the d–q axis currents.

The state space equation of the d–q axis current control system can be described from (1) and (4) as

$$\begin{bmatrix}\dot{e}_d\\ \dot{e}_q\end{bmatrix}=\begin{bmatrix}A_1 & A_{12}\\ A_{21} & A_2\end{bmatrix}\boldsymbol{x}+\begin{bmatrix}B_1 & 0\\ 0 & B_2\end{bmatrix}\boldsymbol{u}+\begin{bmatrix}E_1\\ E_2\end{bmatrix}. \quad (5)$$

where $A_1=-\frac{R_s}{L_d}$, $A_{12}=\frac{L_q}{L_d}\omega_e$, $A_{21}=-\frac{L_d}{L_q}\omega_e$, $A_2=-\frac{R_s}{L_q}$, $B_1=-\frac{1}{L_d}$, $B_2=-\frac{1}{L_q}$, $E_1=\frac{R_s}{L_d}i_{dr}-\frac{L_q}{L_d}\omega_e i_{qr}$, and $E_2=\frac{L_d}{L_q}\omega_e i_{dr}+\frac{R_s}{L_q}i_{qr}+\frac{1}{L_q}\omega_e\psi_f$.

B. Sliding Surface

The design of normal sliding surface may result in static errors and unacceptable performance specifications under random external disturbances. And the design of integral sliding surface can reduce the static error and enhance the control precision. Thus, the integral sliding surfaces with respect to the d–q axis current errors are utilized as follows:

$$\boldsymbol{s}=\begin{bmatrix}s_d\\ s_q\end{bmatrix}=\begin{bmatrix}c_1\int_0^t e_d\,dt+e_d\\ c_2\int_0^t e_q\,dt+e_q\end{bmatrix}. \quad (6)$$

where c_1 and c_2 are the integral coefficients of the d–q axis sliding surfaces.

C. Reaching Law

The exponent reaching law can obtain a quick response and weaken chattering. However, its sliding band doesn't decay with time, that is, the system states track within a sliding band which cannot reach origin but chattering near the origin. This may excite inconsiderable high frequency components in the system model, and thus result in more burdens on the controller.

The reaching law with respect to the d–q axis current errors can then be expressed as

$$\dot{\boldsymbol{s}}=\begin{bmatrix}\dot{s}_d\\ \dot{s}_q\end{bmatrix}=\begin{bmatrix}-\varepsilon_1\,\mathrm{sgn}(s_d)-\eta_1 s_d\\ -\varepsilon_2\,\mathrm{sgn}(s_q)-\eta_2 s_q\end{bmatrix}. \quad (7)$$

where ε_1 and ε_2 are the switching gains of the d–q axis sliding surfaces and η_1 and η_2 are the exponent coefficients of the d–q axis sliding surfaces.

D. Continuous Switching Function

The sign functions in the reaching law (7) can be replaced by a continuous smoothing function to alleviate the high frequency chattering resulting from the sliding mode motion.

$$\mathrm{sgn}(s_{d,q})\approx\frac{s_{d,q}}{|s_{d,q}|+\delta_{d,q}}. \quad (8)$$

where $\delta_{d,q}$ is the smoothing coefficient of either the d-axis or the q-axis smoothing function.

E. Control Law

With E_1 and E_2 as disturbance terms, the current sliding mode control law can be derived from (4) to (8) as follows:

$$\boldsymbol{u}=\begin{bmatrix}u_d\\ u_q\end{bmatrix}=\begin{bmatrix}-\frac{1}{B_1}\left[(c_1+A_1)e_d+A_{12}e_q+\varepsilon_1\,\mathrm{sgn}(s_d)+\eta_1 s_d\right]\\ -\frac{1}{B_2}\left[(c_2+A_2)e_q+A_{21}e_d+\varepsilon_2\,\mathrm{sgn}(s_q)+\eta_2 s_q\right]\end{bmatrix}. \quad (9)$$

F. Stability Analysis

According to Lyapunov's Stability Theory, the sliding mode existence and accessibility condition is expressed as

$$\dot{V}(x)=\boldsymbol{s}^{\mathrm{T}}\dot{\boldsymbol{s}}<0. \quad (10)$$

Substituting (4) to (9) into (10) yields

$$\varepsilon_1>|E_1| \quad \text{and} \quad \varepsilon_2>|E_2|. \quad (11)$$

So it can be seen that the minimum switching gain in the control law (9) only changes with parameter perturbation and load disturbances can it meet the condition (11). However, a greater switching gain may intensify the system chattering, while a smaller one may slow down the dynamic responses. Therefore, we should weigh between these two conditions in order to choose an appropriate value for the switching gain.

In a word, the structure diagram of the current sliding mode controller designed in this paper is shown in Fig. 1.

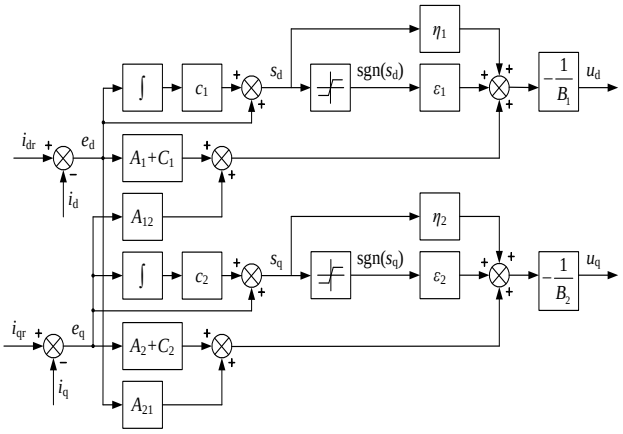


Fig. 1. Structure diagram of current sliding mode controller.

IV. Parameter Setting with Gain-Scheduled Method

A. Gain-Scheduled Rules

If $\varepsilon_i(i=1,2)$ is greater, the system state will reach the sliding surface more quickly, which may cause greater system chattering, or the system chattering may be smaller, but it will take longer time for the system state to reach the sliding surface.

Thus, the gain-scheduled rule with regard to the switching gain ε_i can be described as follows: a smaller ε_i is used near the sliding surface in order to alleviate the system chattering, while a greater ε_i is selected far away from the sliding surface so as for quick approach.

To increase $c_i (i = 1, 2)$ will be beneficial to reduce the static errors and increase the control precision. However, if c_i is too great, the rate of the control variable may be so high that the system chattering will be intensified. Furthermore, the controller may be saturated leading to deteriorated dynamic responses and system vibration.

Consequently, the gain-scheduled rule with regard to the sliding surface coefficient $c_i$can be defined as follows: a smaller c_i is chosen near the sliding surface in order to avoid the controller saturation, while a greater c_i is selected far away from the sliding surface so as to eliminate the system errors.

B. Adaptive Adjusting of Switching Gain Boundaries

The sliding mode existence and accessibility condition (11) can be rewritten as:

$$\varepsilon_1' > E_1' \quad \text{and} \quad \varepsilon_2' > E_2' \tag{12}$$

where $\varepsilon_1' = -B_1^{-1}\varepsilon_1$, $E_1' = R_s i_{dr} - L_q i_{qr}\omega_e$, $\varepsilon_2' = -B_2^{-1}\varepsilon_2$, $E_2' = R_s i_{qr} + (L_d i_{dr} + \psi_f)\omega_e$.

In the motor mode, the reference commands of the d-axis current $i_{dr} < 0$, and the reference commands of the q-axis current $i_{qr} > 0$. The electromagnetic parameters of PMSM are designed as $L_d i_{dr} + \psi_f > 0$ generally. The smaller terms $R_s i_{dr}$ and $R_s i_{qr}$ in the disturbance terms E_1' and E_2' can be neglected. Then it follows that $E_1' < 0$ and $E_2' > 0$. Thus, according to (12), it is evident that the boundaries of the d-axis switching gain ε_1' are not related to E_1' , and the boundaries of the q-axis switching gain ε_2' are limited by E_2'. Furthermore, if ε_2' is too small, the robustness of the sliding mode control system can not be guaranteed. And if ε_2' is too great, it will not contribute to alleviating the system chattering.

In view of the above reasons, the boundaries of the switching gain ε_2' are adjusted in an adaptive method according to the reference command of the d-axis current i_{dr} and the electrical angular speed ω_e in this paper. The adaptive adjustment law with regard to the boundary ε_{2m}' of the switching gain ε_2' is designed as

$$\varepsilon_{2m}' = k_s (L_d i_{dr} + \psi_f)\omega_e \tag{13}$$

where k_s is the adjustment coefficient of the switching gain boundary (a constant greater than 1.0).

On the premise of the sliding mode existence and accessibility condition (12), with the consideration of the parameter changes, external disturbances and speed error, to weigh between the system chattering and the adjusting time, the adjustment coefficient k_s is confined to 1.3-2.2. Hence, the boundary layers of the q-axis switching gain ε_2' can be expressed as

$$\begin{cases} \varepsilon_{2\min}' = 1.3(L_d i_{dr} + \psi_f)\omega_e \\ \varepsilon_{2\max}' = 2.2(L_d i_{dr} + \psi_f)\omega_e \end{cases} \tag{14}$$

C. Gain-Scheduling of Control Parameters

In the constant torque operation area of PMSM, the sliding mode control law (9) can be described as a uniform mathematical model, where the problem of field- weakening control will not be discussed in this paper. Consequently, the gain-scheduled method in the paper is referred to the parameter gain-scheduling of a uniform global sliding mode controller, but not the network gain-scheduling of several local sliding mode controllers. In this method, the boundary layers of the control parameters are determined with a proper adjusting method, and the control parameters are gain-scheduled within the allowed boundary layers with a proper interpolation method. It is not necessary to determine the typical operation points and to optimize the parameters in all the operation points through a lot of simulation and experiments.

In a word, if the absolute value function of the q-axis sliding surface $|s_q|$ is regarded as a scheduling variable, and the switching gain ε_2' is confined to the allowed boundary layers $[\varepsilon_{2\min}', \ \varepsilon_{2\max}']$, then a gain-scheduled rule with regard to the d-axis switching gain ε_2' can be set as follows:

$$\begin{aligned} \varepsilon_2' &= (\varepsilon_{2\max}' - \varepsilon_{2\min}')\text{sat}(|s_q|) + \varepsilon_{2\min}' \\ &= \begin{cases} \varepsilon_{2\max}' & s_q > s_{qmax} \\ (\varepsilon_{2\max}' - \varepsilon_{2\min}')\dfrac{|s_q|}{s_{qmax}} + \varepsilon_{2\min}' & |s_q| \le s_{qmax} \\ \varepsilon_{2\min}' & s_q < -s_{qmax} \end{cases} \end{aligned} \tag{15}$$

where s_{qmax} is the maximum value of the q-axis scheduling variable $|s_q|$. The relationship between the switching gain ε_2' and the scheduling variable $|s_q|$ is shown in Fig. 2.

Similarly, a gain-scheduled rule with regard to the d-axis switching gain ε_1' can be regulated as follows

$$\begin{aligned} \varepsilon_1' &= (\varepsilon_{1\max}' - \varepsilon_{1\min}')\text{sat}(|s_d|) + \varepsilon_{1\min}' \\ &= \begin{cases} \varepsilon_{1\max}' & s_d > s_{dmax} \\ (\varepsilon_{1\max}' - \varepsilon_{1\min}')\dfrac{|s_d|}{s_{dmax}} + \varepsilon_{1\min}' & |s_d| \le s_{dmax} \\ \varepsilon_{1\min}' & s_d < -s_{dmax} \end{cases} \end{aligned} \tag{16}$$

where s_{dmax} is the maximum value of the d-axis scheduling variable $|s_d|$, and $\varepsilon_{1\max}'$ and $\varepsilon_{1\min}'$ are separately the upper and lower boundary layers of the d-axis switching gain ε_1' .

As mentioned above, a gain-scheduled rule with regard to the d-q axis sliding surfaces c_1' and c_2' can be designed as follows

$$\begin{cases} c_1' = (c_{1\max}' - c_{1\min}')\text{sat}(|s_d|) + c_{1\min}' \\ c_2' = (c_{2\max}' - c_{2\min}')\text{sat}(|s_q|) + c_{2\min}' \end{cases} \quad (17)$$

where $c_1' = -B_1^{-1}c_1$, $c_2' = -B_2^{-1}c_2$, $c_{1\max}'$ and $c_{1\min}'$ are separately the upper and lower boundary layers of the d-axis sliding surface coefficient c_1', and $c_{2\max}'$ and $c_{2\min}'$ are separately the upper and lower boundary layers of the q-axis sliding surface coefficient c_2'.

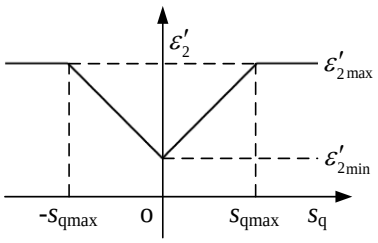


Fig. 2. Relationship between switching gain and scheduling variable.

V. Simulation Results and Analysis

A simulation model of the PMSM drive and control system (Fig. 3) is built and examined in MATLAB.

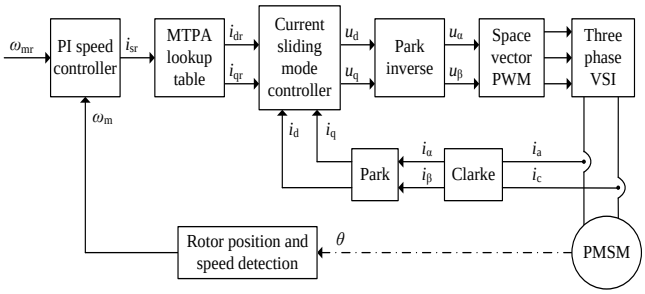


Fig. 3. Structural diagram of the system simulation model.

The PI control method is applied to the speed outer loop in the system model. The speed controller provides current command i_{sr}, which is distributed into d–q axis current commands i_{dr} and i_{qr} according to the maximum torque per ampere (MTPA) vector control rule. The exponent reaching law based SMC method is employed in the current inner loop with the gain-scheduled switching gain.

The main parameters of PMSM are as follows: the output power is 30kW, the rated speed is 4500r/min, the rated torque is 72N m, the d-q axis inductances L_d and L_q are 0.13mH and 0.33mH, the rotor flux linkage ψ_f is 0.062Wb, and the number of pole pairs is 4.

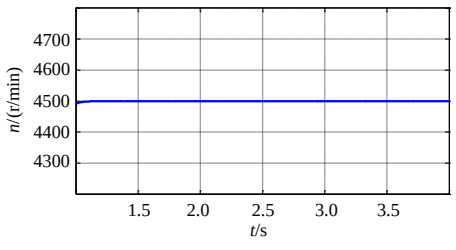
The key parameters of the designed sliding mode controller are shown in Table I.

TABLE I: Parameters of SMC

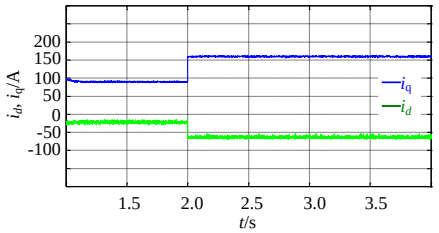
Parameters	Values
$[\varepsilon_{1\min}', \ \varepsilon_{1\max}']$	[0, 185.0]
k_s	[1.3, 2.2]
$[c_{1\min}', \ c_{1\max}']$	[0, 0.08]
$[c_{2\min}', \ c_{2\max}']$	[0, 0.12]

Fig. 4 shows the simulation curves of the current tracking responses of step load under a speed command of 4500 r/min. When the load torque changes abruptly from 36 N m to 72 N m at t=2.0 s, the q–axis current control error and its scheduling variable $|s_q|$ get greater, and hence the switching gain ε_2' and the sliding surface coefficient c_2' get smaller. Then, the q–axis current control error and its scheduling variable $|s_q|$ decay to zero rapidly, and so the sliding surface coefficient c_2' returns to the original value quickly, while the adaptive boundary layers of the switching gain ε_2' decrease with the increasing of $|i_{dr}|$. Thus, in the dynamic process of the current tracking, the SMC parameters are consistent with the defined gain-scheduled rules, and the current and speed response quickly without any significant overshoot, so the designed current SMC has good current tracking performances.

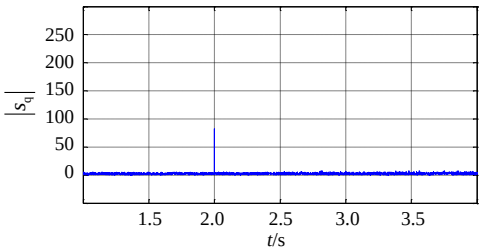
The simulation curves of the speed tracking responses of accelerating are illustrated in Fig. 5 with the load torque of 72 N m. When the step speed command changes suddenly from 1500 r/min to 4500 r/min 72 N m at t=1.5 s, the outputs of the speed controller $|i_{dr}|$ and i_{qr} get greater. And thus the q–axis current control error and its scheduling variable $|s_q|$ get greater, so the switching gain ε_2' and the sliding surface coefficient c_2' get smaller. Then, because the response of the current loop is much quicker than that of the speed loop, the q–axis current control error and its scheduling variable $|s_q|$ decay to zero rapidly, and hence the sliding surface coefficient c_2' returns to the original value quickly. Next, the adaptive boundary layers of the switching gain ε_2' increase with the increasing of the speed until the speed approaches the speed command finally. Consequently, in the dynamic process of the speed tracking, the SMC parameters are consistent with the defined gain-scheduled rules, and the current and speed response quickly without any significant overshoot, so the designed current SMC has good speed tracking performances.



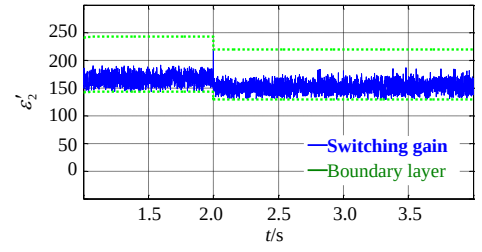
(a)



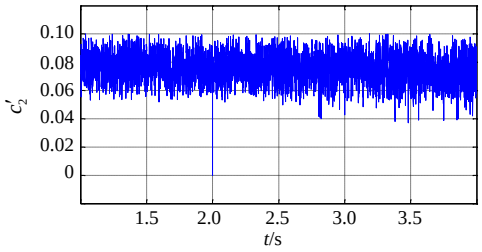
(b)



(c)

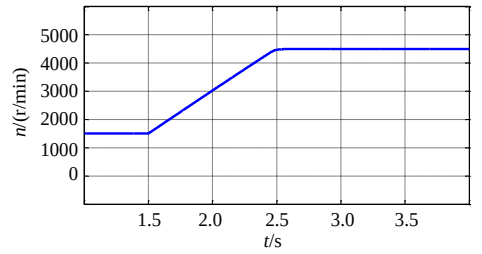


(d)

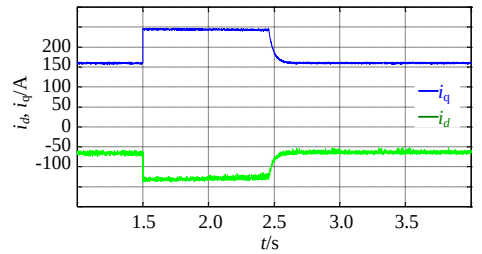


(e)

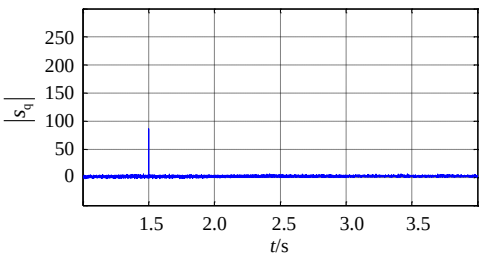
Fig. 4. Responses of loading. (a) speed response. (b) current responses. (c) scheduling variable response. (d) switching gain response. (e) sliding surface coefficient.



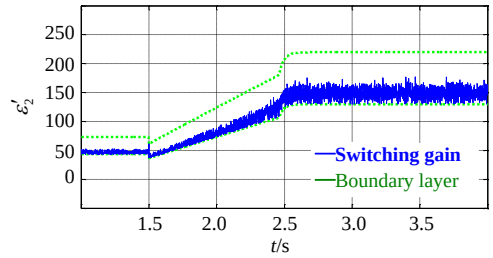
(a)



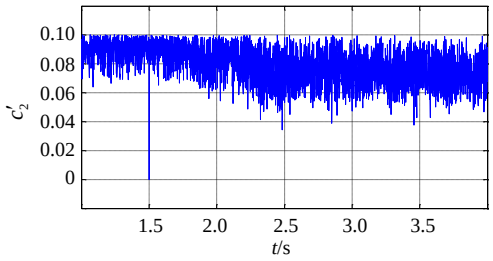
(b)



(c)



(d)



(e)

Fig. 5. Responses of accelerating. (a) speed response. (b) current responses. (c) scheduling variable response. (d) switching gain response. (e) sliding surface coefficient.

VI. Conclusion

The structures and parameters of the sliding mode controller should change with the operating conditions and external environment in order to obtain satisfactory control performances in the global operation range. Gain-scheduled control is an effective method to solve this problem. A novel SMC method with gain-scheduled parameters was developed for PMSM in this paper. The designed controller has the following characteristics:

1) The SMC can be described as a uniform mathematical model in the related operation range.
2) The boundary layers of the switching gains were adjusted on-line with the adaptive method, which was not necessary to determine the typical operation points and optimize a large number of parameters in all the operation points as the regular gain-scheduled one was.
3) The switching gains and the sliding surface coefficients were tuned in real time within the allowed boundary layers with the sliding surfaces as scheduling variables, so the system obtains good control performances in the global operation range.

References

[1] V. I. Utkin, *Sliding Modes in Control and Optimization*, Berlin: Springer-Verlag, 1992, ch. 7.

[2] C. F. Zhang, Y. N. Wang, and J. He, "Variable strcture intelligent control for PM synchronous servo motor drive," in *Proc. the CSEE*, Jul. 2002, vol. 22, no. 7, pp. 13-17.

[3] H. B. Wang, B. Zhou, and S. C. Fang, "A PMSM sliding mode control system based on exponential reaching law," *Transanctions of China Electrotechnical Society*, vol. 24, no. 9, pp. 71-77, Sep. 2009.

[4] S. Seshagiri and H. K. Khalil, "Robust output feedback regulation of minimum-phase nonlinear aystems using conditional integrators," *Automatica*, vol. 41, pp. 43-54, 2005.

[5] K. W. Tong, X. Zhang, Y. Zhang, Z. Xie, and R. X. Cao, "Sliding mode variable structure control of permanent magnet synchronous machine based on a novel reaching law," in *Proc. the CSEE*, Jul. 2008, vol. 28, no. 21, pp. 102-106.

[6] Y. Liu, B. Zhou, and S. C. Fang, "Sliding mode control of PMSM based on a novel disturbance observer," in *Proc. the CSEE*, Mar. 2010,vol. 30, no. 9, pp. 80-85.

[7] W. Q. Lu, Y.W. Hu, J. Y. Liang, and W. X. Huang, "Anti-disturbance adaptive control for permanent magnet synchronous motor servo system," in *Proc. the CSEE*, Jan. 2011, vol. 31, no. 3, pp. 75-81.

[8] X. G. Zhang, L. Sun, and K. Zhao, "Sliding mode control of PMSM based on a novel load torque sliding mode observer," in *Proc. the CSEE*, Jan. 2012, vol. 32, no. 3, pp. 111-116.

[9] Z. Y. Huang, D. H. Li, X. Z. Jiang, and L. M. Sun, "Gain scheduled servo system for boiler-turbine unit," in *Proc. the CSEE*, Oct. 2003, vol. 23, no. 10, pp. 191-198.

[10] T. J. Zhang, J. H. Lv, and Z. G. Hua, "Fuzzy gain scheduled model predictive control for boiler-turbine coordinated system," in *Proc. the CSEE*, Feb. 2005, vol. 25, no. 4, pp. 158-165.

[11] J. X. Lin, J. Shen, and Y. G. Li, "Fuzzy gain scheduled H∞ robust control for boiler-turbine coordinated system based on immune optimization," in *Proc. the CSEE*, Jun. 2008, vol. 28, no. 17, pp. 92-98.

[12] X. X. Fan, Y. Bai, Y.G. Lv, and D. P. Xu, "Linear quadratic Gaussian optimal control strategy for large wind turbine," in *Proc. the CSEE*, Jul. 2010, vol. 30, no. 20, pp. 100-105.

[13] H. L. Xin and J. B. Ho, "Performance comparison for new gain-scheduling variable structure controllers," *Control and Design*, vol. 24, no. 5, pp. 769-772, May 2009

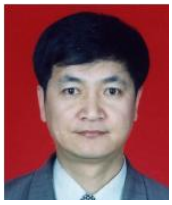
[14] H. L. Xin and J. B. Ho, "The gain-scheduled variable-structure tracking control of nonlinear systems with dead-zones and norm-bounded uncertainties," *Control Theory and Applications*, vol. 27, no. 6, pp. 708-714, Jun. 2010

[15] Y. Shen, Y. Y. Qiu, and B. Y. Ma, "Design of sliding-mode controller with gain-scheduling integral switched term," *System Engineering and Electronics*, vol. 33, no. 9, pp. 2079-2084, Sep. 2011

[16] H. L. Xin and J. B. Ho, "A new design method for gain-scheduling variable structure controllers," *Control and Design*, vol. 26, no. 12, pp. 1824-1828, p. 1834, Dec. 2011.



Ningzhi Jin was born in Harbin, China, in 1980. He received his B.S., M.S., and Ph.D. degrees in electrical engineering from Harbin University of Science and Technology, Harbin, China, in 2003, 2006, and 2012, respectively. He is a lecturer of power electronics and power drive in Harbin University of Science and Technology. His research interests include motor drive and power electronics.



Xudong Wang was born in Jixi, China, in 1956. He received his B.S. and M.S. degrees in electrical engineering from the Harbin Institute of Electrical Engineering, Harbin, China, in 1982 and 1987, respectively, and his Ph.D. degree in mechanical electronics from the Harbin Institute of Technology, Harbin, China, in 2000. He is a professor and doctor supervisor of power electronics and power drive in Harbin University of Science and Technology. Prof. Wang has been the director of the Engineering Research Center of the Automotive Electronic Drive Control and System Integration of the Ministry of Education in China since 2006. His research interests include automotive electronics and the traction motors and drives of electric vehicles.