

Sensorless Back Stepping Control for a Five-Phase Permanent Magnet Synchronous Motor Drive Based on Sliding Mode Observer

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Abstract This paper presents the development of a speed control technique for a five-phase permanent magnet synchronous motor drive (PMSM) based on sliding mode observer (SMO) and back stepping controller. The design of back stepping controller is detailed. The stability of the closed-loop system is demonstrated in the context of Lyapunov theorem. In order to apply a sensorless five-phase PMSM control, a SMO is used which estimates the rotor speed and the rotor position. Simulation results are reported to prove the efficacy of the proposed strategy in closed loop.

Keywords Back stepping control · Five-phase PMSM · Lyapunov stability Multiphase · Sliding mode observer

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1 Introduction

During the last years, multiphase drives have gained interest for their advantages. Among their features are reduction of torque pulsations and reducing stator phase current [1–3]. The high phase order offers greater fault tolerance. Recently, PMSM has acquired interest [4, 5]. The advantages of this type of machine are numerous, among which we can mention: low inertia, robust and low maintenance cost [3, 4]. Various methodologies to achieve the control of multiphase motor drives are presented in the literature. The most famous one is the vector control [6] which has been used in most industrial drive applications due to its applicability and simplicity. Nevertheless, the five-phase PMSM is a highly nonlinear system so that the vector control, based on conventional PI and PID regulators, fails to achieve the high performance requirements of industrial applications. To compensate for the effects of nonlinearity, many nonlinear control strategies have been developed to control PMSM drives such as sliding mode control [7], the direct torque control [8] and the back stepping control [9–12]. Recently, back stepping control technique is widely developed and studied. A back stepping controller is known as a recursive and systematic design with the flexibility to avoid cancellations of useful nonlinearity [13]. It is a robust and powerful methodology that has been studied in the last two decades. Numerous researches have been focused on the back stepping controller to three-phase PMSM [9–11]. In [9], an adaptive backstepping technique is designed to achieve the sensorless control of PMSM supplied by a current source inverter. The control system is based on the adaptive backstepping observer and adaptive backstepping controller. In [10], an improved direct torque control method of three-phase PMSM based on backstepping control with a recursive least squares algorithm to identify machine parameters is presented. Another new adaptive nonlinear backstepping controller is proposed to compensate the unknown system parameters [11]. Furthermore, a novel trajectory generator is designed to constrain the motor reference current. Several research activities were dedicated to the concept of sensorless control technique of three-phase PMSM drives. One of the known classes of nonlinear observers is the sliding mode observer which possesses many special characteristics, namely order reduction control, simple algorithm and disturbance rejection. Numerous papers were dedicated to the observation of PMSM based on SMO [14, 15].

In this paper, the sensorless backstepping controller of five-phase permanent magnet synchronous motor drive is proposed. This paper is organized in five sections including the introduction as follows. Section 2 introduces the model of five-phase PMSM. Then the backstepping controller is discussed in Sect. 3. Section 4 deals with simulation results and the conclusions are presented in Sect. 5.

2 Model of a Five-Phase PMSM

The five-phase PMSM model can be given in a decoupled rotating frame ($d_1q_1 - d_3q_3$) [4]:

$$\begin{cases} \frac{dI_{d1}}{dt} = -b_1 I_{d1} + \omega_e I_{q1} + \frac{1}{L_p} v_{d1} \\ \frac{dI_{q1}}{dt} = -b_1 I_{q1} - \omega_e I_{d1} - b_2 \omega_e + \frac{1}{L_p} v_{q1} \\ \frac{dI_{d3}}{dt} = -b_3 I_{d3} + 3\omega_e I_{q3} + \frac{1}{L_s} v_{d3} \\ \frac{dI_{q3}}{dt} = -b_3 I_{q3} - 3\omega_e I_{d3} + \frac{1}{L_s} v_{q3} \\ \frac{d\Omega}{dt} = \frac{1}{J} \left(\sqrt{\frac{5}{2}} \Phi_f P I_{qp} - T_l \right) - \frac{f}{J} \Omega \end{cases} \quad (1)$$

where

$(I_{d1}, I_{q1}, I_{d3}, I_{q3})$: stator currents in $(d_1 - q_1 - d_3 - q_3)$ frame.

$(v_{d1}, v_{q1}, v_{d3}, v_{q3})$: stator voltages in $(d_1 - q_1 - d_3 - q_3)$ frame.

Ω and ω_e are the mechanical and electrical speed respectively. J , f and Φ_f are the inertia moment, the friction coefficient and amplitude of magnet flux respectively. P pair poles and T_l load torque.

$$b_1 = \frac{R_s}{L_p}; b_2 = \frac{\sqrt{\frac{5}{2}} \Phi_f}{L_p}; b_3 = \frac{R_s}{L_s}$$

R_s is stator resistance, L_p and L_s are the inductances of the main fictitious machine and secondary fictitious machine respectively

Equation (1) can be written as:

$$\begin{cases} \frac{dI_{d1}}{dt} = g_1 + \frac{1}{L_p} v_{d1} \\ \frac{dI_{q1}}{dt} = g_2 + \frac{1}{L_p} v_{q1} \\ \frac{dI_{d3}}{dt} = g_3 + \frac{1}{L_s} v_{d3} \\ \frac{dI_{q3}}{dt} = g_4 + \frac{1}{L_s} v_{q3} \\ \frac{d\Omega}{dt} = g_5 \end{cases} \quad (2)$$

where

$$\begin{cases} g_1 = -b_1 I_{d1} + \omega_e I_{q1} \\ g_2 = -b_1 I_{q1} - \omega_e I_{d1} - b_2 \omega_e \\ g_3 = -b_3 I_{d3} + 3\omega_e I_{q3} \\ g_4 = -b_3 I_{q3} - 3\omega_e I_{d3} \\ g_5 = b_4 I_{qp} - \frac{1}{J} T_l - b_5 \Omega \end{cases} \quad (3)$$

where

$$b_4 = \frac{\sqrt{\frac{5}{2}} \Phi_f P}{J}; \quad b_5 = \frac{f}{J}$$

The control objective is to make the mechanical speed Ω track desired reference Ω_c : such a tracking can be achieved through a backstepping controller algorithm. The stator voltages are $(v_{d1}, v_{q1}, v_{d3}, v_{q3})$ considered as inputs.

3 Speed Backstepping Controller

The basic idea of the backstepping control strategy is to make the complex non-linear closed-loop system equivalent in cascade subsystems of order one. The stability is provided by Lyapunov strategy. The synthesis of the backstepping controller proceeds in two steps.

3.1 Calculation of Current References

The system should follow the trajectory for output variable. The speed error is defined by:

$$e_1 = \Omega_c - \Omega \quad (4)$$

The derivative with respect to time of Eq. (4) gives:

$$\dot{e}_1 = \dot{\Omega}_c - \dot{\Omega} \quad (5)$$

Accounting for Eqs. (2), (5) can be written as:

$$\dot{e}_1 = \dot{\Omega}_c - g_5 \quad (6)$$

In order to check the tracking performances, let us define the first Lyapunov function v_1 associated with speed error, such as:

$$v_1 = \frac{1}{2} e_1^2 \quad (7)$$

Using Eq. (6), the derivative of Eq. (7) is given by:

$$\dot{v}_1 = e_1(\dot{\Omega}_c - g_5) \quad (8)$$

Equation (8) can be rewritten as follows:

$$\dot{v}_1 = e_1(\dot{\Omega}_c - g_5) = -k_1 e_1^2 \quad (9)$$

where $k_1 > 0$, which gives:

$$\dot{e}_1 = \dot{\Omega}_c - \dot{\Omega} = -k_1 e_1 \quad (10)$$

The q_1 axis current contributes towards torque whereas d_1 , d_3 and q_3 current components do not. This allows maintaining d_1 axis current, d_3 axis current and q_3 axis current equals to zero in order to obtain maximum average torque for given copper losses [2].

The references currents then are given by:

$$\begin{cases} (I_{q1})_c = (\dot{\Omega}_c + \frac{1}{J} T_l + b_5 \Omega + k_1 e_1) / b_4 \\ (I_{d1})_c = 0 \\ (I_{q3})_c = 0 \\ (I_{d3})_c = 0 \end{cases} \quad (11)$$

3.2 Calculation of Currents References

The aim is to obtain the references current obtained by the previous step. The stator current errors are defined as:

$$\begin{cases} e_2 = (I_{q1})_c - I_{q1} \\ e_3 = (I_{d1})_c - I_{d1} \\ e_4 = (I_{d3})_c - I_{d3} \\ e_5 = (I_{q3})_c - I_{q3} \end{cases} \quad (12)$$

Considering Eqs. (11), (12) is given by:

$$\begin{cases} e_2 = (\dot{\Omega}_c + \frac{1}{J}T_l + b_5\Omega + k_1e_1)/b_4 - I_{q1} \\ e_3 = -I_{d1} \\ e_4 = -I_{d3} \\ e_5 = -I_{q3} \end{cases} \quad (13)$$

Using Eqs. (13), (6) can be given as:

$$\dot{e}_1 = b_4e_2 - k_1e_1 \quad (14)$$

The derivative of Eq. (14) gives:

$$\begin{cases} \dot{e}_2 = (\dot{I}_{q1})_c - \dot{I}_{q1} \\ \dot{e}_3 = (\dot{I}_{d1})_c - \dot{I}_{d1} \\ \dot{e}_4 = (\dot{I}_{d3})_c - \dot{I}_{d3} \\ \dot{e}_5 = (\dot{I}_{q3})_c - \dot{I}_{q3} \end{cases} \quad (15)$$

By substituting Eq. (2) in Eq. (15), one obtains:

$$\begin{cases} \dot{e}_2 = (\dot{I}_{q1})_c - \dot{I}_{q1} = (\dot{I}_{q1})_c - g_2 - \frac{1}{L_p}v_{q1} \\ \dot{e}_3 = (\dot{I}_{d1})_c - \dot{I}_{d1} = (\dot{I}_{d1})_c - g_1 - \frac{1}{L_p}v_{d1} \\ \dot{e}_4 = (\dot{I}_3)_c - \dot{I}_{d3} = (\dot{I}_{d3})_c - g_3 - \frac{1}{L_s}v_{d3} \\ \dot{e}_5 = (\dot{I}_{q3})_c - \dot{I}_{q3} = (\dot{I}_{q3})_c - g_4 - \frac{1}{L_s}v_{q3} \end{cases} \quad (16)$$

In order to prove the stability of the overall system, let us choose a new Lyapunov function defined as:

$$v_2 = \frac{e_1^2 + e_2^2 + e_3^2 + e_4^2 + e_5^2}{2} \quad (17)$$

The derivative of Eq. (17) is given by:

$$\begin{aligned} \dot{v}_2 = & -k_1e_1^2 - k_2e_2^2 - k_3e_3^2 - k_4e_4^2 - k_5e_5^2 \\ & + e_2 \left(k_2e_2 + a_4e_1 + (\dot{I}_{q1})_c - g_2 - \frac{1}{L_p}v_{q1} \right) + e_3 \left(k_3e_3 + (\dot{I}_{d1})_c - g_1 - \frac{1}{L_p}v_{d1} \right) \\ & + e_4 \left(k_4e_4 + (\dot{I}_{d3})_c - g_3 - \frac{1}{L_s}v_{d3} \right) + e_5 \left(k_5e_5 + (\dot{I}_{q3})_c - g_4 - \frac{1}{L_s}v_{q3} \right) \end{aligned} \quad (18)$$

The derivative of the whole Lyapunov function Eq. (18) is negative, if the quantities between parentheses in the same equation are equal to zero.

$$\begin{cases} k_2 e_2 + b_4 e_1 + (\dot{I}_{q1})_c - g_2 - \frac{1}{L_p} v_{q1} = 0 \\ k_3 e_3 + (\dot{I}_{d1})_c - g_1 - \frac{1}{L_p} v_{d1} = 0 \\ k_4 e_4 + (\dot{I}_{d3})_c - g_3 - \frac{1}{L_s} v_{d3} = 0 \\ k_5 e_5 + (\dot{I}_{q3})_c - g_4 - \frac{1}{L_s} v_{q3} = 0 \end{cases} \quad (19)$$

The stator voltages are given by:

$$\begin{cases} v_{q1} = L_p (k_2 e_2 + b_4 e_1 + (\dot{I}_{q1})_c - g_2) \\ v_{d1} = L_p (k_3 e_3 + (\dot{I}_{d1})_c - g_1) \\ v_{d3} = L_s (k_4 e_4 + (\dot{I}_{d3})_c - g_3) \\ v_{q3} = L_s (k_5 e_5 + (\dot{I}_{q3})_c - g_4) \end{cases} \quad (20)$$

where k_2 , k_3 , k_4 and k_5 , are positive constants.

The synthesis of back stepping controller requires the rotor position and rotor speed information. So that the speed and rotor speed transducers should be installed in the shaft. However, these sensors are sensitive to environment conditions and increase the system cost. The algorithm-based sliding mode observer used in this work was developed with details in [2] but not described in this paper. The sliding mode observer was applied to five-phase PMSM to estimate the rotor speed and the rotor position. For more details refer to [2].

4 Simulation Results

A MATLAB/Simulink environment was used to simulate the feedback back stepping control based on SMO.

The corresponding results under the two different profiles: reversing transient and low speed are illustrated by Figs. 1 and 2 respectively. Figure 1 illustrates the drive performance to reversing the speed command. Figure 1a shows the reference, estimated and real speed. One notes that the observed speed converges to the reference one with good estimation. It seems clear from Fig. 1b that the developed observer displays good results in terms of speed estimation. Indeed, the estimation error of rotor speed is almost zero in steady state. Figure 1c displays the observed and the actual position. The five-phase PMSM performances at low speed are reported in Fig. 2. The reference speed is set at 10 rad/s. Figure 2a displays the real,

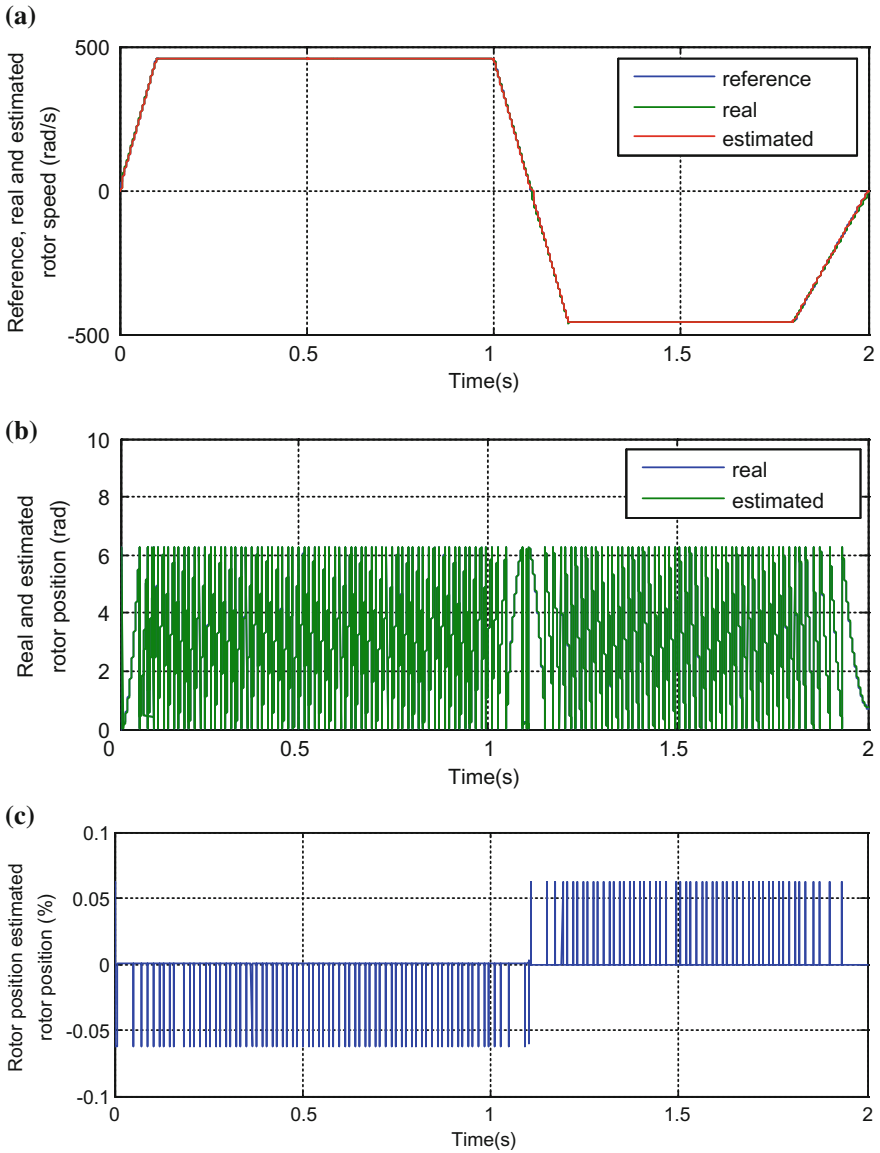


Fig. 1 Performances of five-phase PMSM to speed change: **a** speed; **b** estimation error of rotor speed **c** rotor position

observed and reference rotor speed. We can conclude a good estimation in terms of trajectory tracking. Nevertheless, there is a small estimation error in transient state as shown in Fig. 2b. Figure 2c displays the observed and real rotor position and its estimation error is shown in Fig. 2d. The corresponding results prove the performance of the SMO.

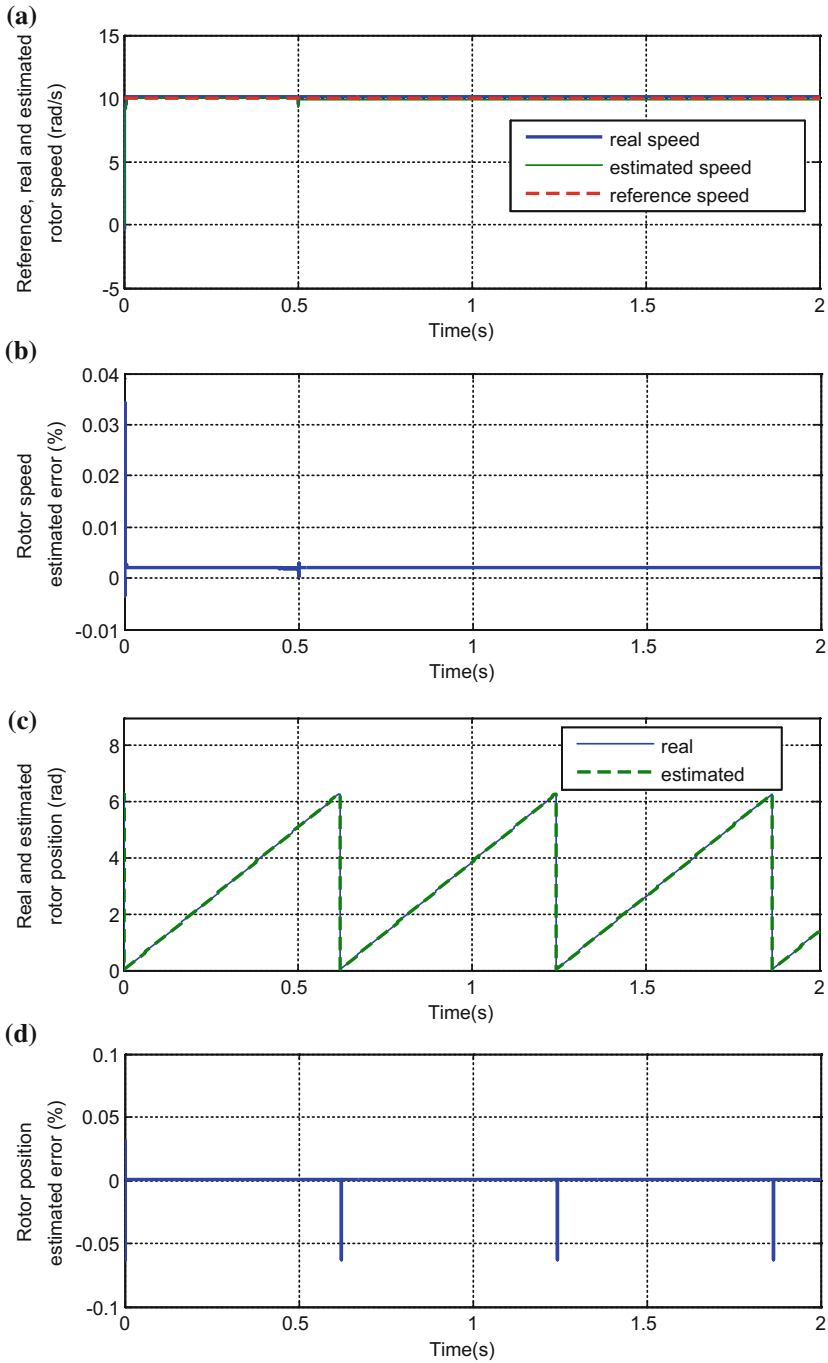


Fig. 2 Performances of five-phase PMSM to speed change: **a** speed; **b** estimation error of rotor speed **c** rotor position, **d** estimation error of rotor position

5 Conclusion

This work presented the sensorless backstepping controller of a five-phase PMSM based on SMO. Developed controller satisfied the stability condition under Lyapunov criterion for both transient and dynamic behaviours. Numerical results verify the developed theoretical background in terms of rotor speed and rotor position estimation under different profiles.

References

1. Hosseyni, A., Trabesi, R., Mimouni, M.F., Iqbal, A.: Vector controlled five-phase permanent magnet synchronous motor drive. In: Conference Proceedings IEEE Indian Symposium on Industrial Electronics IEEE-ISIE'14, Turkey, pp. 2122–2127 (2014)
2. Hosseyni, A., Trabelsi, R., Mimouni, M.F., Iqbal, A., Alammari, R.: Sensorless sliding mode observer for a five-phase permanent magnet synchronous motor drive. *ISA Trans. Elsevier J.* **58**, 462–473 (2015)
3. Guo, L., Parsa, L.: Model reference adaptive control of five-phase IPM Motors based on neural network. *IEEE Trans. Ind. Electron.* **59**(13), 1500–1508 (2012)
4. Parsa, L., Toliyat, H.: Five-phase permanent-magnet motor drives. *IEEE Trans. Ind. Appl.* **41**(11), 30–37 (2005)
5. Mohammadpour, A., Parsa, L.: A unified fault-tolerant current control approach for five-phase pm motors with trapezoidal back Emf under different stator winding connections. *IEEE Trans. Power Electron.* **28**(17), 3517–3527 (2013)
6. AbuRub, H., Iqbal, A., Guzinski, J.: High Performance control of AC Drives with Matlab/Simulink Models. Wiley, West Sussex, United Kingdom (2012)
7. Chang, S.H., Chen, P.Y., Ting, Y.H., Hung, S.W.: Robust current control-based sliding mode control with simple uncertainties estimation in permanent magnet synchronous motor drive systems. *IET. Power Appl.* **4**(6), 441–450 (2010)
8. Changliang, X., Jiabin, Z., Yan, Y., Tingna, S.: A novel direct torque control of matrix converter-fed PMSM drives using duty cycle control for torque ripple reduction. *IEEE Trans. Ind. Electron.* **61**(6), 2700–2713 (2014)
9. Xu, Y., Lei, Y., Sha, D.: Backstepping direct torque control of permanent magnet synchronous motor with RLS parameter identification. In: Proceedings of IEEE International Conference Electrical Machines, IEEE-ICEMS'14, China, pp. 573–578 (2014)
10. Bernat, J., Kolota, J., Stepien, S., Szymanski, G.: Adaptive control of permanent magnet synchronous motor with constrained reference current exploiting backstepping methodology. In: Proceedings of IEEE International Conference Control Applications, IEEE-CCA'14, France, pp. 1545–1550 (2014)
11. Karabacak, M., Eskikurt, H.I.: Speed and current regulation of a permanent magnet synchronous motor via nonlinear and adaptive backstepping control. *Mathematical and Computer Modelling, Elsevier J.* **53**, 2015–2030 (2011)
12. Hsu, C.F.: Adaptive backstepping Elman-based neural control for unknown nonlinear systems. *Neurocomput. Elsevier J.* **136**, 170–179 (2014)
13. Trabelsi, R., Khedher, A., Mimouni, M.F., M'sahli, F.: Backstepping control for an induction motor using an adaptive sliding rotor-flux observer. *Electr. Power Syst. Res. Elsevier J.* **93**, 1–15 (2012)

14. Kim, H., Son, J., Lee, J.: A high-speed sliding-mode observer for the sensorless Speed control of a PMSM. *IEEE Trans. Ind. Electron.* **58**(19), 4069–4077 (2011)
15. Qiao, Z., Shi, T., Wang, Y., Yan, Y., Xia, C., He, X.: New sliding-mode observer for position sensorless control of permanent-magnet synchronous motor. *IEEE Trans. Ind. Electron.* **60**(12), 710–719 (2013)