International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 5, No. 4, April 2015, pp. 512~519
ISSN: 2088-8694

Adaptive Fuzzy Integral Sliding-Mode Regulator for Induction Motor Using Nonlinear Sliding Surface

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Article Info

Article history:

Received Sep 21, 2014
Revised Jan 26, 2015
Accepted Feb 10, 2015

Keyword:

Adaptive fuzzy control term
Induction motor
Integral sliding-mode controller
Nonlinear sliding surface
Speed regulator

ABSTRACT

An adaptive fuzzy integral sliding-mode controller using nonlinear sliding surface is designed for the speed regulator of a field-oriented induction motor drive in this paper. Combining the conventional integral sliding surface with fractional-order integral, a nonlinear sliding surface is proposed for the integral sliding-mode speed control, which can overcome the windup problem and the convergence speed problem. An adaptive fuzzy control term is utilized to approximate the uncertainty. The stability of the controller is analyzed by Lyapunov stability theory. The effectiveness of the proposed speed regulator is demonstrated by the simulation results in comparison with the conventional integral sliding-mode controller based on boundary layer.

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1. INTRODUCTION

Induction motor (IM) has been widely applied in the industrial field owing to its less-maintenance, lower-cost and excellent-reliability. High variable speed performance of induction motor is achieved through field-oriented control (FOC). In field-oriented control (or vector control), the induction motor can be controlled in a manner similar to the control of separately excited DC motor. The major problem of FOC is the sensitivity to large uncertainties which are due to magnetization saturation, temperature variation, load disturbances, etc [1]. In order to improve the performance of speed regulator under uncertainties in mechanical parameters and load torque, many improved speed regulator of FOC were proposed for induction motor drives [1]-[4]. Due to the good robustness, fast dynamics response and easy implementation, the sliding-mode control has been used in the control of induction motor [5]-[7]. But sliding-mode control is suffering from the chattering phenomenon. One effective solution is replacing the sign function by continuous saturation functions [8]. Boundary layer is a popular saturation function at the cost of the increased steady-state tracking error. The investigations on integral sliding-mode controller for induction motor can be found in [9]-[11]. In [9], an integral sliding-mode control strategy using saturation function was used to stabilize speed tracking of each induction motor while synchronizing its speed with the speed of other motors. A sliding-mode controller was presented for sensorless FOC of induction motor with model reference adaptive system in [10], where an integral sliding-mode control using boundary layer was designed. An integral sliding-mode control using boundary layer was adopted for speed controller of induction motor drives with reference model and a Luenberger observer in [11].

However, the windup problem and the convergence speed problem are not discussed in the above integral sliding-mode control strategies for speed regulator of FOC. As mentioned in [12], the integral action may lead to windup problem, and significant overshoot may occur that requires long time for recovery. To eliminate the windup phenomenon for an integral sliding-mode control, the integral action was turned on only when the norm of tracking errors was lower than a predetermined value in [12]. Moreover, it is well-known that the integral action may slow down the convergence speed of tracking error. The derivative action may speed up the convergence speed of tracking error, but as we know the time derivative of mechanical speed (accelerated mechanical speed) is sensitive to the noise and difficult to obtain at present even using improved differentiators such as nonlinear differentiator [13] and sliding mode differentiator [14]. Hence, accelerated mechanical speed is seldom employed in practical speed regulator of FOC. On the other hand, the investigation of fractional-order control has attracted more and more interests. The fractional-order controller is the extension of integer-order controller [15], which introduces extra degrees of freedom. The fractional-order sliding-mode control were discussed in [16] and [17]. A fractional-order integral sliding-mode flux observer was provided to estimate the d- and q-axis fluxes in the stationary reference frame for sensorless vector controlled induction motors in [16]. A fractional-order sliding-mode control scheme based on parameters auto-tuning for the velocity control of permanent magnet synchronous motor was proposed in [17].

The main contribution of this paper lies in the following three aspects: (1) An adaptive fuzzy sliding-mode controller is proposed and successfully applied to the speed regulator of induction motor. (2) Combining the conventional integral sliding surface with fractional-order integral, a nonlinear sliding surface is proposed for the integral sliding-mode speed regulator, which can overcome the windup phenomenon and speed up convergence. (3) The adaptive fuzzy control term based on the nonlinear sliding surface is applied to approximate the uncertainty.

2. DYNAMIC MODEL OF INDUCTION MOTOR

The mathematics model of an induction motor can be written in the rotor rotating reference frame (d-q) [10] as follows:

$$\begin{aligned} \frac{\mathrm{d}\omega_{\mathrm{r}}}{\mathrm{d}t} &= \rho\psi i_{\mathrm{q}} - \beta T_{\mathrm{L}} - \alpha\omega_{\mathrm{r}} \\ \frac{\mathrm{d}\psi}{\mathrm{d}t} &= -a\psi + aL_{\mathrm{m}} i_{\mathrm{d}} \\ \frac{\mathrm{d}i_{\mathrm{q}}}{\mathrm{d}t} &= -\delta i_{\mathrm{q}} - \upsilon\omega_{\mathrm{r}}\psi - \omega i_{\mathrm{d}} + bu_{\mathrm{q}} \\ \frac{\mathrm{d}i_{\mathrm{d}}}{\mathrm{d}t} &= -\delta i_{\mathrm{d}} + \upsilon a\psi + \omega i_{\mathrm{q}} + bu_{\mathrm{d}} \end{aligned} \tag{1}$$

Where $\rho = n_{\mathrm{p}}L_{\mathrm{m}}/(J_{\mathrm{m}}L_{\mathrm{r}})$, $a = R_{\mathrm{r}}/L_{\mathrm{r}}$, $b = 1/(L_{\sigma}L_{\mathrm{S}})$, $\alpha = B_{\mathrm{m}}/J_{\mathrm{m}}$, $\beta = 1/J_{\mathrm{m}}$, $\upsilon = L_{\mathrm{m}}/(L_{\sigma}L_{\mathrm{S}}L_{\mathrm{r}})$, $\delta = (R_{\mathrm{S}}L_{\mathrm{r}}^2 + R_{\mathrm{r}}L_{\mathrm{m}}^2)/(L_{\sigma}L_{\mathrm{S}}L_{\mathrm{r}}^2)$; ω_{r} and ω are the rotor mechanical speed and the synchronous speed; ψ is the rotor flux; L_{m} is the mutual inductance; $L_{\sigma} = 1 - L_{\mathrm{m}}^2/(L_{\mathrm{r}}L_{\mathrm{S}})$ is the motor leakage inductance; i_{d} and i_{q} are the d, q-axis stator currents; R_{r} and L_{r} are the rotor resistance and inductance; R_{S} and L_{S} are the stator resistance and inductance; n_{p} is the number of pole pairs; u_{d} and u_{q} are the d, q-axis stator voltages; T_{L} is the external load torque; J_{m} and B_{m} are the mechanical inertia of moment and the damping torque coefficient; electromagnetic torque of an induction motor is defined as:

$$T_{\mathrm{e}} = n_{\mathrm{p}}L_{\mathrm{m}}\psi i_{\mathrm{q}}/L_{\mathrm{r}} \tag{2}$$

From (1) and (2), one has:

$$\frac{\mathrm{d}\omega_{\mathrm{r}}}{\mathrm{d}t} = -\alpha\omega_{\mathrm{r}} - h + \beta T_{\mathrm{e}} \tag{3}$$

Where $h = T_{\mathrm{L}}/J_{\mathrm{m}}$. Consider the uncertainties in (3), one gets:

$$\frac{\mathrm{d}\omega_{\mathrm{r}}}{\mathrm{d}t} = -(\alpha + \Delta\alpha)\omega_{\mathrm{r}} - (h + \Delta h) + (\beta + \Delta\beta)T_{\mathrm{e}} \tag{4}$$

Where $\Delta\alpha$, Δh and $\Delta\beta$ are the time-varying value of α , h and β ,respectively.

The speed tracking error is defined as:

$$e(t) = \omega_r^*(t) - \omega_r(t) \tag{5}$$

Where ω_r^* is the speed reference.

The time derivative of Equation (5) is:

$$\frac{de(t)}{dt} = -\alpha e(t) - \beta u(t) + \xi(t) + \eta(t) \tag{6}$$

Where $\xi(t) = \alpha\omega_r^*(t) + \frac{d\omega_r^*(t)}{dt} + h(t)$, uncertainty term $\eta(t) = \Delta\alpha\omega_r(t) - \Delta\beta T_e(t) + \Delta h(t)$, $u = T_e$.

The control objective is to find a speed regulator using adaptive fuzzy sliding-mode controller in rotor flux oriented reference frame for the tracking of speed in presence of model uncertainty.

The overall block diagram for a direct field-oriented induction motor drive is shown in Figure 1, which consists of an induction motor (IM), a SPWM voltage source inverter, two current controllers, two coordinate translators, a current model, and a speed regulator using adaptive fuzzy sliding-mode controller based on a novel nonlinear sliding surface.

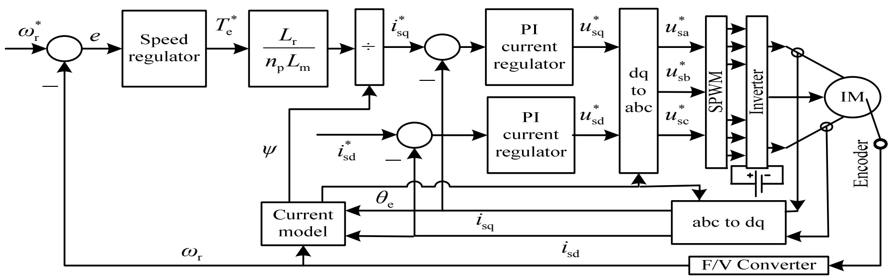

Figure 1. Overall block diagram for a direct field-oriented induction motor drive

3. DESIGN OF ADAPTIVE FUZZY SLIDING-MODE CONTROLLER

The nonlinear sliding surface can be defined as:

$$S = \begin{cases} e + a_1 e_1 & |e| \le \gamma_1 \\ e + a_2 e_2 & \gamma_1 < |e| \le \gamma_2 \\ e & |e| > \gamma_2 \end{cases} \tag{7}$$

Where a_1 , a_2 , γ_1 and γ_2 are positive design parameters, $e_1 = \int_0^t e(\tau)d\tau$, $e_2 = {}_0D_t^v(e)$, ${}_0D_t^v(e)$ is the fractional-order integral operator, $-1 < v < 0$, the conventional integral sliding surface is used in the small speed tracking error interval to eliminate the windup phenomenon.

According to the exponential reaching law:

$$\frac{dS}{dt} = -fS - K\text{sat}(S/\varphi) \tag{8}$$

Where f and K are positive design parameters, $K \ge |\eta(t)|$. The control law can be designed as:

$$u=\begin{cases}J_{\mathrm{m}}[\xi+u_{\mathrm{f}}+fS+K\mathrm{sat}(S/\varphi)]+(J_{\mathrm{m}}-B_{\mathrm{m}})e & |e|\le\gamma_1\\ J_{\mathrm{m}}[\xi+u_{\mathrm{f}}+fS+K\mathrm{sat}(S/\varphi)]+J_{\mathrm{m}}\,{}_0\mathrm{D}_t^{v+1}e-B_{\mathrm{m}}e & \gamma_1<|e|\le\gamma_2\\ -B_{\mathrm{m}}e+J_{\mathrm{m}}\xi+J_{\mathrm{m}}u_{\mathrm{f}}+fJ_{\mathrm{m}}S+KJ_{\mathrm{m}}\mathrm{sat}(S/\varphi) & |e|>\gamma_2\end{cases}\tag{9}$$

Where u_{f} is the adaptive fuzzy control term to approximate the uncertainty term, $\mathrm{sat}(\cdot)$ is the saturation function defined as:

$$\mathrm{sat}(S/\varphi)=\begin{cases}S/\varphi & |S|\le\varphi\\ \mathrm{sgn}(S) & |S|>\varphi\end{cases}\tag{10}$$

Where $\mathrm{sgn}(\cdot)$ is the sign function, φ is the width of boundary layer which can reduce the chattering phenomenon.

The fractional-order derivative control term $J_{\mathrm{m}}\,{}_0\mathrm{D}_t^{v+1}e$ in (9) is used to speed up convergence of speed tracking error. The approximation of fractional-order derivate and integral plays an important role in the fractional-order control. We adopt the integer-order model to approximate the fractional-order derivate and integral in a suitable frequency interval [18]. The fractional-order derivative used in the proposed controller is not sensitive to the noise beyond the selected frequency interval.

The fuzzy input variables of the adaptive fuzzy control term [19], [20] are S and e. By using the singleton fuzzification, product inference engine and center average defuzzification, the adaptive fuzzy control term is given as:

$$u_{\mathrm{f}}=\boldsymbol{b}^{\mathrm{T}}\boldsymbol{w}=\sum_{j=1}^{m}\frac{\prod_{i=1}^{n}\mu_{\mathrm{F}_{ij}}\cdot\hat{u}_j}{\sum_{j=1}^{m}\prod_{i=1}^{n}\mu_{\mathrm{F}_{ij}}}\tag{11}$$

Where $\boldsymbol{b}=[\hat{u}_1,\hat{u}_2,\ldots,\hat{u}_m]^{\mathrm{T}}$ is the consequent parameter vector, $\boldsymbol{w}$ is the vector of fuzzy basis functions, $n=2$, $\mu_{\mathrm{F}_{ij}}$ are the membership functions of input variables, $\hat{u}_j$ is the point in output space of the fuzzy system at which the membership function of output variable achieves its maximum value, m is the number of fuzzy rules.

The parameter vector is adapted according to the following updating law:

$$\frac{\mathrm{d}\boldsymbol{b}}{\mathrm{d}t}=\begin{cases}rS\boldsymbol{w} & ((\|\boldsymbol{b}\|<M_1)\ \text{ or }\ (\|\boldsymbol{b}\|=M_1\ \text{ and }\ S\boldsymbol{b}^{\mathrm{T}}\boldsymbol{w}\le 0))\\ 0 & \text{others}\end{cases}\tag{12}$$

Where r and M_1 are the positive design parameters.

4. STABILITYANALYSIS

The optimal parameter vector is defined as:

$$\boldsymbol{b}_0=\arg\min_{\boldsymbol{b}\in\Omega}[\sup_{\|\boldsymbol{x}\|\le N_1}|\eta(\boldsymbol{x})-u_{\mathrm{f}}|]\tag{13}$$

And λ is defined as the minimal approximation error.

Choose the Lyapunov functions as:

$$V_1=\frac{1}{2}S^2(t)\tag{14}$$

$$V_2=\frac{1}{2}S^2(t)+\frac{1}{2r}\boldsymbol{q}^{\mathrm{T}}(t)\boldsymbol{q}(t)\tag{15}$$

Where $\boldsymbol{q}=\boldsymbol{b}-\boldsymbol{b}_0$.

The derivative of Equation (14) with respect to time is:

$$\frac{\mathrm{d}V_1}{\mathrm{d}t} = S\frac{\mathrm{d}S}{\mathrm{d}t} = S(-fS - K\mathrm{sat}(S/\varphi) + \eta(t)) \tag{16}$$

If $|S| > \varphi$, then:

$$\frac{\mathrm{d}V_1}{\mathrm{d}t} = S(-fS - K\mathrm{sat}(S/\varphi) + \eta(t)) \le -fS^2 - K|S| + |\eta(t)||S| \tag{17}$$

Thus, if the condition of $K \ge |\eta(t)|$ is satisfied, $\frac{\mathrm{d}V_1}{\mathrm{d}t} \le 0$ holds, and $\frac{\mathrm{d}V_1}{\mathrm{d}t} = 0$ only when $S = 0$.

On the other hand, If $|S| \le \varphi$, considering (13), the derivative of Equation (15) with respect to time is:

$$\frac{\mathrm{d}V_2}{\mathrm{d}t} = S\frac{\mathrm{d}S}{\mathrm{d}t} + \frac{1}{r}\boldsymbol{q}^{\mathrm{T}}\frac{\mathrm{d}\boldsymbol{b}}{\mathrm{d}t} \tag{18}$$

From (10) , (11) , (12) and (18), then:

$$\frac{\mathrm{d}V_2}{\mathrm{d}t} = S\frac{\mathrm{d}S}{\mathrm{d}t} + \frac{1}{r}\boldsymbol{q}^{\mathrm{T}}\frac{\mathrm{d}\boldsymbol{b}}{\mathrm{d}t} = S[-fS - K\mathrm{sat}(S/\varphi) + \lambda] = S[-fS - KS/\varphi + \lambda] \tag{19}$$

If the adaptive fuzzy control term is properly designed, λ is sufficiently small, then $\frac{\mathrm{d}V_2}{\mathrm{d}t} \le 0$ holds, and $\frac{\mathrm{d}V_2}{\mathrm{d}t} = 0$ only when $S = 0$. That means Lyapunov function V_2 will decrease gradually and the sliding surface will converge to zero. If the system of sliding surface is stable, the speed tracking error will converge to zero.

5. SIMULATION RESULTS

Simulations are carried out using the Simulink package of MATLAB. The overall control structure for the simulation is shown in Figure 1.The specifications and nominal parameters of motor operated using direct rotor field orientation are given in Table 1 [1].

Table 1. Specifications and Nominal Parameters of an Induction Motor

Motor parameter	Value
Output power (HP)	50
Rated voltage (V)	460
Number of pole pairs (P)	2
Rated frequency (Hz)	60
Stator resistance(Ω)	0.087
Rotor resistance (Ω)	0.228
Stator inductance (mH)	35.5
Rotor inductance (mH)	35.5
Mutual inductance (mH)	34.7
Mechanical inertia of moment(kg•m^2)	2
Damping torque coefficient(N•m•s)	0.2

The operating sequences are described as follows. The initial load torque is constant (0N•m).After the initial constant speed reference of 90rad/s from time *t*=0 to 0.1s. From time *t*=0.1 to 0.25s, the speed reference is increased linearly from 90 to 120rad/s, and then from *t*=0.6 to 0.9s speed reference is decreased from 120 to 90rad/s. At time *t*=1.1s constant load torque (190N•m) is applied.

The values of mechanical inertia of moment J_{m} and damping torque coefficient B_{m} are 0.831kg•m^2 and 0.5N•m•s during the simulation, i.e., there are uncertainties in the mechanical parameters. Simulation tests have been performed in order to compare the dynamic performance of the proposed speed regulator with the conventional integral sliding-mode controller based on boundary layer, i.e., the proposed controller without the nonlinear sliding surface of Equation (7) and the adaptive fuzzy control term of Equation (11).

In the frequency domain, the fractional-order derivative of ${}_0D_t^{v+1}e$ can be expressed as s^{v+1}, where s is the Laplace variable. Figure 2 and Figure 3 show the bode diagram of the fractional-order derivative $s^{0.2}$ in the simulation and the bode diagram of the integer-order derivative s.

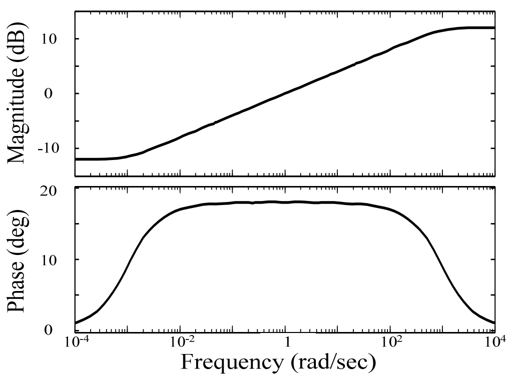

Figure 2. Bode diagram of $s^{0.2}$ in the simulation

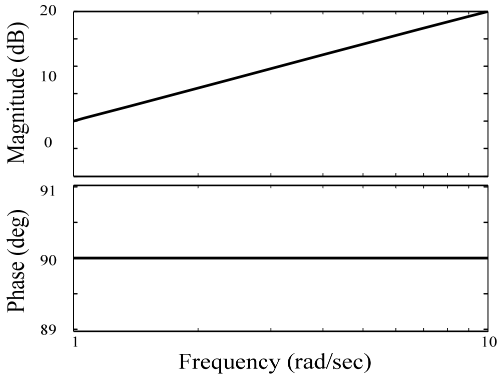

Figure 3. Bode diagram of s

The design parameters of the proposed speed regulator are $v = -0.8$, $\varphi = 1.5$, $\gamma_1 = 1$, $\gamma_2 = 5$, $r = 100$, $M_1 = 20$, $a_1 = 1$, $a_2 = 1$, $f = 1$, $K = 100$ and the fuzzy membership functions of e are designed as:

$\mu_{F_{11}} = \min(1, \max(0, 1 - (4e + 6)/3))$; $\mu_{F_{12}} = \max(0, \min(1 + (4e + 3)/3, 1 - (8e + 6)/3))$;

$\mu_{F_{13}} = \max(0, \min(1 + (8e + 3)/3, 1 - (8e + 3)/3))$; $\mu_{F_{14}} = \max(0, \min(1 + 8e/3, 1 - 8e/3))$;

$\mu_{F_{15}} = \max(0, \min(1 + (8e - 3)/3, 1 - (8e - 3)/3))$; $\mu_{F_{16}} = \max(0, \min(1 + (8e - 6)/3, 1 - (4e - 3)/3))$;

$\mu_{F_{17}} = \min(1, \max(0, 1 + (4e - 6)/3))$.

The fuzzy membership functions of S are the same as those of e. The sliding surface of the compared controller is selected as $S = e + e_1$.

Figure 4 shows the desired motor speed (Dash-dot line), the rotor speed based on the compared controller (Dashed line) and the rotor speed based on the proposed controller (Solid line). It is clear that the rotor speed performance of the proposed controller is better than that of the compared controller after the step change of external load torque.

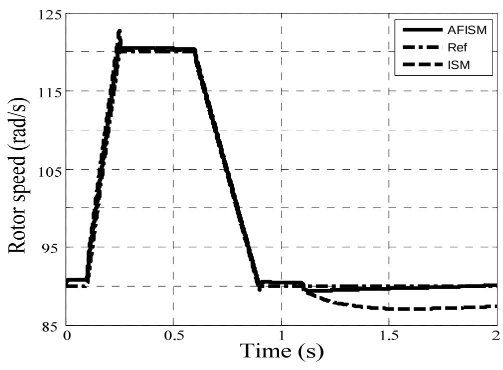

Figure 4. Reference speed and rotor speed response

The performances of the motor torque are illustrated by Figure 5 and Figure 6. It is seen that the motor torques are within reasonable ranges in Figure 5-6.

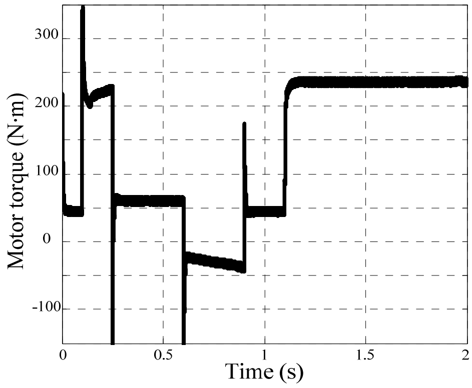

Figure 5. Torque response of the proposed controller

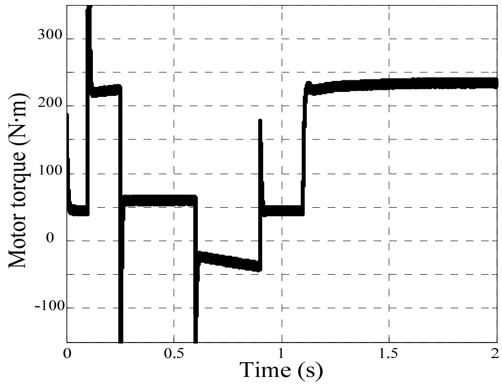

Figure 6. Torque response of the compared controller

The simulation results reveal that the presented method has better tracking performance than the conventional integral sliding-mode controller based on boundary layer under uncertainties in the mechanical parameters and load torque.

6. CONCLUSION

In this paper, an adaptive fuzzy sliding-mode vector control has been presented for speed regulator of induction motor. It is proposed as a sliding-mode controller which has a nonlinear sliding surface to overcome the windup phenomenon of conventional integral sliding-mode speed controller strategy and speed up convergence by fractional-order derivative control term which is not sensitive to the noise beyond the selected frequency interval. Moreover, the proposed sliding-mode controller incorporates a fractional-order adaptive fuzzy control term based on the nonlinear sliding surface to approximate the uncertainty. Then the closed loop stability of the presented design has been proved by Lyapunov stability theory. Finally, by means of simulation examples, it has been shown that the proposed control method improves tracking performance of speed in comparison with the conventional integral sliding-mode controller based on boundary layer in presence of external load disturbance and mechanical parameter variations.

ACKNOWLEDGEMENTS

This work is supported by the Science and Technology Development Foundation of the Higher Education Institutions of Tianjin Municipality of China (No. 20130722).

REFERENCES

[1] O Barambones, AJ Garrido. An Adaptive Variable Structure Control Law for Sensorless Induction Motors. *European Journal of Control*. 2007; 13: 382-392.
[2] ZMS Barbary. DSP Based Vector Control of Five-Phase Induction Motor Using Fuzzy Logic Control. *International Journal of Power Electronics and Drive System*. 2012; 2: 192-202.
[3] ESD Santana, E Bim, WCD Amaral. A Predictive Algorithm for Controlling Speed and Rotor Flux of Induction Motor. *IEEE Transactions on Industrial Electronics*. 2008; 55: 4398-4407.
[4] A Mishra, P Choudhary. Artificial Neural Network Based Controller for Speed Control of an Induction Motor Using Indirect Vector Control Method. *International Journal of Power Electronics and Drive System*. 2012; 2: 402-408.
[5] ZH Akpolat, H Guldemir. Trajectory Following Sliding Mode Control of Induction Motors. *Electrical Engineering*. 2003; 85: 205-209.
[6] M Hajian, GR Markadeh, J Soltani, *et al.* Energy Optimized Sliding-Mode Control of Sensorless Induction Motor Drives. *Energy Conversion and Management*. 2009; 50: 2296-2306.
[7] JB Oliveira, AD Araujo, SM Dias. Controlling the Speed of a Three-Phase Induction Motor Using a Simplified Indirect Adaptive Sliding Mode Scheme. *Control Engineering Practice*. 2010; 18: 577-584.
[8] M Sulaiman, FA Patakor, Z lbrahim. New Methodology for Chattering Suppression of Sliding Mode Control for Three-Phase Induction Motor Drives. *WSEAS Transactions on System and Control*. 2014; 9: 1-9.
[9] DZ Zhao, CW Li, J Ren. Speed Synchronization of Multiple Induction Motors with Total Sliding Mode Control. *Systems Engineering-Theory and Practice*. 2009; 29: 110-117.

[10] G Abdelmadjid, BM Seghir, S Ahmed*, et al.* Sensorless Sliding Mode Vector Control of Induction Motor Drives. *International Journal of Power Electronics and Drive System*. 2012; 2: 277-284.
[11] SE Rezgui, H Benalla. New Robust and Mechanical Sensorless Scheme for SVM Inverter Fed Induction Motor Drive Using Variabe Structure Controllers and MRAS. *Arabian Journal for Science and Engineering*. 2013; 38: 1449-1458.
[12] H Joe, M Kim, SC Yu. Second-Order Sliding-Mode Controller for Autonomous Underwater Vehicle in the Presence of Unknown Disturbances. *Nonlinear Dynamics*. 2014; 78: 183-196.
[13] XH Wang, B Shirinzadeh. High-Order Nonlinear Differentiator and Application to Aircraft Control. *Mechanical Systems and Signal Processing*. 2014; 46; 227-252.
[14] H Alwi, C Edwards. An Adaptive Sliding Mode Differentiator for Actuator Oscillatory Failure Case Reconstruction. *Automatica*. 2013; 49: 642-651.
[15] DJ Wang, XL Gao. H∞ Design with Fractional-Order Controllers. *Automatica*. 2012; 48: 974-977.
[16] YH Chang, CI Wu, HC Chen*, et al.* Fractional-Order Integral Sliding-Mode Flux Observer for Sensorless Vector-Controlled Induction Motors. *American Control Conference. ACC 2011*. 2011: 190-195.
[17] B Zhang, Y Pi, Y Luo. Fractional Order Sliding-Mode Control Based on Parameters Auto-Tuning for Velocity Control of Permanent Magnet Synchronous Motor. *ISA Transactions*. 2012; 51: 649-656.
[18] W Krajewski, U Viaro. A Method for the Integer-Order Approximation of Fractional-Order Systems. *Journal of the Franklin Institute*. 2014; 351: 555-564.
[19] YJ Liu, YX Li. Adaptive Fuzzy Output-Feedback Control of Uncertain SISO Nonlinear Systems. *Nonlinear Dynamics*. 2010; 61: 749-761.
[20] L Li, XZ Zhang. Indirect Adaptive Fuzzy Sliding-Mode Control for Induction Motor Drive. *Journal of Electrical Systems*. 2011; 7: 412-422.

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