Grey Fuzzy Sliding Mode Control with Grey Estimator for Brushless Doubly Fed Motor

Z.K. Shao, Y.D. Zhan, Y.G. Guo, and J.G. Zhu

Abstract—**In this paper, a grey fuzzy sliding mode controller (GFSMC) for brushless doubly fed motor (BDFM) adjustable speed system is presented. A grey model estimator and adaptive fuzzy control technology are incorporated into the sliding mode control (SMC) to adaptively regulate the adaptive law of SMC. The proposed adaptive fuzzy equivalent controller, adaptive fuzzy switching controller, and grey model compensation controller for BDFM can eliminate the average chattering encountered by most SMC schemes, improve the robustness, and obtain excellent static and dynamic performances of SMC. Simulation results show that the proposed control strategy is feasible, correct and effective.**

Keywords—**Brushless doubly fed motor, dynamic model, grey model, adaptive fuzzy control, sliding mode control.**

1. Introduction

Brushless double fed motor (BDFM) is a new type of AC adjustable-speed motor, which consists of two independent stator windings (power winding and control winding) and a special structured rotor. Its performance is similar to that of a synchronous machine, whose speed can be controlled by adjusting the power frequency of control winding using a reversible inverter. BDFM also has advantages such as brushless, simple structure, small capacity of inverter, adjustable power factor, and reduced frequency converter rating required by operating the control winding, leading to significant system cost savings. BDFM is a strong competitor against the traditional DC and AC adjustable-speed motors.

With the development of power electronics technology and computer control technology, BDFM adjustable speed system is more and more widely applied in the cases of high performances required. Moreover, Brushless doubly fed generator is also very suited for variable-speed constant-frequency (VSCF) wind power generation system in which the rotor speed is allowed to operate in sub-synchronous and super-synchronous speed. Generally, for the BDFM application in these cases, there are single brushless doubly fed machine (SBDFM), and cascaded brushless doubly fed induction motor (CBDFM).

Nowadays, in order to acquire high dynamic performance, many kinds of dynamic models have been studied, such as the d-q coordinate frame dynamic model [1,2]. Several types of control strategies are mainly used to control the BDFM, including the scalar control, the field oriented control (FOC) or vector control (VC), the direct torque control (DTC), the fuzzy logic control, and the model reference adaptive control.

Sarasola et al. [3] presented a direct torque control strategy for the BDFM by using the voltage vector table, which has been developed by analyzing the flux and torque derivatives for each voltage vector as a function of control winding flux angle. Huang et al. [4] proposed a fuzzy PID control strategy for power factor based on the model of BDFM and its simulation, and the results show that the power factor of BDFM can be controlled effectively by adjusting the voltage and current amplitude of its control winding with the fuzzy PID controller. Wang et al. [5] analyzed the mathematical model for BDFM based on double synchronous reference frame using rotor d-q model as a start point. It designed a new type of power control system by applying flux oriented vector transformation control technology, based on characteristics of BDFM. The proposed system realized the decoupling control of active and reactive power of variable speed constant-frequency (VSCF) generator by using the fuzzy sliding mode control windings of the generator to carry out the AC excitation. Computer simulation results verified the correctness and effectiveness of this control strategy. Sarasola et al. [6] presented a predictive direct torque control strategy with constant switching frequency of BDFM. In the paper, a reduced torque ripple strategy was implemented to improve the behavior at constant switching frequency. Simulation results showed effectiveness of the proposed control algorithm.

This paper firstly introduces the operating principle of

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Z. K. Shao is with the School of Hydropower and Information Engineering, Huazhong University of Science and Technology, Wuhan 430074, China (e-mail: shaozongkai@126.com).

Y. D. Zhan is with the Department of Automation, Kunming University of Science and Technology, Kunming 650051, China (e-mail: ydzhan@163.com).

Y. G. Guo, and J. G. Zhu is with the School of Electrical, Mechanical and Mechatronic Systems, University of Technology Sydney, Sydney, NSW 2007, Australia (e-mail: Youguang.Guo-1@uts.edu.au, Jianguo.Zhu@uts.edu.au).

BDFM in Section 2, and analyzes the mathematical model for BDFM based on double synchronous reference frame using rotor d-q model in Section 3. Secondly, in order to eliminate the chattering encountered by most SMC schemes, a grey estimator-based grey fuzzy sliding mode control (GFSMC) has been employed for the BDFM speed loop to further enhance the robustness of the system in Section 4. Finally, in Section 5, computer simulation is carried out and the results show that the control strategy is feasible, correct and effective.

2. Operating Principle

For a brushless doubly fed adjustable speed system, the power winding (PW) of the BDFM is connected to the power grid with fixed voltage and frequency, and the current and frequency of the control winding (CW) are controlled by a power bi-directional inverter. Fig. 1 shows the schematic block diagram of a brushless doubly fed variable speed system, which consists of a BDFM, bi-directional inverter, sensors (CT_1, CT_2, CT_3, VT_1, VT_2, VT_3, VT, and encoder), power transformer T, monitoring and control system, and other components. Because the voltage level of the CW is less than that of the PW, the power transformer T is used to output the AC voltages matched with the CW. By adjusting the excitation frequency of the bi-directional inverter acted on the CW of BDFM, the system can achieve the goal of controlling the speed of BDFM. The PW of BDFM is not controlled, and is connected to the power grid through a power filter, which is employed to eliminate the high order harmonics generated by a lot of harmonic field existing in BDFM and inverter, and to avoid the harmonic pollution to the power grid.

As mentioned above, the objective of controlling the BDFM speed can be reached by the frequency controller to adjust the excitation frequency of CW using the bi-directional inverter. If the frequencies of the PW and CW currents are f_1 and f_2 respectively, the rotor speed is given by

$$n = \frac{60(f_1 \mp f_2)}{p_p + p_c} \tag{1}$$

where p_p and p_c are the number of pole pairs for PW and CW respectively, and the symbols “-” and “+” are applied for the operating states below and above synchronous speed respectively.

According to (1), the BDFM speed can be adjusted below or over synchronous speed by changing the amplitude, frequency and phase sequence of the CW excitation currents, which can ensure that the output speed and voltage of BDFM are constant.

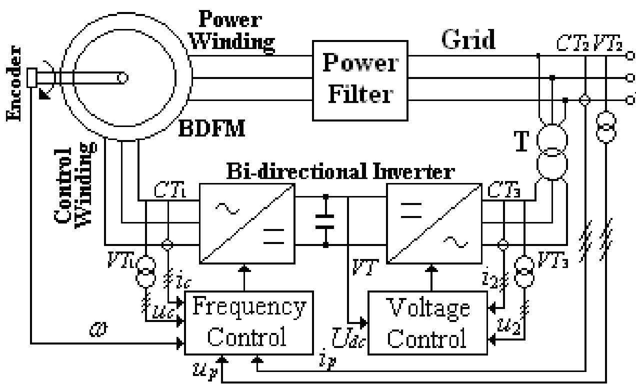

Fig. 1. Schematic block diagram of adjustable speed system and adjustable power system for brushless doubly fed machine.

3. Dynamic Model of BDFM

In order to improve the static and dynamic performances of BDFM adjustable-speed system, a closed loop control system must be used, but it is a very important prerequisite that an accurate dynamic mathematics model of BDFM should be obtained. When the speed of BDFM is adjusted, we need to coordinate and control the three-phase voltage and frequency. In the output variables of BDFM, as the rotating speed and flux affect each other, the BDFM adjustable-speed system is strongly coupled and multi-variable. Moreover, because the stator windings and rotor winding can realize the conversion and transmission of energy by the electromagnetic coupling and relative motion, the inductance coefficients are time-varying function related to the space position. Therefore, the model of BDFM is nonlinear.

According to the theory of BDFM and coordinate transformation method, in its rotor field oriented control motion and in double synchronous reference d-q coordinate frame, to simplify the model of BDFM, the d-axes of the control subsystem and power subsystem are fixed in the direction of their rotor flux linkage respectively. Therefore, the rotor flux linkage in the direction of q-axis is zero, so we have

$$\psi_{drp} = L_{rp2} i_{drp} + L_{srp2} i_{dsp} = \psi_{rp} \tag{2}$$

$$\psi_{qrp} = L_{rp2} i_{qrp} + L_{srp2} i_{qsp} = 0 \tag{3}$$

$$\psi_{drc} = L_{rc2} i_{drc} + L_{src2} i_{dsc} = \psi_{rc} \tag{4}$$

$$\psi_{qrc} = L_{rc2} i_{qrc} + L_{src2} i_{qsc} = 0 \tag{5}$$

where ψ_{rp} and ψ_{rc} are the flux linkage of the PW and CW of BDFM; ψ_{drp}, ψ_{qrp}, ψ_{drc}, and ψ_{qrc} are the d-axis and q-axis orientation flux linkage of PW and CW, respectively.

The voltage equation of BDFM in rotor field orientation frame is given by Ref. [2]

$$\begin{bmatrix} u_{dsp} \\ u_{qsp} \\ u_{dsc} \\ u_{qsc} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_{sp}+L_{sp2}p & -\omega_p L_{sp2} & 0 & 0 & L_{srp2}p & -\omega_p L_{srp2} \\ \omega_p L_{sp2} & r_{sp}+L_{sp2}p & 0 & 0 & \omega_p L_{srp2} & L_{srp2}p \\ 0 & 0 & r_{sc}+L_{sc2}p & -\omega_c L_{sc2} & L_{src2}p & \omega_c L_{src2} \\ 0 & 0 & \omega_c L_{sc2} & r_{sc}+L_{sc2}p & \omega_c L_{src2} & -L_{src2}p \\ L_{srp2}p & 0 & L_{src2}p & 0 & r_r+L_r p & 0 \\ \omega_s L_{srp2} & 0 & -\omega_s L_{src2} & 0 & -\omega_s L_{rc2}+\omega_s L_{rp2} & r_r \end{bmatrix} \begin{bmatrix} i_{dsp} \\ i_{qsp} \\ i_{dsc} \\ i_{qsc} \\ i_{dr} \\ i_{qr} \end{bmatrix} \tag{6}$$

where r_{sp}, L_{sp2}, L_{srp2} and ω_p are power winding resistance, self-inductance, mutual inductance between power winding and rotor, and power winding field mechanical angular speed respectively; r_{sc}, L_{sc2}, L_{src2} and ω_c are control winding resistance, self-inductance, mutual inductance between control winding and rotor, and control winding field mechanical angular speed respectively; L_{rp2} and L_{rc2} the self-inductance of power winding and control winding respectively; r_r, L_r and ω_s are the rotor winding resistance, self-inductance and rotor mechanical angular speed respectively; u_{dsp}, u_{qsp}, u_{dsc}, u_{qsc}, i_{dsp}, i_{qsp}, i_{dsc}, i_{qsc}, i_{dr}, i_{qr} are instantaneous values for voltage and current; p is the time derivative; subscript *sp* represents for PW; *sc* for CW; *r* for rotor; *q* for q-axis components; and *d* for d-axis components.

When BDFM runs in the doubly fed mode, one has

$$\omega_s = \omega_p = \omega_c = \omega \tag{7}$$

The electromagnetic torque can be expressed as

$$T_e = p_p \frac{L_{srp2}}{L_{rp2}} \psi_{rp} i_{qsp} + p_c \frac{L_{src2}}{L_{rc2}} \psi_{rc} i_{qsc} \tag{8}$$

The d-axis component of stator current is

$$i_{dsc} = \frac{T_{c2}p+1}{L_{src}} \psi_{rc} + \frac{L_{rc}}{L_{src2}} p \psi_{rp} \tag{9}$$

where T_{c2} is the time constant of rotor excitation, $T_{c2} = L_{rc2}/r_r$.

The slip frequency control equation becomes

$$\omega_s = \frac{L_{src2}}{T_{c2}(\psi_{rp} - \psi_{rc})} i_{qsc} \tag{10}$$

Therefore, (8), (9), and (10) form the rotor field oriented control equations of BDFM. The rotor flux linkage ψ_{rc} is controlled by i_{dsc}, and the torque T_{em} is controlled by i_{qsc}. When ψ_{rc} is kept invariable, the dynamical control of BDFM can be achieved by controlling i_{qsc}. Thus, (8) becomes

$$T_e = p_c \frac{L_{src2}}{L_{rc2}} \psi_{rc} i_{qsc} \tag{11}$$

The mechanical motion equation of BDFM is

$$\frac{d\omega_r}{dt} = \frac{1}{J}(T_e - T_l - K_d \omega_r) \tag{12}$$

where J and K_d are the rotor mechanism inertia and turning damping coefficient, and T_e and T_l are electromagnetic torque and mechanical load torque.

4. Grey Fuzzy SMC Strategy of BDFM

Because the sliding mode control (SMC) is of the excellent robustness and excellent static and dynamic performances, it will be applied in nonlinear BDFM speed control system, as shown in Fig. 2.

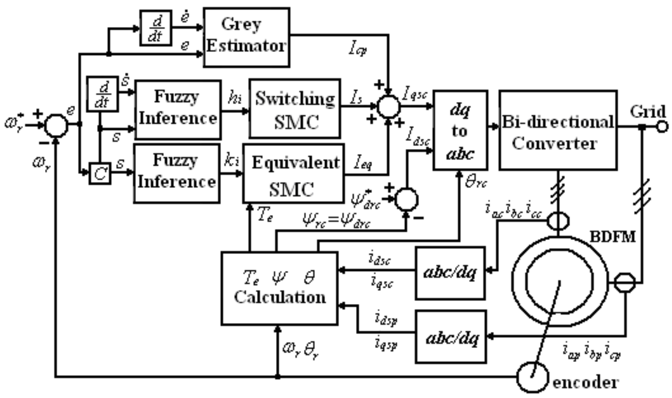

Fig. 2. Block diagram of BDFM adjustable speed control system.

Fig. 2 shows a control method in BDFM speed regulation system based on the dynamic model of BDFM mentioned above. In this figure, ω_r is the synchronous speed, and ω_r^* is the given speed [7-9].

4.1 Design of Sliding Mode Controller for BDFM

According to (4) to (9), we have

$$\frac{d\omega_r}{dt} = -\frac{K_d}{J}\omega_r + \frac{p_c}{J}\frac{L_{src2}}{L_{rc2}}\psi_{rc} i_{qsc} - \frac{1}{J}T_l \tag{13}$$

The state variables may be defined as

$$x_1 = e = \omega_r^* - \omega_r \tag{14}$$

$$\begin{aligned} x_2 &= \dot{x}_1 = \dot{e} = \dot{\omega}_r^* - \dot{\omega}_r \\ &= \frac{K_d}{J}\omega_r - \frac{P_c}{J}\frac{L_{src2}}{L_{rc2}}\psi_{rc} i_{qsc} + \frac{1}{J}T_l \end{aligned} \tag{15}$$

According to (14) and (15), a discrete expression can be obtained

$$x(k+1) = Ax(k) + bi_{qsc}(k) + bD(x,k) \tag{16}$$

where $A = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$; $b = \frac{p_c}{J}\frac{L_{src2}}{L_{rc2}}\psi_{rc}T$; T is the sampling period; $D(\omega_r, k)$ indicates the uncertain parts of BDFM because of the magnetic saturation, skin effect, temperature changing, rotor resistance, load torque, and so on.

The switching function for sliding mode can be selected as follows

$$s(k) = c^T x(k) \tag{17}$$

where c is the constant $(c > 0)$.

According to (16) and (17), there is

$$s(k+1) = c^T Ax(k) + c^T bi_{qsc}(k) + c^T bD(x,k) \tag{18}$$

Based on the index reaching law, there is

$$s(k+1) = (1 - Tq)s(k) - hT \operatorname{sgn} s(k) \tag{19}$$

where h and q are constants, which are larger than zero.

Because the matrix $[c^T b]$ is of full rank, comparing (18) with (19), the SMC control formula is given by

$$\begin{aligned} i_{qsc}(k) &= -(c^T b)^{-1} c^T Ax(k) - \\ &\quad -(c^T b)[(Tq-1)s(k) + hT \operatorname{sgn} s(k)] - D(x,k) \\ &= i_{eq}(k) + i_s(k) + i_{cp}(k) \end{aligned} \tag{20}$$

where $i_{eq}(k)$ is called the equivalent controller of SMC, $i_s(k)$ the switching controller of SMC, and $i_{cp}(k)$ the compensation controller of SMC, which are given by

$$i_{eq}(k) = -(c^T b)^{-1} c^T Ax(k) = -k_i x(k) \tag{21}$$

$$i_s(k) = -(c^T b)^{-1}(hT \operatorname{sgn}(s(k)) + (Tq-1)s(k)) \tag{22}$$

$$i_{cp}(k) = -D(\omega_r, k) \tag{23}$$

4.2 Design of Adaptive Fuzzy Switching Controller

To the practical SMC variable structure control system, when the system track arrives the switching surface, its speed is finite, then the inertial makes the motion points across the switching surface, and then the chattering is formed, which will overlay on the sliding mode. In order to eliminate the average chattering encountered by most SMC schemes, a lot of methods have been employed, such as the quasi-sliding mode method, the driving law method, the filtering method, the observer method, the dynamic sliding-mode method, the switching gain method, the fuzzy control, the neural network control, the genetic algorithm, and other approaches.

A. Switching Control Using Fuzzy Interring Rules

Making it a condition that the sampling period is fixed, the parameter h of the index reaching law in the integrated uncertain term $f_i(s(k))$ decides the chartering amplitude of SMC controller. Because the fuzzy inferring method can effectively realize the control objective using previous expert knowledge, the adaptive fuzzy estimator combined with SMC can overcome the uncertain disturbance in SMC system. Therefore, employing the adaptive fuzzy method, the parameter h can be estimated and adjusted to decrease the chartering of SMC system. In this paper, an adaptive fuzzy inferring method combined with designed SMC for BDFM speed control system is used [10].

As shown in Fig. 2, an adaptive fuzzy inferring controller has been designed, which takes the switching function $s(k)$ and its change variable $\dot{s}(k)$ as input values, and the parameter h as the output value. Meanwhile, their universe is defined as all for [-3, 3] and [-4, 4]. Using the switching control of fuzzy control rules and inferring makes $s(k) \to 0$.

In fuzzy control rules, the related fuzzy subsets are defined as follows: positive very big (PV), positive big (PB), positive medium (PM), positive small (PS), nearly zero (ZE), negative small (NS), negative medium (NM), negative big (NB), and negative very big (NV). The fuzzy membership functions correspond to the switching surface $s(k)$ and $\dot{s}(k)$, and parameter h of integrated uncertain term $f_i(s(k))$ are defined in Fig. 3, and Fig. 4.

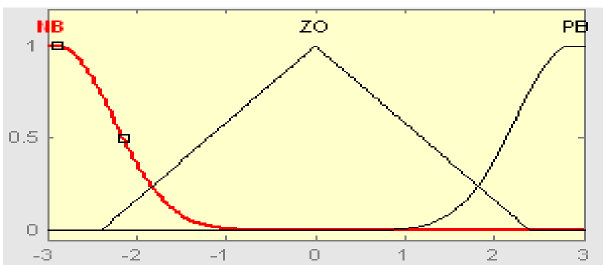

Fig. 3. Membership functions for $s(k)$, $\dot{s}(k)$.

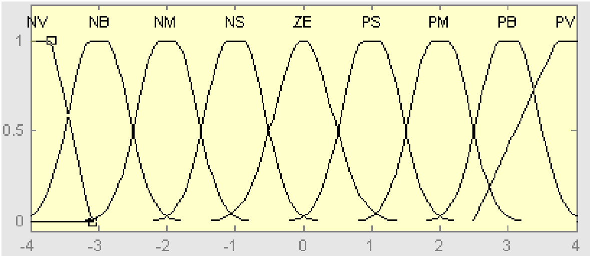

Fig. 4. Membership functions for $f_i(s(k))$.

The fuzzy rules are indicated in Table 1.

Table 1. Fuzzy inferring rules

h_i \ $\dot{s}(k)$ / $s(k)$	N	Z	P
N	PV	PB	PM
Z	PS	ZE	NS
P	NM	NB	NV

The center of gravity (COG) is selected to calculate the defuzzification process for the fuzzy output h_i, which is

$$h_i = \frac{\sum_{i=1}^{9} w_i a_i}{\sum_{i=1}^{9} w_i} = \upsilon^T W \tag{24}$$

where $\upsilon = [a_1\, a_2 \cdots a_9]^T$ is the adjusting factors, $a_1 - a_9$ the central value of membership function for h_i, and W the weight factor, which is as follows

$$W = [w_1\, w_2 \cdots w_9] \Big/ \sum_{i=1}^{9} w_i \tag{25}$$

B. Adaptive Fuzzy Switching Control

Suppose an optimal value of h_i is h_i^*, in order to meet the existing condition of sliding mode. However, because of unknown uncertainty and system complexity, the value h_i^* cannot be obtained accurately. Therefore, based on SMC principle, an adaptive fuzzy control method is employed to estimate the optimal value h_i^* of integrated uncertain term, and the minimum control action $i_s^*(k)$.

Assuming that the minimum control can be obtained, a special $\hat{h}_i$ exists, and it meets the sliding condition and

$$\hat{h}_i - h_i^* = \varepsilon \tag{26}$$

where ε is a small positive number. Furthermore, $\hat{h}_i$ can take the form

$$\hat{h}_i = \hat{\upsilon}^T W \tag{27}$$

Here, $\hat{\upsilon}$ is the optimal vector of the minimum control. The parameter error vector is defined as

$$\tilde{\upsilon} = \upsilon - \hat{\upsilon} \tag{28}$$

Lyapunov function is selected as follows

$$V_i = \frac{1}{2}(s^2(k) + \frac{1}{\alpha}\tilde{\upsilon}^T \tilde{\upsilon}) \tag{29}$$

where α is a positive constant, which is called the adjusting factor and is used in the SMC system for changing the total output gain of fuzzy controller, and removing the chartering generated by SMC controller.

By taking the derivative of above equation, the following equation is obtained

$$\dot{V}_i = s(k)\dot{s}(k) + \frac{1}{\alpha}\tilde{\upsilon}^T \dot{\upsilon} \tag{30}$$

When $\dot{s}(k)$ replaces the above (30), and the condition $\dot{V}_i < 0$ is met, the adaptive law is defined as

$$\dot{\upsilon} = \alpha T |s(k)| W \tag{31}$$

Therefore, when the parameters change or the external disturbances appear, moreover, $s(k) \neq 0$, then the integrated uncertain term will change. At this time, fuzzy inferring engine and adaptive law $\dot{\upsilon}$ will automatically search a new $\hat{h}_i$.

4.3 Design of Adaptive Fuzzy Equivalent Controller

To the equivalent control part $i_{eq}(k)$ of SMC, if the fixation gain control is used, with the change of the running conditions, the control performance will not be good. Therefore, to improve the dynamic characteristic of BDFM, the gain k_i should be automatically regulated according to the information of switching surface s_i.

The fuzzy subsets of s_i and k_i are {NB, NM, NS, ZE, PS, PM, PB}, the universe of s_i is [-0.3, 0.3], and the universe of k_i is [-1, 1]. The fuzzy inferring rules for equivalent controller are expressed as

If s_i is NB, then k_i is NB;

If s_i is NM, then k_i is NM;

If s_i is NS, then k_i is NS;

If s_i is ZE, then k_i is ZE;

If s_i is PS, then k_i is PS;

If s_i is PM, then k_i is PM;

If s_i is PB, then k_i is PB.

Employing the COG, the defuzzification process for the fuzzy output k_i is

$$k_i = \frac{\sum_{m=1}^{M} \theta_j^m \mu_A(s_i)}{\sum_{m=1}^{M} \mu_A(s_i)} = \theta_{k_i}^T \Psi_{k_i}(s_i) \tag{32}$$

where

$$\theta_{k_i} = [\theta_{k_i}^1, \theta_{k_i}^2, \cdots, \theta_{k_i}^M]^T,$$
$$\Psi_{k_i}(s_i) = [\psi_{k_i}^1, \cdots, \psi_{k_i}^m, \cdots, \psi_{k_i}^M]^T,$$
$$\psi^m(x) = \frac{\prod_{i=1}^{n} \mu_{A_i^m}(x_i^*)}{\sum_{m=1}^{M}\prod_{i=1}^{n} \mu_{A_i^m}(x_i^*)},$$

and $\mu_A(s_i)$ is the membership of fuzzy subset, which is a Gaussian function.

The adaptive law is

$$\dot{\hat{\theta}}_{k_i} = s_i \psi_{k_i}(s_i) \tag{33}$$

4.4 Design of Compensation Controller

The uncertain parts $D(\omega_r, k)$ cannot be ignored because of the effects on the dynamic performance of SMC system, and when the conventional controller cannot meet the control demands, based on the grey model method (Accumulated Generating Operation, AGO) of grey system theory, the grey estimator model of uncertain parts for BDFM can be built. After finite steps, the uncertain parts can be compensated according to the estimating parameter, to reduce the effect of chartering in SMC system.

Suppose that $D(x,k)$ meets the matching condition and is bounded, the grey model of the uncertain parts is given by Ref. [11]

$$D(x,k) = \nu x + d \tag{34}$$

where ν and d are unknown numbers.

There are two stages of control law in the designed SMC system.

A. First Control Stage

In this control stage, the control law of SMC is

$$i_{qsc} = i_{eq} + i_s \tag{35}$$

During the $N = n+1$ steps, the number sequences below should be established and calculated as follows

$$x_i^{(0)} = \{x_i(0), x_i(1), \cdots, x_i(N)\} (i = 1, 2; N = n+1)$$
$$x_i^{(1)} = \{x_i^{(1)}(0), x_i^{(1)}(1), \cdots, x_i^{(1)}(N)\} (i = 1,2;\ N = n+1) \tag{36}$$

where $x_i^{(1)}(k) = \sum_{l=0}^{k} x_i(l)$.

$D(x,k)$ can be calculated as follows

$$s(k+1) = c^T x(k+1)$$
$$= (1-Tq)s(k) - hT \operatorname{sgn} s(k) + c^T bD(\omega_r, k)$$
$$D(x,k) = (c^T b)^{-1}[s(k+1) + (Tq-1)s(k) + hT \operatorname{sgn} s(k)] \tag{37}$$

The discrete sequence vectors are

$$d^{(0)} = [D(0), D(1), \cdots, D(N-1)]^T$$
$$d^{(1)} = [D^{(1)}(0), D^{(1)}(1), \cdots, D^{(1)}(N-1)]^T$$

where $d^{(1)}(k) = \sum_{l=0}^{k} D(l)$.

Therefore, after N steps, the grey model can be estimated as

$$D^{(1)}(x,k) = \nu x^{(1)}(k) + d^{(1)}(k) \tag{38}$$

where $d^{(1)}(k) = \sum_{l=0}^{k} d(l)$.

According to the least square method, there is

$$\lfloor \hat{\nu} \quad \hat{d} \rfloor^T = (B^T B) B^T d^{(1)} \tag{39}$$

where $B = \begin{bmatrix} x_1^{(1)}(0) & x_2^{(1)}(0) & 1 \\ x_1^{(1)}(1) & x_2^{(1)}(1) & 2 \\ \vdots & \vdots & \vdots \\ x_1^{(1)}(N-1) & x_2^{(1)}(N-1) & N \end{bmatrix}$.

It is required that $\left|\det(B^T B)\right| > \varepsilon > 0$, and going to next stage.

B. Second Control Stage

After $N = n+1$ steps, the compensation control i_{cp} is added to the control law of SMC, which is

$$i_{qsc} = i_{eq} + i_s + i_{cp} \tag{40}$$

where $i_{cp} = \hat{D}(x,k) = \sum_{i=1}^{2} \hat{v}_i x_i + \hat{d}$.

5. Simulation Results

In order to evaluate the correctness and feasibility of the proposed control strategy, the performance of the BDFM variable speed system as shown in Fig. 2, has been simulated using Matlab/Simulink. The parameters of BDFM are listed in Table 2. The mechanical parameters are [6]: $J = 0.4Kgm^2$, $K_d = 0.1Kgm^2/s$, $p_p = 3$, and $p_c = 1$.

Table 2. BDFM parameters [6]

Parameters	PW	CW	Rotor
Resistance (Ω)	1.732	1.079	0.473
Self-inductance (mH)	714.8	121.7	132.6
Mutual inductance (mH)	242.1	59.8	

During the simulation process, the sample period T = 0.02 s, the sliding mode constants q = 6 and c = [10,-30].

The SMC results based on the RBF neural network are shown in Fig. 5-7. Fig. 5 shows the starting characteristic with the proposed control strategy when the BDFM operates from 0 to 1500 rpm and the nominal torque is 5 Nm. When the load torque changes from 5 Nm to 20 Nm, as shown in Fig. 6, the current responding curve is illustrated in Fig. 7; meanwhile, the speed can keep almost constant as shown in Fig. 5.

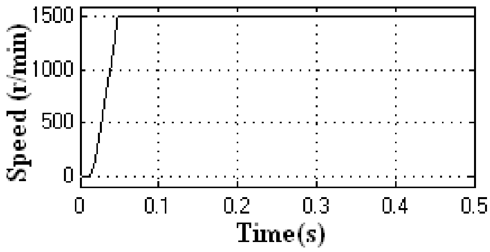

Fig. 5. Step response starting characteristerics.

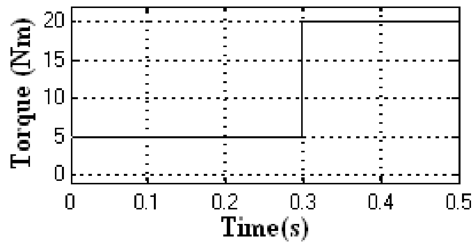

Fig. 6. Step change of load torque.

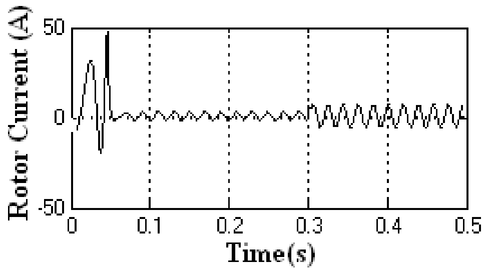

Fig. 7. Current response curve when load changes.

Because the adaptive fuzzy SMC with grey estimator is that the adaptive fuzzy control and grey system control are combined with the conventional SMC, the BDFM adjustable speed system integrates the advantages between them. In other words, the system can keep the characteristics of SMC, which is independent of model and of strong anti-interference ability, such as fast speed response, no speed overshoot, and no static speed error. By introducing the adaptive fuzzy, the control signals can be softened, and then the chartering phenomenon generated by SMC can be reduced or avoided. The control quality and robustness of SMC can be improved.

6. Conclusions

Based on the adaptive fuzzy control and grey model estimator, a sliding mode control (SMC) for BDFM adjustable speed system has been implemented. The adaptive fuzzy control is used to eliminate the chattering encountered by most SMC schemes. The grey model estimating can effectively decrease the effects of uncertain parts of BDFM by compensation control. The adaptive fuzzy control algorithm, grey model estimating algorithm, and SMC control algorithm have been described in details. Simulation results show the feasibility, correctness and effectiveness of the proposed control strategy.

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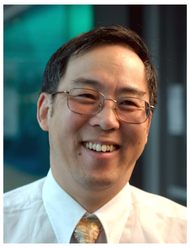
Zong Kai Shao was born in Yunnan, China in 1973. He received the B.E. degree from Kunming University of Science and Technology (KUST), China in 1996, the M.E. degree from Northwestern Polytechnical University, China in 1999, and has been a doctorial candidate at Huazhong University of Science and Technology, China since 2004.
Since 1999, he has worked in the Department of Automation, KUST. His research fields include intelligent control, intelligent traffic, and wind power generation.

Yue Dong Zhan was born in Yunnan, China in 1963. He received the Ph.D. degree from Kunming University of Science and Technology (KUST), China in 2009, the B.E. degree from Xi'an Jiaotong University, China in 1989, and the M.E. degree from KUST, China in 1984.
He joined the Department of Automation, KUST in 1984, where he has been a professor in power electronics and electrical control engineering since 2002. His research fields include autonomous intelligent system, intelligent control theory and application, and modeling and control of fuel cell systems.

You Guang Guo was born in Hubei, China in 1965. He received the B.E. degree from Huazhong University of Science and Technology (HUST), China in 1985, the M.E. degree from Zhejiang University, China in 1988, and the Ph.D. degree from University of Technology, Sydney (UTS), Australia in 2004, all in electrical engineering.
From 1988 to 1998, he lectured in the Department of Electric Power Engineering, HUST. From March 1998 to July 2008, he worked as visiting research fellow, Ph.D. candidate, postdoctoral fellow and research fellow in the Center for Electrical Machines and Power Electronics, Faculty of Engineering, UTS. He is currently a lecturer at the School of Electrical, Mechanical and Mechatronic Systems, UTS.
His research fields include measurement and modeling of magnetic properties of magnetic materials, numerical analysis of electromagnetic field, electrical machine design and optimization, power electronic drives and control. In these fields, he has published over 230 refereed technical papers including 117 journal articles.



Jian Guo Zhu received his BE in 1982 from Jiangsu Institute of Technology, China, M.E. in 1987 from Shanghai University of Technology, China, and Ph.D. in 1995 from University of Technology, Sydney (UTS), Australia, He currently holds the positions of Professor of Electrical Engineering and Head for School of Electrical, Mechanical and Mechatronic Systems at UTS, Australia. His research interests include electromagnetics, magnetic properties of materials, electrical machines and drives, power electronics, and renewable energy systems.