Rotor Field Orientation Speed and Torque Control of BDFM with Adaptive Second Order Sliding Mode

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Abstract — This paper presents two cascaded second order sliding mode controllers (SOSMCs) for brushless doubly fed motor (BDFM) adjustable speed system, which regulate the speed and torque. And an adaptive super twisting algorithm is incorporated into the SOSMCs to adaptively regulate the law of SOSMC. The proposed controllers for BDFM eliminate the average chattering encountered by most sliding mode control (SMC) schemes, and also possess the robustness and excellent static and dynamic performances of SMC. Simulation results show that the proposed control strategy is feasible, proper and effective.

I. INSTRODUCTION

Brushless double fed machine (BDFM) is a new type of machine with special structure and its performance is similar to a synchronous machine. BDFM also has advantages, such as adjustable power factor and reduced frequency converter rating required by operating the control windings, which lead to significant system cost savings. With the development of power electronic technology and computer control technology, BDFM adjustable speed system is more and more widely applied in the cases of high performances. Moreover, BDFM also is most 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, to the BDFM in applications to these cases, there are the single brushless doubly fed machine (SBDFM), the cascaded brushless doubly fed induction machine (CBDFM), and the disk brushless doubly fed machine (DBDFM).

Nowadays, in order to acquire high dynamic performance, a lot of scholars have conducted study on various kinds of dynamic models, such as the d-q coordinate frame dynamic model. And several types of control strategies are mainly used to control the BDFM, including the scalar control, the field oriented control, so called vector control (VC), the direct torque control (DTC), fuzzy logic control, neural network control, model reference adaptive control, sliding mode control (SMC), and so on.

Because it is difficult to obtain the accurate mathematical model of BDFM system, the model-based SMC and the second-order sliding-mode control (SOSMC) approaches can be employed in the BDFM applications. The major advantage of SMC methods is its insensitivity to parameter variations and external disturbance when the system trajectory reaches and stays on the sliding surface. On the other hand, the SMC strategy generates the large control chattering caused by a switching function in the control rules. However, due to that the SOSMC uses the integration method to obtain the practical control efforts, the chattering phenomenon can be improved effectively [1].

The SMC and SOSMC strategies of motors or BDFM have already been studied recently. For instance, Fernando [2] developed a decoupled active and reactive power control for a variable-speed constant-frequency (VSCF) power generation system based on a BDFM through SOSM techniques. Yong *et al.* [3] proposed a terminal sliding-mode (TSM) observer for estimating the immeasurable mechanical parameters of permanent-magnet synchronous motors (PMSMs) used for complex mechanical systems. Jing *et al.* [4] presented a novel adaptive control design of nonlinear pure-feedback systems on a servo motor system without using back-stepping. Jediael *et al.* [5] proposed a robust SOSM observer based control scheme using a nonlinear complete order model of a synchronous motor. Fezzani *et al.* [6] dealt with speed sensorless flatness based on the control of permanent magnet synchronous motor (PMSM) using a second order sliding mode observer. Mara *et al.* [7] proposed a novel switched SOSMC strategy in the application of the wheel slip control of two-wheeled vehicles. Evangelista *et al.* [8] explored an adaptive SOSMC strategy to maximize the energy production of a wind energy conversion system (WECS). Mondal *et al.* [9] proposed an adaptive SOSM controller to control a laboratory helicopter called the twin-rotor multi-input–multi-output system (TRMS). Borujeni *et al.* [10] proposed the electromagnetic torque and the square of the stator flux magnitude control using the SOSM controller of a synchronous reluctance motor (SRM).

This paper firstly analyses the mathematical model for BDFM based on double synchronous reference frame using rotor d-q model in Section 2. Secondly, in order to eliminate the chattering encountered by most SMC schemes, an adaptive SOSMC has been employed for the BDFM speed loop and torque loop to further enhance the robustness of the system in Section 3. Finally, in Section 4, computer simulation results show that the control strategy is of the feasibility, correctness and effectiveness.

II. DYNAMIC MODEL OF BDFM

According to the theory of BDFM and coordinate transformation method, its rotor field oriented control motion double synchronous reference model in *d-q* coordinate frame is given by [11]

$$\begin{bmatrix} u_{dsp} \\ u_{qsp} \\ u_{dsc} \\ u_{qsc} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_{sp}+L_{sp2}p & -\omega_p L_{sp2} & 0 & 0 & L_{srp2}p & -\omega_p L_{srp2} \\ \omega_p L_{sp2} & r_{sp}+L_{sp2}p & 0 & 0 & \omega_p L_{srp2} & L_{srp2}p \\ 0 & 0 & r_{sc}+L_{sc2}p & -\omega_c L_{sc2} & L_{src2}p & \omega_c L_{src2} \\ 0 & 0 & \omega_c L_{sc2} & r_{sc}+L_{sc2}p & \omega_c L_{src2} & -L_{src2}p \\ L_{srp2}p & 0 & L_{src2}p & 0 & r_r+L_r p & 0 \\ \omega_s L_{srp2} & 0 & -\omega_s L_{src2} & 0 & -\omega_s L_{rc2}+\omega_s L_{rp2} & r_r \end{bmatrix} \begin{bmatrix} i_{dsp} \\ i_{qsp} \\ i_{dsc} \\ i_{qsc} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (1)$$

where r_{sp}, L_{sp2}, L_{srp2} and ω_p are power winding resistance, self-inductance of power winding and mutual inductance between power winding and rotor, power winding mechanical angular speed respectively; r_{sc}, L_{sc2}, L_{src2} and ω_c are the corresponding parameters of the control winding as those of power winding; L_{rp2} and L_{rc2} the self-inductance of power winding and control winding respectively; r_r, L_r and ω_s the rotor total resistance, total self-inductance of rotor 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 parameters for PW; *sc* for CW; *r* for rotor; *q* for q-axis components; and *d* for d-axis components.

When BDFM is in the doubly fed status, the slip frequency is the same as the winding frequency as follows

$$\omega_s = \omega_p = \omega_c = \omega \quad (2)$$

The electromagnetic torque can be expressed as

$$T_e = p_p \frac{L_{srp2}}{L_{rp2}} \psi_{rp} i_{qsp} + p_c \frac{L_{src2}}{L_{rc2}} \psi_{rc} i_{qsc} \quad (3)$$

where ψ_{rp} and ψ_{rc} are the flux linkage of the power winding and control winding of BDFM, which are defined by

$$\psi_{rp} = L_{rp2} i_{drp} + L_{srp2} i_{dsp} \quad (4)$$

$$0 = L_{rp2} i_{qrp} + L_{srp2} i_{qsp} \quad (5)$$

$$\psi_{rc} = L_{rc2} i_{drc} + L_{src2} i_{dsc} \quad (6)$$

$$0 = L_{rc2} i_{qrc} + L_{src2} i_{qsc} \quad (7)$$

The *d*-axis component of stator current is

$$i_{dsc} = \frac{T_{c2}p+1}{L_{src}} \psi_{rc} + \frac{L_{rc}}{L_{src2}} p \psi_{rp} \quad (8)$$

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

The slip frequency control equation becomes

$$\omega_s = \frac{L_{src2}}{T_{c2}(\psi_{rp} - \psi_{rc})} i_{qsc} \quad (9)$$

Therefore, (3), (8), and (9) 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 the ψ_{rc} is kept invariable, the dynamical control of BDFM can be reached by changing the i_{qsc}. Thus, (3) becomes

$$T_e = p_c \frac{L_{src2}}{L_{rc2}} \psi_{rc} i_{qsc} \quad (10)$$

The mechanical motion equation of BDFM becomes

$$\frac{d\omega}{dt} = \frac{1}{J}(T_e - T_l - K_d \omega) \quad (11)$$

where J and K_d are the rotor mechanism inertia and turning damping coefficient; T_e and T_l are the electromagnetic torque and mechanism torque, respectively

III. ADAPTIVE SOSMC STRATEGY OF BDFM

Because the sliding mode control (SMC) is of the excellent robustness and excellent static and dynamic performances, it has been widely applied in nonlinear control system.

Fig. 1 shows a control method in BDFM speed and torque control system based on the dynamic model of BDFM mentioned above, where ω_r is the synchronous speed, ω_r^* is the given speed.

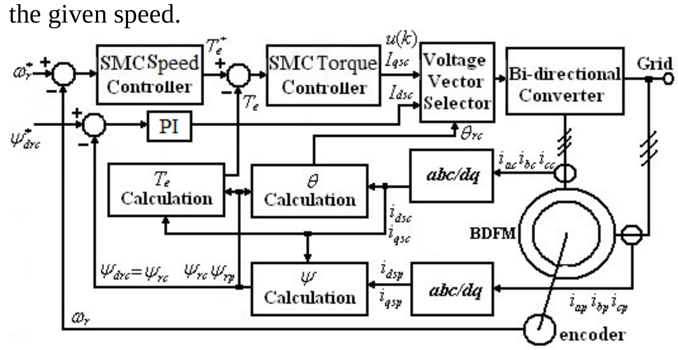

Fig. 1. Proposed cascaded SMC control structure.

A. Problem statement

As mentioned above, according to (10) to (11), the mechanical motion equation can be expressed as

$$\frac{d\omega}{dt} = -\frac{K_d}{J}\omega + \frac{p_c}{J}\frac{L_{src2}}{L_{rc2}}\psi_{rc} i_{qsc} - \frac{1}{J}T_l \quad (12)$$

The BDFM control system state variable and output variables are simply defined by

$$x = \omega \quad (13)$$

$$y = [T_e, \omega]^T \quad (14)$$

Equation (12) becomes as follows

$$\dot{x} = f(x) + g(x)u + d(x,u) \quad (15)$$

where $f(x) = -\frac{K_d}{J}\omega$ and $g(x) = \frac{p_c}{J}\frac{L_{src2}}{L_{rc2}}\psi_{rc}$ are the smooth uncertain functions; and $d(x) = -\frac{1}{J}T_l$ is the uncertainly external disturbance.

Because the control law designed must meet the reaching conditions required, the sliding mode cannot be affected by the $d(x,u,t)$, which can be realized to compensate completely by designing the control rates $u(t) = i_{qsc}$. Thus, the disturbance term can be ignored in the dynamical model of BDFM, and let the BDFM system be controlled:

$$\begin{aligned} &\dot{x} = f(x,t) + g(x,t)u, \quad x \in \mathbb{R}^n, \quad u \in \mathbb{R} \\ &y = s(x,t): \quad (x,t) \mapsto s(x,t) \in \mathbb{R} \end{aligned} \tag{16}$$

Design sliding variable or output function $y = s(x,t)$, which asymptotically requires the stable sliding movement, and there is a good dynamic quality.

The BDFM control system (16) satisfies an SOSM with respect to $s(x,t)$ if its state trajectories lie on the intersection of the two manifolds $s(x,t) = 0$ and $\dot{s}(x,t) = 0$ in the state space.

Suppose that the control objective is to force a defined sliding variable or output function $s(x,t)$ to zero. Trajectories of BDFM system are assumed infinitely extendible in time for any Lebesgue-measurable bounded control $u(t)$. Therefore, by differentiating s, there is

$$\begin{aligned} \dot{s} &= \underbrace{\frac{\partial s(x,t)}{\partial t} + \frac{\partial s(x,t)}{\partial x} f(x,t)}_{a(x,t)} + \underbrace{\frac{\partial s(x,t)}{\partial x} g(x,t)}_{b(x,t)} u \\ &= a(x,t) + b(x,t)u \end{aligned} \tag{17}$$

The function $a(x,t) \in \mathbb{R}$ is presented as

$$a(x,t) = a_1(x,t) + a_2(x,t) \tag{18}$$

With the bounded terms

$$\begin{aligned} &|a_1(x,t)| \le \delta_1 |s|^{\frac{1}{2}} \\ &|\dot{a}_2(x,t)| \le \delta_2 \end{aligned} \tag{19}$$

where the finite boundaries $\delta_1, \delta_2 > 0$ exist but they are not known.

The function $b(x,t) \in \mathbb{R}$ is uncertain and can be presented as

$$b(x,t) = b_0(x,t) + \Delta b(x,t) \tag{20}$$

where $b_0(x,t) > 0$ is a known function and $\Delta b(x,t)$ is a bounded perturbation so that $\forall x \in \mathbb{R}^n$ and $t \in [0, \infty)$ with an unknown boundary γ_1 .

$$\frac{|\Delta b(x,t)|}{b_0(x,t)} = \gamma(x,t) \le \gamma_1 < 1 \tag{21}$$

Finally, (17) becomes

$$\dot{s} = a(x,t) + \underbrace{\left(1 + \frac{\Delta b(x,t)}{b_0(x,t)}\right)}_{b_1(x,t)} v \tag{22}$$

where $v = b_0(x,t)u$. And there is

$$1 - \gamma_1 \le b_1(x,t) \le 1 + \gamma_1 \tag{23}$$

B. Control structure

Based on the control law mentioned above, there are several types of controllers, such as the twisting SOSM controller, supper twisting SOSM controller, supper twisting controller with a given convergence law (terminal sliding mode), and adaptive supper twisting SOSM controller.

In this paper, an adaptive super twisting algorithm relies on inserting an integrator into the controller loop, such that control becomes a continuous time function. This algorithm is defined by the following control rule [12]

$$\begin{aligned} &v = -\alpha |s|^{\frac{1}{2}} sign(s) + \kappa \\ &\dot{\kappa} = -\frac{\beta}{2} sign(s) \end{aligned} \tag{24}$$

where $\alpha = \alpha(s, \dot{s}, t)$ and $\beta = \beta(s, \dot{s}, t)$ are the adaptive gains.

If $|s(0) > \mu|$ so that a real 2-sliding mode, i.e. $|s| \le \eta_1$ and $|\dot{s}| \le \eta_2$ is established $\forall t \ge t_F$ via the super twisting control law (24) with the adaptive gains ($\alpha(0) > \alpha_m$)

$$\begin{aligned} &\dot{\alpha} = \begin{cases} v\sqrt{\dfrac{\gamma}{2}} sign(|s| - \mu), & if\, \alpha > \alpha_m \\ \eta, & if\, \alpha \le \alpha_m \end{cases} \\ &\beta = 2\varepsilon\alpha \end{aligned} \tag{25}$$

where v , γ , μ , η , ε are arbitrary positive constants, and $\eta_1 \ge \mu$, $\eta_2 > 0$. The parameter α_m is an arbitrary small positive constant.

C. SOSM Speed Controller Design for BDFM

The SOSM speed controller contains the adaptive super twisting algorithm with the speed error as input. The manifold of the speed loop is defined as

$$s_1 = \omega_r^* - \omega_r \tag{26}$$

$$\dot{s}_1 = \dot{\omega}_r = \frac{1}{J}(T_e - T_l - K_d \omega_r) \tag{27}$$

The torque reference T_e appears in the first derivative of s_1 . This will be used as a virtual control in the system, as

$$\begin{aligned} &T_e^* = v_1 \\ &v_1 = -\alpha_1 |s_1|^{\frac{1}{2}} sign(s_1) + \kappa_1 \\ &\dot{\kappa}_1 = -\frac{\beta_1}{2} sign(s_1) \end{aligned} \tag{28}$$

The adaptive gains α_1 and β_1 are expressed as

$$\begin{aligned} &\dot{\alpha}_1 = \begin{cases} v_1\sqrt{\dfrac{\gamma_1}{2}} sign(|s_1| - \mu_1), & if\, \alpha_1 > \alpha_{1m} \\ \eta_1, & if\, \alpha_1 \le \alpha_{1m} \end{cases} \\ &\beta_1 = 2\varepsilon_1\alpha_1 \end{aligned} \tag{29}$$

In order to obtain the best behavior of controller, the parameters have been tuned as follows

$$v_1 = 300, \gamma_1 = 2, \mu_1 = 0.02, \alpha_{1m} = 20, \eta_1 = 18, \varepsilon_1 = 5.$$

D. SOSM Torque Controller Design for BDFM

The internal loop contains an SOSM torque controller which produces the control value $u(t) = i_{qsc}$ to be applied to the BDFM. The manifold of the internal loop is defined as

$$s_2 = T_e^* - T_e = T_e^* - p_c \frac{L_{src2}}{L_{rc2}} \psi_{rc} i_{qsc} \tag{30}$$

Using feedback linearization technique, the control output $u(t) = v_2$ leads to one integrator $\dot{s}_2 = v_2$ and is designed to stabilize this new control system.

$$\begin{aligned} i_{qsc} &= v_2 \\ v_2 &= -\alpha_2 |s_2|^{\frac{1}{2}} sign(s_2) + \kappa_2 \\ \dot{\kappa}_2 &= -\frac{\beta_2}{2} sign(s_2) \end{aligned} \tag{31}$$

The adaptive gains α_2 and β_2 are expressed as

$$\dot{\alpha}_2 = \begin{cases} \nu_2 \sqrt{\frac{\gamma_2}{2}} sign(|s_2| - \mu_2), & if\, \alpha_2 > \alpha_{2m} \\ \eta_2, & if\, \alpha_2 \le \alpha_{2m} \end{cases} \tag{32}$$

$$\beta_2 = 2\varepsilon_2 \alpha_2$$

The parameters have been tuned to obtain the best controller behavior as follows

$$\nu_2 = 100, \gamma_2 = 2, \mu_2 = 200, \alpha_{2m} = 120, \eta_2 = 120, \varepsilon_2 = 1.$$

IV. SIMULATION RESULTS

In order to evaluate the correctness and feasibility of the proposed control strategy, the performances of the BDFM have been simulated using MATLAB/SIMULINK. The parameters of BDFM are shown in table I. The mechanical parameters are

$$J = 0.04 Kg/m^2, K_d = 0.11 Kgm^2/s, p_p = 3, p_c = 1.$$

TABLE I
BDFM PARAMETERS

Parameters	*PW*	*CW*	*Rotor*
Resistance (Ω)	2.3	5.9	3.6
Self-inductance (mH)	221	200	133
Mutual inductance (mH)	210	196	

The simulation results based on the adaptive SOSM control strategy are shown in Figs. 2, and 3. Fig. 2 shows the starting characteristic with the proposed control strategy when the BDFM can operate from 0 to 750 rpm. When the load torque changes from 0 Nm to 20 Nm, as shown in Fig. 3, the speed can almost keep constant as shown in Fig. 2. The proposed SOSM control system makes BDFM faster response, no overshoot and no steady state error. Furthermore, it maintains the strong robustness of the sliding mode variable structure, and weakens the chattering phenomenon.

V. CONCLUSION

Based on the super twisting control law, an adaptive SOSM control strategy for BDFM adjustable speed system has been implemented. The adaptive gains are used to eliminate the chattering encountered by most SMC schemes. The adaptive super twisting algorithm and SOSM control strategy have been described in details. Simulation results show the feasibility, correctness and effectiveness of the proposed control strategy.

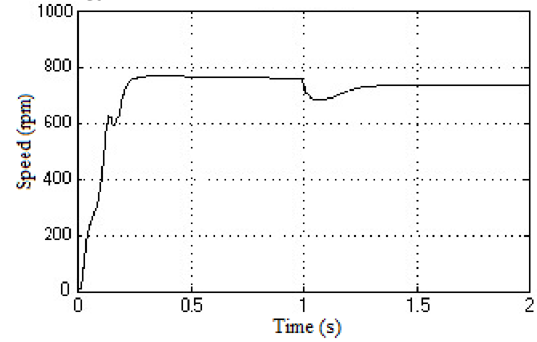

Fig. 2. Step responding starting characteristics.

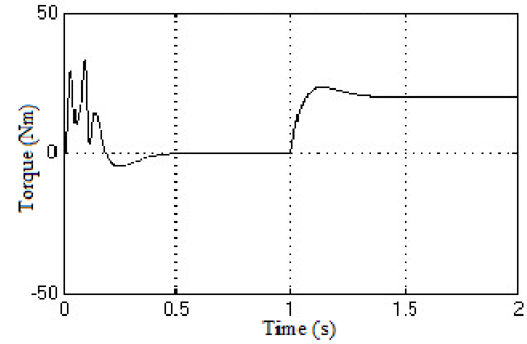

Fig. 3. Step change of load torque.

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