

# BDFIG Control using Dynamic Sliding Mode based on Discrete Time Disturbance Observer

M. Ehsani, N. S. Gogani, A. Ramsey, S. Razmara, V. Behnamgol, R. Barzamini

**Abstract**— This paper presents an innovative observer-based sliding mode controller specifically designed for effective current tracking in brushless doubly-fed induction generator wind turbines. The adoption of sliding mode control is motivated by the inherently nonlinear dynamics of the BDFIG system, which pose challenges to conventional control methods. By employing a dynamic sliding mode controller, a smooth and reliable control signal is achieved, enhancing system performance and stability. Additionally, a discrete-time sliding mode disturbance observer is introduced to provide accurate estimation of system uncertainties. A notable advantage of this observer lies in its time-discontinuous nature, which simplifies its implementation on digital processors. This feature is particularly advantageous as it incorporates the sampling time directly into the design phase, ensuring compatibility with digital processing requirements. The proposed controller's performance is thoroughly validated through detailed computer simulations, demonstrating its robustness and effectiveness in managing the nonlinear dynamics of BDFIG wind turbines.

**Keywords:** Wind Turbine, Brushless Doubly-Fed Induction Machine, Dynamic Sliding Mode Control, Discrete Time Disturbance Observer

## NOMENCLATURE

$P_w, C_w$	Power winding, control winding
$V_r, V_{sc}, V_{sp}$	Voltage of Rotor, Cw, Pw
$\Phi_r, \Phi_{sc}, \Phi_{sp}$	Flux of Rotor, Cw, Pw
$I_r, I_{sc}, I_{sp}$	Current of Rotor, Cw, Pw
$R_r, R_{sc}, R_{sp}$	Resistance of Rotor, Cw, Pw
$P_c, P_p$	Number of pole pair of Cw, Pw
$\omega_r, \omega_{sc}, \omega_{sp}$	Electrical angular velocities of Rotor, Cw, Pw
$L_r, L_{sc}, L_{sp}$	Self-inductance of Rotor, Cw, Pw
$M_c, M_p$	Mutual inductance Cw, Pw
$P_{sp}, Q_{sp}$	Active and reactive power of Pw

## I. INTRODUCTION

The growing prevalence of distributed energy production in the energy sector is driven by the rapid expansion of alternative energy sources. Among these, wind power is particularly prominent due to its global accessibility and the technological advancements that enable efficient energy capture. Within wind energy systems, Doubly-Fed Induction Generators (DFIGs) are a preferred choice because of their variable speed capabilities, which offer advantages such as reduced mechanical stress, noise reduction, and independent control of active and reactive power [1, 2].

A notable variant, the Brushless Doubly-Fed Induction Generator (BDFIG), is highly valued for its robust design that eliminates the need for brushes and slip rings, thereby reducing maintenance costs and improving reliability [3]. Like other AC machines, BDFIGs are controlled using scalar and vector control techniques, with vector control being particularly advantageous due to its independence from machine parameters [4].

The non-linear dynamics and inherent uncertainties in the behavior of BDFIGs require a robust control approach. Sliding Mode Control (SMC) has proven to be well-suited for handling such complexities. Reference [5] discusses an energy-based SMC tailored for BDFIGs, highlighting its effectiveness in mitigating system disturbances and maintaining operational stability. Similarly, reference [6] compares standard SMC with Terminal SMC methods, focusing on their application in regulating BDFIG output voltage, and emphasizes their robustness and stability. Expanding on these techniques, reference [7] introduces a fuzzy SMC for wind turbines using DFIGs, demonstrating the adaptability of SMC methods in renewable energy systems.

One key challenge in SMC implementation is the phenomenon of chattering, which can render the control approach impractical [8]. High-order SMC techniques, such as the well-known second-order super-twisting algorithm, have been employed to address this issue. For instance, the super-twisting method was used for BDFIG control in [1] and for DFIGs in [9]. To further mitigate chattering in Dynamic Sliding Mode Control (DSMC), the derivative of the control input is calculated and integrated, effectively eliminating high-frequency oscillations [10, 11]. While dynamic SMC effectively reduces

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chattering, it requires derivative information of the sliding surface, which is challenging to measure directly from sensors. The Extended State Observer (ESO) offers a practical solution by estimating the sliding variable's derivative as a new state variable [12].

The versatility of ESOs is evidenced by their wide range of applications. For example, [13] employs ESOs for estimating unknown dynamics in cardiac rhythm models, while [15] uses sliding mode observers for state estimation in autonomous underwater vehicles. Dual ESOs are implemented in [16] to estimate state vectors and disturbances for controlling glue pump motors. Moreover, [17] presents an ESO-based SMC that accounts for internal parameter variations and external load changes in motor speed regulation. Discrete-time observers provide distinct advantages when implemented on digital processors. Unlike their continuous-time counterparts, discrete-time observers incorporate sampling time directly during the design phase, facilitating practical implementation [18]. Recent studies highlight their potential, such as in [19], where a sliding mode observer is introduced, eliminating the need for voltage sensors. Similarly, [20] investigates a discrete-time linear extended state observer's effectiveness in managing disturbances and uncertainties in nonlinear discrete-time systems.

In this paper an observer-based dynamic SMC is presented for controlling the active and reactive power of BDFIGs. A Dynamic Sliding Mode Disturbance Observer (DSMDO) is employed to estimate both the sliding variable's derivative and the uncertain elements within the system dynamics. Additionally, dynamic SMC is utilized to generate a smooth control signal, enhancing the overall system performance.

This paper is organized as follows: Section 2 introduces the mathematical model. Section 3 describes the observer-based dynamic sliding mode control (SMC) strategy for controlling BDFIG wind turbines. Section 4 presents the simulation results, and Section 5 provides the conclusions.

## II. BDFIG DYNAMICS MODEL

In this section, the equations governing the BDFIG are formulated in the d-q reference frame, as outlined in [1] and [21]. The stator power winding rotates with an angular speed  $\omega_{sp}$ , while the angular speed of the rotor is given by:

$$\omega_r = \frac{\omega_{sc} \pm \omega_{sp}}{P_c + P_p} \quad (1)$$

The relationships for the power and control sections of both the stator and rotor are described as follows:

$$\begin{aligned} v_{sp} &= R_{sp} I_{sp} + \frac{d}{dt} \Phi_{sp} + j \omega_{sp} \Phi_{sp} \theta \\ v_{sc} &= R_{sc} I_{sc} + \frac{d}{dt} \Phi_{sc} + j (\omega_{sp} - (p_p + p_c) \omega_r) \Phi_{sc} \\ v_r &= R_r I_r + \frac{d}{dt} \Phi_r + j (\omega_{sp} - p_p \omega_r) \Phi_r \end{aligned} \quad (2)$$

The flux relationship can be represented as:

$$\begin{aligned} \Phi_{sp} &= L_{sp} I_{sp} + M_p I_r \\ \Phi_{sc} &= L_{sc} I_{sc} + M_c I_r \\ \Phi_r &= L_r I_r + M_c I_{sc} + M_p I_{sp} \end{aligned} \quad (3)$$

The electromagnetic torque is:

$$T_{em} = \frac{3}{2} P_p M_p (I_{sp}^q I_r^d - I_{sp}^d I_r^q) - \frac{3}{2} P_c M_c (I_{sc}^q I_r^d - I_{sc}^d I_r^q) \quad (4)$$

The active and reactive power relations are:

$$\begin{aligned} P_{sp} &= \frac{3}{2} (v_{sp}^d I_{sp}^d + v_{sp}^q I_{sp}^q) \\ Q_{sp} &= \frac{3}{2} (v_{sp}^q I_{sp}^d + v_{sp}^d I_{sp}^q) \end{aligned} \quad (5)$$

and from Eq. (3) we have:

$$\begin{aligned} I_{sp} &= \frac{\Phi_{sp} - M_p I_r^d}{L_{sp}} \\ I_r &= \frac{\Phi_r - M_p I_{sp} - M_c I_{sc}}{L_r} \end{aligned} \quad (6)$$

Then from Eqs. (3) and (6):

$$I_{sp} = \frac{L_r}{L_{sp} L_r - M_p^2} \Phi_{sp} + \frac{M_p}{L_{sp} L_r - M_p^2} \Phi_r + \frac{M_c M_p}{L_{sp} L_r - M_p^2} I_{sc} \quad (7)$$

That gives:

$$\begin{aligned} P_{sp} &= \frac{3}{2} V_{sp} (\lambda_5 \Phi_{sp}^q - \lambda_4 \Phi_r^q + \lambda_3 I_{sc}^q) \\ Q_{sp} &= \frac{3}{2} V_{sp} (\lambda_5 \Phi_{sp}^d - \lambda_4 \Phi_r^d + \lambda_3 I_{sc}^d) \end{aligned} \quad (8)$$

$$\begin{aligned} \lambda_1 &= \frac{L_{sp} M_c}{L_r L_{sp} - M_p^2}, \quad \lambda_2 = L_{sc} - \frac{L_{sp} M_c^2}{L_r L_{sp} - M_p^2} \\ \lambda_3 &= \frac{M_c M_p}{L_r L_{sp} - M_p^2}, \quad \lambda_4 = \frac{M_p}{L_r L_{sp} - M_p^2}, \quad \lambda_5 = \frac{L_r}{L_r L_{sp} - M_p^2} \end{aligned} \quad (9)$$

From the above equations, voltages in the d-q axis is defined as:

$$\begin{aligned} V_{sc}^d &= R_{sc} I_{sc}^d \left( \frac{d}{dt} (\lambda_1 \Phi_r^d + \lambda_2 I_{sc}^d) \right. \\ &\quad \left. - \omega_{sc} (\lambda_1 \Phi_r^q + \lambda_2 I_{sc}^q - \lambda_3 \Phi_{sp}^q) \right) \\ V_{sc}^q &= R_{sc} I_{sc}^q \left( \frac{d}{dt} (\lambda_1 \Phi_r^q + \lambda_2 I_{sc}^q) \right. \\ &\quad \left. + \omega_{sc} (\lambda_1 \Phi_r^d + \lambda_2 I_{sc}^d - \lambda_3 \Phi_{sp}^d) \right) \end{aligned} \quad (10)$$

### III. CONTROL SYSTEM

Observer based DSMC method is applied to the regulation of a BDFIG.

#### A. Dynamic Observer Based SMC

The dynamic sliding method provides a robust framework for control system design, especially suited for nonlinear systems. This approach effectively relocates discontinuous terms, as described in [22, 23]. The following nonlinear system is considered:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f(x) + g(x)u + d(t) \\ y = x_1 \end{cases} \quad (11)$$

Defining  $e = y - y_d$  and  $s = ce + \dot{e}$ , where  $c > 0$  must be Hurwitz, we have:

$$\dot{s} = f(x) + g(x)u + d(t) - \ddot{y}_d + c\dot{e} \quad (12)$$

A dynamic sliding variable is constructed as:

$$\sigma = \dot{s} + \lambda s \quad (13)$$

where  $\lambda > 0$ . Time derivative of (13) is:

$$\begin{aligned} \dot{\sigma} = & \dot{f}(x) - (c + \lambda)\ddot{y}_d - \ddot{y}_d + \dot{d}(t) + (c + \lambda)d(t) \\ & + (\dot{g}(x) + cg(x) + \lambda g(x))u \\ & + (c + \lambda)f(x) + g(x)\dot{u} + \lambda c\dot{e} \end{aligned} \quad (14)$$

Dynamic sliding mode controller is selected as:

$$\begin{aligned} \dot{u} = & \frac{1}{g(x)} \left( -\dot{f}(x) + (c + \lambda)\ddot{y}_d + \ddot{y}_d \right. \\ & \left. - (\dot{g}(x) + cg(x) + \lambda g(x))u \right. \\ & \left. - (c + \lambda)f(x) - \lambda c\dot{e} - \eta \operatorname{sgn}(\sigma) \right) \end{aligned} \quad (15)$$

From (22) and (23), it is obtained:

$$\dot{\sigma} = \dot{d}(t) + (c + \lambda)d(t) - \eta \operatorname{sgn}(\sigma) \quad (16)$$

where

$$|d(t)| \leq L_d, \quad |\dot{d}(t)| \leq L_{\dot{d}} \quad (17)$$

then, Let  $\eta > L_{\dot{d}} + (c + \lambda)L_d$ , therefore,

$$\begin{aligned} \sigma \dot{\sigma} = & \sigma \left( \dot{d}(t) + (c + \lambda)d(t) \right) - \eta |\sigma| \\ \leq & (L_{\dot{d}} + (c + \lambda)L_d) \sigma - \eta |\sigma| < 0 \end{aligned} \quad (18)$$

If the estimate of the uncertain part is provided by an Observer, (16) can be modified as follows:

$$\begin{aligned} \dot{u} = & \frac{1}{g(x)} \left( -\dot{f}(x) + (c + \lambda)\ddot{y}_d + \ddot{y}_d \right. \\ & \left. - (\dot{g}(x) + cg(x) + \lambda g(x)) \right. \\ & \left. - (c + \lambda)f(x) - \lambda c\dot{e} - \eta \operatorname{sgn}(\sigma) - z \right) \end{aligned} \quad (19)$$

where  $z = \dot{\hat{d}}(t) + (c + \lambda)\hat{d}(t)$ .

#### B. Disturbance Observer Design

For sliding variable dynamics as:

$$\dot{s} = \alpha + \beta u + d(t) \quad (20)$$

Here,  $\alpha$  and  $\beta$  are known, while  $d(t)$  represents the system uncertainty. Additionally,  $S$  denotes the sliding variable, and  $u$  is the control law. Assuming  $S$ , nonlinear functions, and controller are accessible, and the second derivative of  $d(t)$  is zero, an extended state observer can be designed by incorporating the system uncertainty as a new state variable in the state-space equations. Thus, system (20) is reformulated as:

$$\begin{cases} \dot{x}_1 = \alpha + \beta u + x_2 \\ \dot{x}_2 = x_3 \\ \dot{x}_3 = 0 \\ y = x_1 \end{cases} \quad (21)$$

Where  $x_1 = s, x_2 = d$  and  $x_3 = \dot{d}$ . To design the discrete time observer, the model of system must be written in discrete time form. For discrete time systems, the derivative is defined as (22) [24]:

$$\left. \frac{d}{dt} y \right|_t = kT = \frac{y((k+1)T) - y(kT)}{T} = \frac{y(k+1) - y(k)}{T} \quad (22)$$

Therefore, the model of system (21) will be as:

$$\begin{cases} x_1(k+1) = x_1(k) + Tx_2(k) + T[\alpha(k) + \beta(k)u(k)] \\ x_2(k+1) = x_2(k) + Tx_3(k) \\ x_3(k+1) = x_3(k) \\ y(k) = x_1(k) \end{cases} \quad (23)$$

For system (23), the sliding mode observer is proposed as (24) [25]:

$$\begin{cases} \hat{x}(k+1) = A\hat{x}(k) + Bu(k) + L(y(k) - \hat{y}(k)) + J(k) \\ \hat{y}(k) = C\hat{x}(k) \\ J(k) = R \operatorname{sat} \left( \frac{y(k) - \hat{y}(k)}{\gamma} \right) \end{cases} \quad (24)$$

Where  $\hat{x}(k)$  is the estimation state variables vector  $x(k)$ ,  $L$  is the observer gain vector,  $R = [r_1, r_2, r_3, \dots]^T$  and  $r_1, r_2, r_3, \dots, \gamma > 0$ . In addition to system states, the proposed observer can also estimate the uncertainty of the system. To check the stability of the observer, the estimation error and  $Q(k)$  are defined as:

$$\begin{cases} e(k) = x(k) - \hat{x}(k) \\ Q(k) = y(k) - \hat{y}(k) = Cx(k) - C\hat{x}(k) = Ce(k) \end{cases} \quad (25)$$

Now the error dynamic is analyzed for outside and inside the boundary layer.

#### A) Error dynamic outside the boundary layer ( $|Q(k)| > \gamma$ )

Consider the error dynamic as:

$$e(k+1) = x(k+1) - \hat{x}(k+1) \quad (26)$$

By using system and observer dynamics in (26) we have:

$$e(k+1) = (A - LC)e(k) + E - J(k) \quad (27)$$

**Lemma 1:** For ( $|Q(k)| > \gamma$ ), there exists a vector  $P(k)$ , where  $0 < P(k) < \frac{2R}{\gamma}$  such that:

$$E - J(k) = -P(k)Q(k) \quad (28)$$

**Proof:** For ( $|Q(k)| > \gamma$ ) it is evident:

$$J(k) = \begin{cases} +R & ; \text{if } Q > \gamma \\ -R & ; \text{if } Q < -\gamma \end{cases} \quad (29)$$

By choosing  $R$  such that  $R_1 > |T\alpha(k)|$  and  $R_2, R_3 > 0$ , it's evident that  $|E - J(k)|$  lies between  $(0, 2R)$ . So for ( $|Q(k)| > \gamma$ ) and  $0 < P(k) < \frac{2R}{\gamma}$ ,  $|-P(k)Q(k)|$  lies in  $(0, 2R)$ .

By placing (32) in (31) the error dynamic can rewrite:

$$e(k+1) = (A - LC - P(k)C)e(k) \quad (30)$$

The choose of  $L$  determine the stability of observer like this if  $A_m = (A - LC - P(k)C)$  has it's eigenvalues inside a unit circle  $\forall k > 0$ , then the error is bounded (as  $P(k)$  is bounded) [18].

#### B) Error dynamic inside the boundary layer ( $|Q(k)| \leq \gamma$ )

For ( $|Q(k)| \leq \gamma$ ), we have:

$$J(k) = R \text{sat}\left(\frac{y(k) - \hat{y}(k)}{\gamma}\right) = R\left(\frac{Ce(k)}{\gamma}\right) \quad (31)$$

So, the error is obtained

$$e(k+1) = \left(A - LC - \frac{RC}{\gamma}\right)e(k) + E \quad (32)$$

If  $A_m$  has its eigenvalues inside the unit circle  $\forall k > 0$ , then  $A_n = A - LC - \frac{RC}{\gamma}$  also has its eigenvalues inside the unit circle  $\forall k > 0$ . As  $E$  is bounded, the error in the layer will also be bounded [18].

#### C. OB DSMC in BDFIG

The relationship between CW and the PW are as [1]:

$$\begin{cases} I_{sc}^d = \frac{Q_{sp}}{1.5V_{sp}^q \lambda_3} + \frac{\lambda_4}{\lambda_3} \Phi_r^d - \frac{\lambda_5}{\lambda_3} \Phi_{sp}^d \\ I_{sc}^q = \frac{P_{sp}}{1.5V_{sp}^q \lambda_3} + \frac{\lambda_4}{\lambda_3} \Phi_r^q \end{cases} \quad (33)$$

We have:

$$\begin{cases} I_{sc}^{d-ref} = \frac{Q_{sp}^{ref}}{1.5V_{sp}^q \lambda_3} + \frac{\lambda_4}{\lambda_3} \Phi_r^d - \frac{\lambda_5}{\lambda_3} \Phi_{sp}^d \\ I_{sc}^{q-ref} = \frac{P_{sp}^{ref}}{1.5V_{sp}^q \lambda_3} + \frac{\lambda_4}{\lambda_3} \Phi_r^q \end{cases} \quad (34)$$

Now based on standard SMC theory, sliding variables can be introduced as:

$$\begin{cases} S(P_{sp}) = (I_{sc}^q - I_{sc}^{q-ref}) \\ S(Q_{sp}) = (I_{sc}^d - I_{sc}^{d-ref}) \end{cases} \quad (35)$$

Dynamic sliding functions is:

$$\begin{aligned} \sigma(P_{sp}) &= \dot{S}(P_{sp}) + \lambda_p S(P_{sp}) \\ \sigma(Q_{sp}) &= \dot{S}(Q_{sp}) + \lambda_q S(Q_{sp}) \end{aligned} \quad (36)$$

Where  $\lambda_p, \lambda_q > 0$ . The derivation of (37) is:

$$\begin{aligned} \dot{\sigma}(P_{sp}) &= \beta_p \dot{u}_p + D_p \\ \dot{\sigma}(Q_{sp}) &= \beta_q \dot{u}_q + D_q \end{aligned} \quad (37)$$

where  $\beta_p = b_p$ ,  $D_p = \dot{b}_p u_p + \dot{d}_p(t) + \lambda_p (b_p u_p + d_p(t))$ ,  $\beta_q = b_q$  and  $D_q = \dot{b}_q u_q + \dot{d}_q(t) + \lambda_q (b_q u_q + d_q(t))$ .

According to observer based dynamic sliding mode theory, controller vector is calculated as follow:

$$\begin{aligned} \dot{u}_p &= \frac{1}{\beta_p}(-z_p - k_p \operatorname{sgn}(\sigma(P_{SP}))) \\ \dot{u}_q &= \frac{1}{\beta_q}(-z_q - k_q \operatorname{sgn}(\sigma(Q_{SP}))) \end{aligned} \quad (38)$$

where  $k_p = \eta_p$  and  $k_q = \eta_q$ . Also  $z_p$  and  $z_q$  are the uncertain part in active and reactive power dynamic, which will be provided using a discrete time sliding mode observer.

#### IV. SIMULATION RESULTS

The proposed controller is evaluated using MATLAB software, demonstrating its effectiveness and robustness. Figures (1) and (2) illustrate the behavior of the sliding variables along the d and q axes when the proposed discrete-time observer-based dynamic SMC is applied. These figures confirm that the sliding variables reaches to zero with high accuracy, validating the precision of the control methodology. In particular, Figure (2) highlights the accurate estimation of the sliding variable in the q-axis using the discrete-time SM observer.

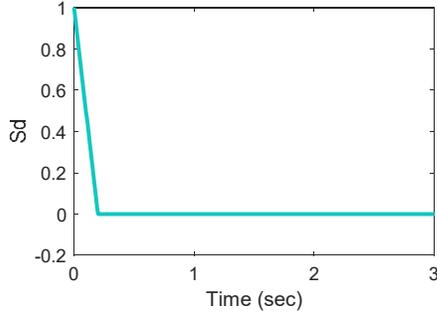


Figure 1. Sliding variable along the d-axis

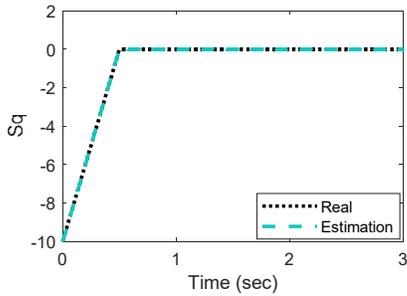


Figure 2. Sliding variable and its estimation along the q-axis

Figure (3) shows a comparison of the system uncertainties and their corresponding estimated values obtained through the discrete-time sliding mode observer. The results show that the observer achieves a high level of precision in estimating these uncertainties, making the estimates reliable for generating the control signals required for the system's operation.

Figures (4) and (5) depict the control signals generated within the d-q coordinate framework. These signals, produced by the proposed discrete-time observer-based dynamic SMC, are notably smooth and free from chattering. This smoothness is

attributed to the dynamic nature of the SMC, which effectively mitigates the chattering issue typically associated with conventional SMC techniques.

Figures (6) and (7) showcase the system's output variables along the d and q axes under the influence of the proposed controller. These results show that the output variables converge to their desired reference values with precision, further validating the reliability and effectiveness of the proposed control system.

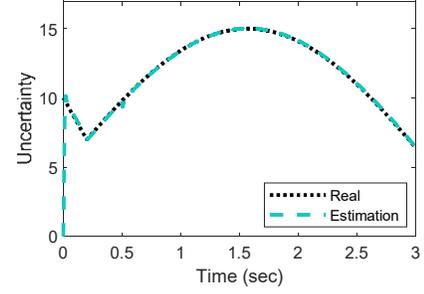


Figure 3. Uncertainties and estimation

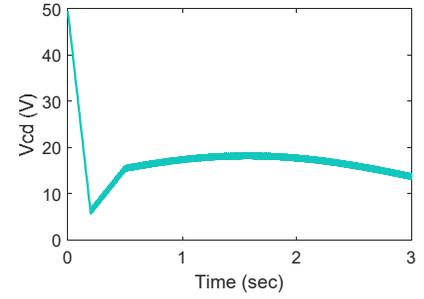


Figure 4. Control signal along the d-axis

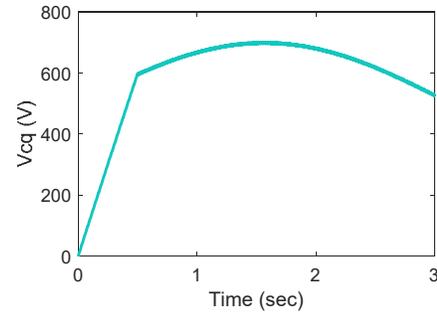


Figure 5. Control signal along the q-axis

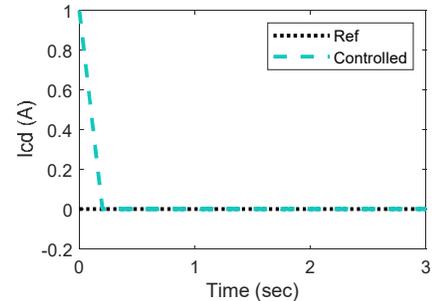


Figure 6. Output current variable along the d-axis

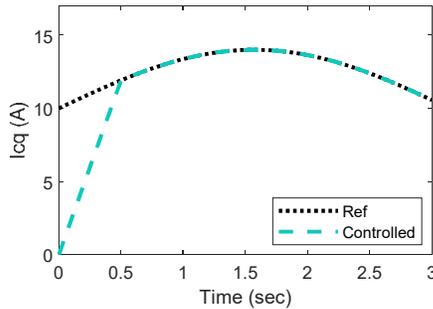


Figure 7. Output current variable along the q-axis

## V. CONCLUSIONS

This paper presents the development of a discrete-time disturbance SMO specifically designed to estimate uncertainties in the BDFIG wind turbine system. Complementing this, a dynamic SMC is implemented to generate precise and reliable control signals. The proposed approach represents a robust nonlinear control strategy tailored for Brushless DFIGs, characterized by its dynamic capabilities that enable the production of smooth control signals. This smoothness not only enhances system stability but also simplifies implementation when compared to conventional Sliding Mode Control (SMC) techniques.

A key feature of the proposed method is its ability to remain effective regardless of the bounds of system uncertainty, achieved through the seamless integration of the discrete-time observer. This ensures that uncertainties are accurately estimated and effectively utilized in generating control signals. The simulation results provide strong evidence of the controller's performance, demonstrating its capability to produce smooth control signals. Additionally, the sliding variable and system uncertainties are estimated with high precision, further validating the observer's reliability and the overall robustness. This innovative method offers a practical and efficient solution for managing the nonlinear dynamics of Brushless DFIG wind turbine systems.

## REFERENCE

- [1] O. Moussa, R. Abdessemed, and S. Benagoune, "Super twisting sliding mode control for brushless doubly fed induction generator based on WECS," *Int. J. Syst. Assur. Eng. Manag.*, vol. 10, 2019.
- [2] B. Kelkoul and A. Boumediene, "Stability analysis and study between classical sliding mode control (SMC) and super twisting algorithm (STA) for doubly fed induction generator (DFIG) under wind turbine," *Energy*, vol. 214, 2021.
- [3] S. Hu, G. Zhu, and Y. Kang, "Modeling and coordinated control design for brushless doubly-fed induction generator-based wind turbine to withstand grid voltage unbalance," *IEEE Access*, vol. 9, 2021.
- [4] M. Ehsani and A. Oraee, "Design of control system based on adaptive sliding mode theory for power tracking in a brushless doubly-fed wind turbine," *J. Novel Res. Electr. Power*, vol. 10, no. 4, pp. 39–47, 2022.
- [5] H. Huerta and A. Loukianov, "Energy based sliding mode control of brushless double-fed induction generator," *Int. J. Electr. Power Energy Syst.*, vol. 130, 2021.
- [6] H. Zahedi Abdolhadi, G. Arab Markadeh, and S. Taghipour Boroujeni, "Sliding mode and terminal sliding mode control of cascaded doubly fed induction generator," *Iranian J. Electr. Electron. Eng. (IJEET)*, vol. 17, no. 3, 2021.
- [7] M. Aghaseyedabdollah, Y. Alaviyan, H. Azmi, and A. Yazdizadeh, "Fuzzy fractional order sliding mode controller design for a wind turbine with DFIG," in *Proc. 29th Iranian Conf. Electr. Eng. (ICEE)*, 2021.
- [8] M. Mbukani and N. Gule, "Comparison of high-order and second-order sliding mode observer based estimators for speed sensorless control of rotor-tied DFIG systems," *IET Power Electron.*, vol. 12, no. 12, 2019.
- [9] E. Muhammad *et al.*, "Coordination of active front steering and direct yaw control systems using MIMO sliding mode control," *Int. J. Control Autom. Syst.*, vol. 22, no. 1, pp. 1–15, 2024.
- [10] Y. Chen and J. Fei, "Dynamic sliding mode control of active power filter with integral switching gain," *IEEE Access*, vol. 7, 2019.
- [11] M. Ehsani *et al.*, "Adaptive dynamic sliding mode algorithm for BDFIG control," *Iranian J. Electr. Electron. Eng.*, vol. 19, no. 1, 2023.
- [12] M. A. Semnani *et al.*, "Modelling and design of observer based smooth sliding mode controller for heart rhythm regulation," *Int. J. Dyn. Control*, 2021.
- [13] M. Ehsani, A. Oraee, B. Abdi, V. Behnamgol, and M. Hakimi, "Adaptive dynamic sliding mode controller based on extended state observer for brushless doubly fed induction generator," *Int. J. Dyn. Control*, pp. 1–14, 2024.
- [14] M. A. Semnani *et al.*, "Heartbeat ECG tracking systems using observer based nonlinear controller," *J. Appl. Dyn. Syst. Control*, vol. 4, no. 2, pp. 69–78, 2021.
- [15] V. Behnamgol, M. Ehsani, A. Oraee, R. Barzamini, and B. Sohani, "Finite time power regulation of BDFIG using adaptive nonlinear method," *Power Control Data Process. Syst.*, vol. 2, no. 2, 2025.
- [16] P. Wang, L. Zhu, C. Zhang, C. Wang, and K. Xiao, "Prescribed performance control with sliding-mode dynamic surface for a glue pump motor based on extended state observers," *Actuators*, vol. 10, no. 282, 2021.
- [17] L. Qu, W. Qiao, and L. Qu, "An extended-state-observer-based sliding-mode speed control for permanent-magnet synchronous motors," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 9, no. 2, 2021.
- [18] M. Javaheripour *et al.*, "Line of sight (LOS) rate estimation in strap down seekers using discrete-time extended state observer," *J. Control*, vol. 16, no. 2, pp. 55–67, 2022.
- [19] R. Chakraborty *et al.*, "Capacitor voltage estimation of MMC using a discrete-time sliding mode observer based on discrete model approach," in *Proc. IEEE Int. Conf. Power Electron. Smart Grid Renew. Energy (PESGRE)*, 2020.
- [20] Y. Huang *et al.*, "Performance assessment of discrete-time extended state observers: Theoretical and experimental results," *IEEE Trans. Circuits Syst. I: Reg. Papers*, 2017.
- [21] S. Shao, "Control of brushless doubly-fed (induction) machines," Ph.D. dissertation, Dept. Eng., Univ. Cambridge, Cambridge, U.K., 2010.
- [22] A. Karami, A. Mollae, H. Tirandaz, and O. Barambones, "On dynamic sliding mode control of nonlinear fractional-order systems using sliding observer," *Nonlinear Dyn.*, vol. 92, 2018.
- [23] J. K. Liu and X. H. Wang, *Advanced Sliding Mode Control for Mechanical Systems: Design, Analysis and MATLAB Simulation*. Springer, Tsinghua Univ. Press, Berlin and Beijing, 2012.
- [24] H. J. Marquez, *Nonlinear Control Systems*. Hoboken, NJ, USA: Wiley, 2003.
- [25] K. Harikumar *et al.*, "Discrete-time sliding mode observer for the state estimation of a manoeuvring target," *Proc. Inst. Mech. Eng. Part I: J. Syst. Control Eng.*, vol. 233, no. 7, 2019