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Disturbance Observer-Based Fuzzy SMC of WECSs Without Wind Speed Measurement

TON DUC DO, (Member, IEEE)
Department of Robotics and Mechantronics, School of Science and Technology, Nazarbayev University, Astana Z05H0P9, Kazakhstan (doduc.ton@nu.edu.kz)

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ABSTRACT The main role of control system for wind turbines is tracking the optimal power via regulating the rotor speed of the generator. A high performance controller, which can deal with unmodeled dynamics, uncertainties, and external disturbance, can effectively increase the captured power from the wind. This paper focuses on designing an advanced sliding mode control (SMC) scheme for wind energy conversion systems (WECSs). As the proposed SMC scheme includes a nonlinear disturbance observer (DOB) for estimating aerodynamic torque and wind speed, there is no requirement to measure aerodynamic torque or wind speed. The proposed control scheme considers not only the uncertainties and disturbance but also the random nature of wind speed and intrinsic nonlinear behavior of the WESCs. Via designing sliding surface based on estimated information, the proposed control system can avoid disadvantages associated with the robust control techniques. To totally remove chattering as well as improving other control criteria, a fuzzy-based variable switching gain scheme is introduced. Comparative simulation results are shown to verify the effectiveness and superior performance of the proposed DOB-based fuzzy SMC scheme.

INDEX TERMS Disturbance observer (DOB), fuzzy control, sliding mode control (SMC), uncertainties, wind energy conversion system (WECS).

I. INTRODUCTION

Renewable energies (such as wind, solar, and biomass) are promising candidates as they are the solution to problems associated with the traditional energy sources such as pollution, global warming, rising cost and finite energy sources [1]–[3]. Among renewable energy sources, wind energy is one of the best sources. It does not produce any pollutants or emissions during operation, other than requirement for maintenance. Therefore, it is one of cleanest and safest methods for generating electricity. As we know, at each wind speed, there is an optimal operating point, at which the turbine captures maximum power. Therefore, there is a demand for designing feedback control schemes to track the optimal reference of rotor speed associated with variable wind velocity [4], [5]. Wind energy conversion systems (WECSs) are highly nonlinear systems with strongly coupled internal variables, external disturbances, and parameter uncertainties. Thus, linear controllers [6], [7] are unable to achieve good performance. Consequently, there is a requirement for advanced nonlinear control schemes. Nonlinear control methods such as nonlinear controller [8], fuzzy and neural networks based controller [9], [10], linear parameter-varying control [11], for WECSs were investigated. These methods significantly improve the control performance in different aspects.

To calculate the optimal speed reference for generator, the information of wind speed is required. Unfortunately, wind speed is difficult to precisely measure via traditional cup-anemometers. Physical estimation methods in [12] are ineffective for short-term estimation. Gray models and Kalman filters are used to predict wind speed [13], [14], but the estimation performances seem to be not satisfied. In [15], a genetic algorithm based support vector machine model is applied to estimate the wind speed. Although the estimation error is small, the algorithm is required big computation effort and a lot of inputs.

Sliding-mode control (SMC) has been proven to be an effective control technique for dealing with uncertainties of nonlinear systems. The most distinguished characteristics of SMC are the switching nature of its control action, providing excellent performance, including robustness to parameter variations, disturbances, and finite-time convergence. Besides these precious advantages, traditional SMC has two main drawbacks. The first is the undesirable chattering due to the discontinuous control command. The second one is related to the mismatched uncertainties, which severely degrades the SMC. In other words, traditional SMC is incapable to deal with mismatched uncertainties. These two disadvantages of classical SMC have been solved by numerous advanced SMC techniques: higher-order SMC [16]–[18] for mitigating chattering; and Riccati approach [19], LMI-based approach [20], and integral SMC [21], [22] for dealing with mismatched uncertainties. Several type of SMCs were successfully applied to WECSs such as adaptive second-order SMC in [4] and super-twisting SMC in [23]–[25]. Although good system performances were achieved, these SMC techniques required the information of bounding functions which is unable to calculate in some cases.

In this paper, a disturbance observer (DOB) based fuzzy SMC is introduced for WECSs. First, the dynamic equations of WECS and generator are formed. As the aerodynamic torque is unmeasurable, the system dynamics is apparently included a mismatched disturbance. After transforming the dynamics to the appropriate form, the DOB-based SMC is designed. Then, a variable switching gain scheme based on fuzzy control is introduced. Compared to recent robust control techniques [16]–[22], the proposed DOB-based fuzzy SMC method has three main advantages: the mismatched uncertainty in this technique does not need to satisfy the H_2 norm-bound condition; the switching gain is only required to be higher than the bound of the disturbance estimation error rather than that of disturbance; the fuzzy-based variable switching gain technique is proposed to totally remove the chattering problem; the nominal performance is preserved since the DOB work like a patch to the controller and does not cause any negating effects on the system in case uncertainties are absent. Note that the third advantage is very important since the inherent chattering problems associated with SMC are solved. Also the last advantage is significant as the attenuation of mismatched uncertainties in the robust methods is achieved at the price of sacrificing it nominal control performance. Considering the random nature of wind velocity, comparative simulation results are shown to prove the feasibility of the proposed control scheme as well as it superior performance compared to conventional control methods.

II. DYNAMIC EQUATIONS OF WECS

Wind energy is transformed to electrical energy via two stages: first, from wind energy to mechanical energy through wind blades, and then from mechanical energy to electrical energy through the electric generator. By referring to [1], [4], [5], [23], and [24], the system model is presented in this this section.

A. WIND POWER EXTRACTION

The aerodynamic power that the wind turbine extracts from the wind is expressed as follows,

$$P_a = \frac{1}{2}\rho\pi R^2 C_p(\lambda, \beta) v^3, \tag{1}$$

where ρ is the air density, R is the wind turbine (WT) rotor radius, v is the wind speed, and the power coefficient $C_p(\lambda, \beta)$ represent the turbine efficiency to convert the kinetic energy of the wind into mechanical energy. This coefficient depends on the shape and geometrical dimensions of the turbine and it is a nonlinear function of the pitch angle of the blades β and of the tip-speed ratio $\lambda = \omega R/v$, where ω is the angular shaft speed. Coefficient C_p is generally determined experimentally and provided by the manufacturer.

According to (1), the captured power is linearly promotional to coefficient C_p, which is maximized at the optimal tip-speed ratio λ_{opt}. For a given wind turbine, λ_{opt} is a constant value; therefore, maximum captured power is achieved by tracking the optimum reference of rotor speed given by,

$$\omega_{ref} = \frac{\lambda_{opt}}{R} v \tag{2}$$

B. OPERATION REGIONS OF A WIND TURBINE

Typically, there are four regions of operation for a variable-speed WT depending on the wind speed. For wind speeds lower than a given threshold $v_{cut\text{-}in}$, Region I, the wind is not strong enough to move the blades. The second zone, Region II, is called partial-load region, is ranges between the cut-in speed $v_{cut\text{-}in}$ and the rated one v_{rated}. The control objective in this region is to maximize the captured power. In this region, the pitch angle of the blades is typically fixed at its optimum and the generator speed is controlled to track ω_{ref} in (2). The Region III, called full-load region, covers the wind speed from v_{rated} to $v_{cut\text{-}off}$. In this region, the turbine must limit the captured power at its rated value such that safe electrical and mechanical load are not exceeded. In Region IV, above $v_{cut\text{-}off}$, the turbine should be turned out of the wind to prevent damages, so the generated power is zero [4], [5].

C. GENERATOR MODELLING

There are two main types of generators for WECS: permanent magnet synchronous generators (PMSGs) and double-fed induction generators (DFIGs). This paper focuses on designing a control system for the PMSGs-based WECS.

The dynamic model of a PMSG in the synchronously rotating reference frame is given by the following equations [24],

$$\begin{cases} J\dfrac{d\omega}{dt} = -B\omega + T_a - T_e \\ \dfrac{di_q}{dt} = -\dfrac{R_s}{L}i_q - P\omega i_d - \dfrac{\psi_m P}{L}\omega + \dfrac{1}{L}v_q \\ \dfrac{di_d}{dt} = -\dfrac{R_s}{L}i_d + P\omega i_q + \dfrac{1}{L}v_d \end{cases} \tag{3}$$

where i_d and i_q are the d-axis and q-axis currents, respectively; v_d and v_q are the d-axis and q-axis voltages, respectively; T_a is the mechanical torque ($T_a = P_a/\omega$); P is the number of pole pairs, R_s is the stator resistance, $L = L_d = L_q$ is the d-axis and q-axis inductances, J is the rotor inertia; B is the viscous friction coefficient; ψ_m is the magnet flux linkage;

and T_e is the electromagnetic torque, which is given by,

$$T_e = Ki_q, \tag{4}$$

where $K = 3/2\ \psi_m P$.

From (3) and (4), the dynamic equation of a PMSG can be rewritten as,

$$\begin{cases} \frac{d\omega}{dt} = -\frac{B}{J}\omega - \frac{1}{J}T_e + \frac{1}{J}T_a \\ \frac{dT_e}{dt} = -\frac{R_s}{L}T_e - PK\omega i_d - \frac{\psi_m PK}{L}\omega + \frac{K}{L}v_q \\ \frac{di_d}{dt} = -\frac{R_s}{L}i_d + \frac{P}{K}\omega T_e + \frac{1}{L}v_d \end{cases} \tag{5}$$

In next section, based on the equations in (5), a nonlinear DOB-SMC scheme will be design based on the following assumptions:

1) ω, i_q (and also T_e), and i_d are measureable;
2) Wind speed v and mechanical torque T_a are unknown;

III. CONTROL SYSTEM DESIGN AND STABILITY ANALYSIS

Before designing the control scheme, let us transform the dynamic equations in (5) to another form. First, by setting,

$$u_q = Kv_q \tag{6}$$

and u_q is decomposed into two terms as

$$u_q = u_{qc} + u_{qf} \tag{7}$$

with $u_{qc} = PK\omega\,(Li_d + \psi_m)$, then the second equation in (5) becomes,

$$\frac{dT_e}{dt} = -\frac{R_s}{L}T_e + \frac{1}{L}u_{qf} \tag{8}$$

Note that the dynamic equation in (8) has the same form with the simplified electrical dynamics in [1] and [5].

Next, let us define a new variable q as,

$$q = -\frac{B}{J}\omega - \frac{1}{J}T_e \tag{9}$$

Then the first equation of (5) become

$$\frac{d\omega}{dt} = q + d \tag{10}$$

with $d = T_a/J$.

Based on (8) and 10, the time derivative of q is given as follows,

$$\frac{dq}{dt} = k_1\omega + k_2 q - \frac{B}{J}d + k_3 u_{qf} \tag{11}$$

where $k_1 = B \cdot R_s/(J \cdot L)$, $k_2 = R_s/L - B/J$, $k_3 = -1/(J \cdot L)$.

Equations in (10), (11), and the third equation in (5) form the following dynamics,

$$\begin{cases} \frac{d\omega}{dt} = q + d \\ \frac{dq}{dt} = k_1\omega + k_2 q - \frac{B}{J}d + k_3 u_{qf} \\ \frac{di_d}{dt} = -\frac{R_s}{L}i_d + \frac{P}{K}\omega T_e + \frac{1}{L}v_d \end{cases} \tag{12}$$

By defining the following tracking error,

$$\tilde{\omega} = \omega - \omega_{ref}; \quad \tilde{q} = q - \dot{\omega}_{ref} \tag{13}$$

we achieve the following error dynamics,

$$\begin{cases} \frac{d\tilde{\omega}}{dt} = \tilde{q} + d \\ \frac{d\tilde{q}}{dt} = k_1\omega + k_2 q - \frac{B}{J}d - \ddot{\omega}_{ref} + k_3 u_{qf} \\ \frac{di_d}{dt} = -\frac{R_s}{L}i_d + \frac{P}{K}\omega T_e + \frac{1}{L}v_d \end{cases} \tag{14}$$

It should be noted that the PMSG considered in this paper is the surface-mounted type. For this type of machine, the d-axis current is set to zero to optimize the operation conditions. Thus, the d-axis current reference is also chosen to be zero [26].

A. SLIDING-MODE CONTROL SYSTEM DESIGN AND STABILITY ANALYSIS

As seen in (14), the system includes a mismatched disturbance d. In order to estimate this disturbance, a nonlinear disturbance observer is introduced as follows [27]–[31],

$$\begin{cases} \dot{p} = -lg_2\,(p + lx) - l\left(\hat{f} + g_1 u\right) \\ \hat{d} = p + lx \end{cases} \tag{15}$$

where $x = \begin{bmatrix} \tilde{\omega} \\ \tilde{q} \end{bmatrix}$, $\hat{f} = \begin{bmatrix} \tilde{q} \\ k_1\omega + k_2 q - \frac{B}{J}\hat{d} - \ddot{\omega}_{ref} \end{bmatrix}$, $u = u_{qf}$, $g_1 = \begin{bmatrix} 0 \\ k_3 \end{bmatrix}$, $g_2 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$, $l = \begin{bmatrix} l_1 \\ l_2 \end{bmatrix}^T$; Here $\hat{d}$ is the estimation of the disturbance, p is the internal state of the nonlinear observer, and l_1 and l_2 are non-negative observer gains to be designed.

With the estimated information $\hat{d}$; according to (1), (2), and (10), the estimation of mechanical torque and speed reference can be achieved directly by the following relations,

$$\begin{cases} \hat{T}_a = J\hat{d} \\ \hat{\omega}_{ref} = \sqrt{\frac{\hat{T}_a}{k_{opt}}} \end{cases} \tag{16}$$

where $k_{opt} = \frac{1}{2}\rho\pi R^5 C_{pmax}/\lambda_{opt}^3$.

Then sliding surface based on the disturbance estimation is defined as

$$\begin{cases} \sigma_q = \tilde{q} + \hat{d} + c\tilde{\omega} \\ \sigma_d = i_d \end{cases} \tag{17}$$

where c is a the positive control parameter to be selected.

Then DOB-SMC law can be designed as

$$\begin{cases} u_{qf} = -\frac{1}{k_3}\begin{pmatrix} k_1\omega + k_2 q - \frac{B}{J}\hat{d} - \ddot{\omega}_{ref} \\ +c\left(\tilde{q} + \hat{d}\right) + u_{qs} \end{pmatrix} \\ v_d = -L\left(\frac{P}{K}\omega T_e + u_{ds}\right) \end{cases} \tag{18}$$

where $u_{qs} = k_q \cdot sgn(\sigma_q)$, $u_{ds} = k_d \cdot sgn(\sigma_d)$, and k_q and k_d are positive control gains.

By referring to [29], the stability of the system is substantiated.

Assumption 1 [27]–[29]: The disturbance d in the system slowly varies.

Assumption 2 [27]–[29]: The estimation error, $e_d = d - \hat{d}$, is bounded with $e_d^* = \sup_{t>0} |e_d|$.

Consider the following Lyapunov function,

$$V = \frac{1}{2}\left(\sigma_q^2 + \sigma_d^2\right) (19) \tag{19}$$

From (17) we have

$$\begin{cases} \dot{\sigma}_q = k_1\omega + k_2 q - \frac{B}{J}d - \ddot{\omega}_{ref} + k_3 u_{qf} + \dot{\hat{d}} + c(\tilde{q} + d) \\ \dot{\sigma}_d = -\frac{R_s}{L}i_d + \frac{P}{K}\omega T_e + \frac{1}{L}v_d \end{cases} \tag{20}$$

Substituting (18) into (19), we achieve,

$$\begin{cases} \dot{\sigma}_q = -k_q \cdot sgn(\sigma_q) + \left(c - \frac{B}{J}\right)\left(d - \hat{d}\right) + \dot{\hat{d}} \\ \dot{\sigma}_d = -k_d \cdot sgn(\sigma_d) - \frac{R_s}{L}\sigma_d \end{cases} \tag{21}$$

On the other hand, from (15), the time derivative of d are given as,

$$\dot{\hat{d}} = k_e e_d, \tag{22}$$

where $k_e = l\left(g_2 - \frac{B}{J \cdot k_3} g_1\right)$.

Substituting (22) into (21), then

$$\begin{cases} \dot{\sigma}_q = -k_q \cdot sgn(\sigma_q) + \left(c + lg_2 - \frac{B}{J}\right) e_d \\ \dot{\sigma}_d = -k_d \cdot sgn(\sigma_d) - \frac{R_s}{L}\sigma_d \end{cases} \tag{23}$$

From (19) and (23), the time derivative of Lyapunov function can be achieved as

$$\begin{aligned} \dot{V} &= \dot{\sigma}_q\sigma_q + \dot{\sigma}_d\sigma_d \\ &= -k_q|\sigma_q| + \left(c + k_e - \frac{B}{J}\right) e_d\sigma_q - k_d|\sigma_d| - \frac{R_s}{L}\sigma_d^2 \\ &\le -|\sigma_q|\left[k_q - \left(c + k_e - \frac{B}{J}\right) e_d^*\right] - k_d|\sigma_d| - \frac{R_s}{L}\sigma_d^2 \end{aligned} \tag{24}$$

With k_q is chosen such that the condition $k_q > \left(c + k_e - \frac{B}{J}\right) e_d^*$ is satisfied, then $\dot{V} < 0$, it implies that the system state will asymptotically reach the sliding surface $\sigma_q = \sigma_d = 0$.

Substituting the condition $\sigma_q = 0$ to (17), then,

$$\tilde{q} = -c\tilde{\omega} - \hat{d}. \tag{25}$$

Combining (14), (15), and (26) gives,

$$\begin{cases} \dot{\tilde{\omega}} = -c\tilde{\omega} + e_d \\ \dot{e}_d = -lg_2 e_d + \dot{d} \end{cases} \tag{26}$$

With the defined coefficients, it is easy to observe that the system

$$\begin{cases} \dot{\tilde{\omega}} = -c\tilde{\omega} + e_d \\ \dot{e}_d = -lg_2 e_d \end{cases} \tag{27}$$

is exponentially stable. Then based on the [32, Lemma 5.5], the system in (26) is input-to-state stable. This implies that the state variables in (14) and the estimation error will asymptotically slide to zero with the proposed observer-based control law in (15), (17), and (18).

Remark 1: To guarantee the stability, the switching gain k_q has to be selected to satisfy: $k_q > (c + lg_2 - B/J)\, e_d$, where e_d is the estimation error and expected to asymptotically converged to zero. Consequently, the switching gain k_q can be kept much smaller than that of the traditional or integral SMC [29], [33].

B. FUZZY SLIDING-MODE CONTROL SYSTEM DESIGN AND STABILITY ANALYSIS

In practice, the SMC law in (18) may excite the neglected or unmodeled high-frequency dynamics, which is a well-known phenomenon called chattering.

At the cost of performance, the discontinuous sign function in u_{qs} and u_{qs} can be replaced by a continuous function as,

$$\begin{cases} u_{qs} = k_q \cdot \frac{\sigma_q}{|\sigma_q| + \varepsilon_q} \\ u_{ds} = k_d \cdot \frac{\sigma_d}{|\sigma_d| + \varepsilon_d} \end{cases} \tag{28}$$

where ε_q and ε_d are positive constant. As ε_q and ε_d tend to zero, the continuous function in (28) are arbitrarily close to the discontinuous sign function. Also, in order to improve transient performance together with avoid chattering, the switching gains k_q and k_d are required to be adjustable according to the tracking error, such that, they are necessary to be big when the tracking error is big, and vice versa.

To solve the tradeoff between chattering and control performance of the approximated continuous function in (28) and the requirement of the switching gains, the fuzzy inference mechanism is utilized. The proposed fuzzy switching law u_{qs} and u_{qs} are represented by a set of fuzzy rules of as follows [34],

Rule i: IF $\tilde{\omega}$ is F_i, THEN

$$\begin{cases} u_{qs} = k_{qi} \cdot \frac{\sigma_q}{|\sigma_q| + \varepsilon_{qi}} \\ u_{ds} = k_{di} \cdot \frac{\sigma_d}{|\sigma_d| + \varepsilon_{di}} \end{cases} \tag{29}$$

where F_i $(i = 1, 2, \ldots, 2n-1;\ n > 1)$ are the fuzzy sets, k_{qi}, k_{di}, ε_{qi}, and ε_{di} are the positive constants. The fuzzy set Fn is arranged so that it covers $\tilde{\omega} = 0$, F_i covers more negative $\tilde{\omega}$ than $F_{(i+1)}$ does for $1 \le i \le n-1$, and $F_{(i+1)}$ covers more positive $\tilde{\omega}$ than F_i does for $n \le i \le 2n-2$.

Based on aforementioned discussion, the parameters k_{qi}, k_{di}, ε_{qi}, and ε_{di} are arranged as

$$\begin{cases} k_{q1} \geq k_{q2} \geq \cdots \geq k_{q(n-1)} \geq k_{qn} > 0 \\ k_{q(2n-1)} \geq k_{q(2n-2)} \geq \cdots \geq k_{q(n+1)} \geq k_{qn} > 0 \\ k_{d1} \geq k_{d2} \geq \cdots \geq k_{d(n-1)} \geq k_{dn} > 0 \\ k_{d(2n-1)} \geq k_{d(2n-2)} \geq \cdots \geq k_{d(n+1)} \geq k_{dn} > 0 \\ 0 < \varepsilon_{q1} \leq \varepsilon_{q2} \leq \cdots \leq \varepsilon_{q(n-1)} \leq \varepsilon_{qn} \\ 0 < \varepsilon_{q(2n-1)} \leq \varepsilon_{q(2n-2)} \leq \cdots \leq \varepsilon_{q(n+1)} \leq \varepsilon_{qn} \\ 0 < \varepsilon_{d1} \leq \varepsilon_{d2} \leq \cdots \leq \varepsilon_{d(n-1)} \leq \varepsilon_{dn} \\ 0 < \varepsilon_{d(2n-1)} \leq \varepsilon_{d(2n-2)} \leq \cdots \leq \varepsilon_{d(n+1)} \leq \varepsilon_{dn} \end{cases} \quad (30)$$

By using a singleton fuzzifier, a product fuzzy inference, and a weighted average defuzzifier, the final fuzzy switching law u_{qs} and u_{qs} is given as follows,

$$\begin{cases} u_{qs} = \sum_{i=1}^{2n-1} h_i(\tilde{\omega}) \dfrac{k_{qi} \cdot \sigma_q}{|\sigma_q| + \varepsilon_{qi}} \\ u_{ds} = \sum_{i=1}^{2n-1} h_i(\tilde{\omega}) \dfrac{k_{di} \cdot \sigma_d}{|\sigma_d| + \varepsilon_{di}} \end{cases} \quad (31)$$

where $h_i(\tilde{\omega}) = m_i(\tilde{\omega}) / \sum_{j=1}^{2n-1} m_j(\tilde{\omega})$ is the normalized weight of each IF-THEN rule and satisfy $h_i \geq 0$, $\sum_{j=1}^{2n-1} h_i(\tilde{\omega}) = 1$.

By following similar procedure of stability analysis for SMC in previous subsection. The time derivative of the Lyapunov function satisfies,

$$\begin{aligned} \dot{V} &\leq -|\sigma_q| \left[k_{qn} - \left(c + k_e - \frac{B}{J} \right) e_d^* \right] - k_{dn} |\sigma_d| \\ &\quad - \frac{R_s}{L} \sigma_d^2 + \psi \\ &\leq -|\sigma_q| \left[k_{qn} - \left(c + k_e - \frac{B}{J} \right) e_d^* \right] - k_{dn} |\sigma_d| + \psi \end{aligned} \quad (32)$$

where $\psi = k_{qn}\varepsilon_{qn} + k_{dn}\varepsilon_{dn}$.

Let us define the sets

$$\begin{cases} M_1 = \{z : |\sigma_i| < \psi / p_{in}\} \\ M_2 = \{z : c|\tilde{\omega}| + |e_d| < \psi / p_{dn}\} \end{cases} \quad (33)$$

where $z = [\tilde{\omega}\ \tilde{q}\ i_d]^T$; $i = d, q$; $p_{qn} = k_{qn} - (c + lg_2 - B/J) e_d^*$, $p_{dn} = k_{dn}$. Then (33) implies that the trajectory must enter the set $M_1 \cap M_2$ and remains in the set for all time thereafter [35], [36]. In other words, the state variables z are guaranteed to be global uniform ultimate boundedness with the proposed observer-based fuzzy SMC control law in (15), (17), (18), and (31).

Remark 2: In recent publications regarding robust control design [37]–[39], the authors use linear matrix inequality (LMI) – based approach and/or fuzzy model for designing the controller. Different from these approaches, in the proposed fuzzy SMC method, fuzzy is used to automatically change the control gains according to the tracking error. Moreover, by using (29) instead of sign function in (18) together with fuzzy tuning of control parameters, the chattering phenomenon is totally removed whereas others control aspects are improved.

Fig. 1 shows the block diagram of the PMSG-based WECS using the proposed DOB-based fuzzy SMC scheme.

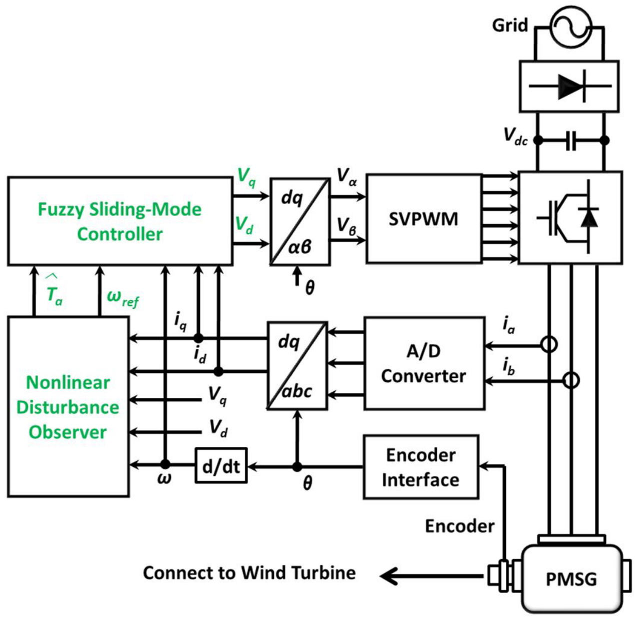

FIGURE 1. PMSG-based WECS using proposed DOB-based Fuzzy SMC scheme.

TABLE 1. WECS parameters.

Symbol	Parameter	Value	Unit
PMSG parameters			
P_{rated}	Rated power	20	kW
P	Pole pairs	2	-
R_s	Stator resistance	4.3	Ω
L	Stator inductance	27	mH
ψ_m	Magnet flux linkage	0.272	V· s/rad
J	Mechanical inertia	1	kg· m^2
B	Viscous friction coefficient	0.002	kg· m^2/s
Wind turbine parameters			
R	Rotor radius	3	m
v_{rated}	Rated wind speed	12.5	m/s
-	Rated rotational speed	310	rpm
Other parameters			
ρ	Air density	1.25	kg/m^3

IV. SIMULATION STUDY

Let us consider the PMSG-based WECS with the given parameters in [24, Table I]. To access the performance of the proposed fuzzy SMC, all simulations run correspond to 100 s of system operation in MATLAB/Simulink. The wind profile is illustrated in Fig. 2. It should be noted that, in this paper, the power coefficient C_p is approximated by a nonlinear function given in [24] with the maximum value $C_{pmax} = 0.48$ achieved at a tip speed ratio $\lambda_{opt} = 8.1$.

A. FIXED SWITCHING GAINS VERSUS FUZZY-BASED VARIABLE SWITCHING GAINS

In order to clarify the superior of the proposed DOB-based fuzzy SMC system (fuzzy-based variable switching gains),

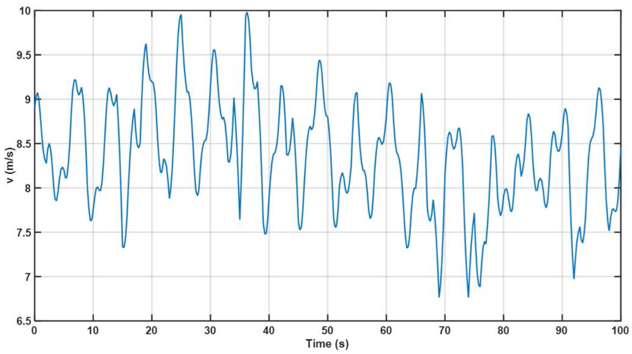

FIGURE 2. Wind speed profile.

the simulation results of the corresponding DOB-SMC system (fixed switching gains) in [29] are also shown. Via extensive simulation studies with the guidelines in [29] and [34], the parameters of both control schemes are selected. Table II details these control parameters.

TABLE 2. Control parameters.

Control Method	Parameters
DOB-SMC	$l_1 = 20;\ l_2 = 0$ $c = 50;\ k_q = 50{,}000;\ k_d = 1$
DOB-Based fuzzy SMC	$l_1 = 20, l_2 = 0;\ c = 50;\ n = 3;$ $W_1 = -15; W_2 = -7.5, W_3 = 0, W_4 = 7.5, W_5 = 15;$ $k_{q1} = k_{q5} = 500{,}000;$ $k_{q2} = k_{q4} = 100{,}000;\ k_{q3} = 50{,}000;$ $\varepsilon_{q1} = \varepsilon_{q5} = 50;\ \varepsilon_{q2} = \varepsilon_{q4} = 100; \varepsilon_{q3} = 150;$ $k_{q1} = k_{q2} = k_{q3} = k_{q4} = k_{q5} = 10;$ $\varepsilon_{d1} = \varepsilon_{d2} = \varepsilon_{d3} = \varepsilon_{d4} = \varepsilon_{d5} = 5;$

The time revolution of angular shaft speed reference (ω_{ref}), angular shaft speed response (ω), aerodynamic torque (T_a), aerodynamic torque estimation ($\hat{T}_a$), tracking error ($\tilde{\omega}$), estimation error ($e_T = \hat{T}_a - T_a$), d-axis voltage (v_d), q-axis voltage (v_q), and generated power (P) using DOB-SMC in [29] and proposed DOB-based fuzzy SMC schemes are illustrated in Figs. 3 and 4. As can be observed, both control methods achieves satisfied tracking and estimation performance (Nonfuzzy/fuzzy SMC, $\tilde{\omega}$: 0.15/0.13 rad/s e_T: 7.8/7.8 N · m). However, the response signals include chattering, especially q-axis voltage (v_q). When the proposed fuzzy SMC is employed, the chattering is removed without affecting the control and estimation performance.

B. PARAMETER AND UNSTRUCTURED UNCERTAINTIES EFFECTS

For further investigating performance of the proposed DOB-based fuzzy SMC system, parameter uncertainties and noise are included in the system. For electrical parameter uncertainties, the stator resistance is increased 50% whereas the stator inductance is decreased 10% [37]. On the other hand, for mechanical parameters in WECS are very stable since the generator is connected to the wind turbine

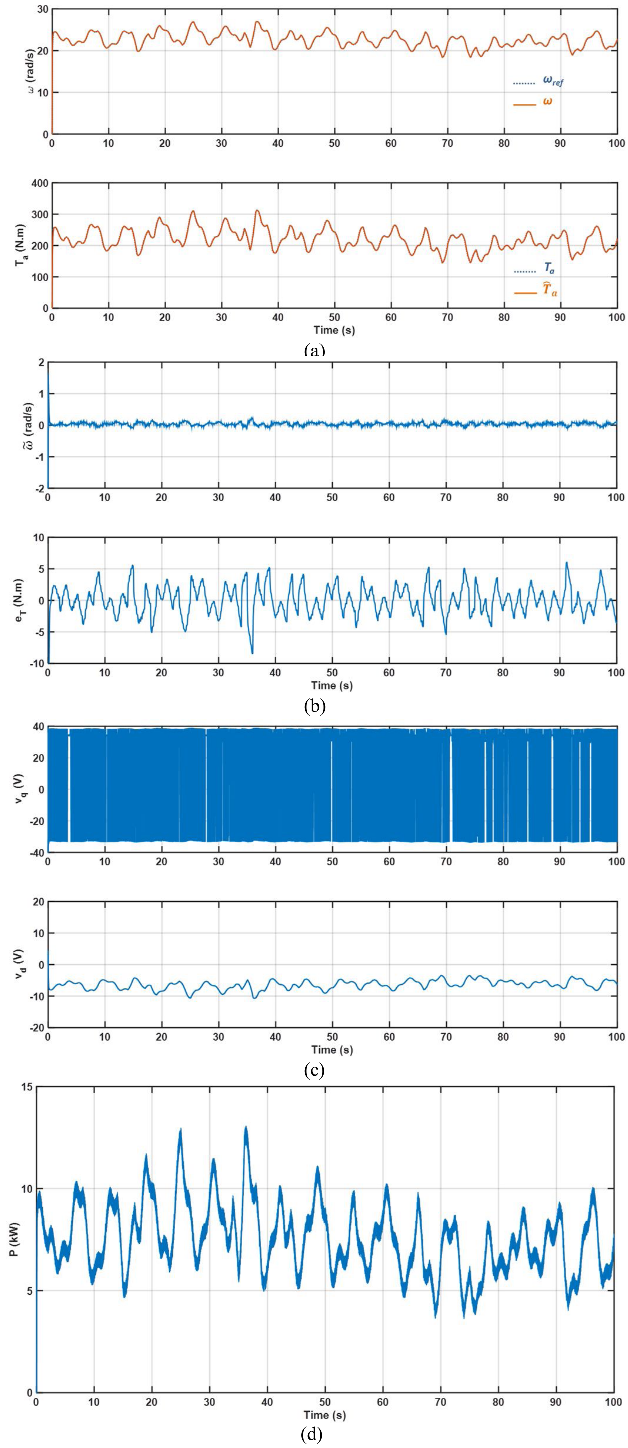

FIGURE 3. Simulation Results of the DOB-SMC method in [29]. (a) Angular shaft speed reference (ω_{ref}), angular shaft speed response (ω), aerodynamic torque (T_a), and aerodynamic torque estimation ($\hat{T}_a$). (b) Tracking error ($\tilde{\omega}$) and estimation error ($e_T = \hat{T}_a - T_a$). (c) q-axis voltage (v_d) and d-axis voltage (v_q). (d) Generated Power (P).

all the time. However, because WECSs are highly nonlinear systems, there are some unstructured uncertainties in the mechanical dynamics. To model these uncertainties, a time-varying term $\tau_d(t)$ is added to the mechanical

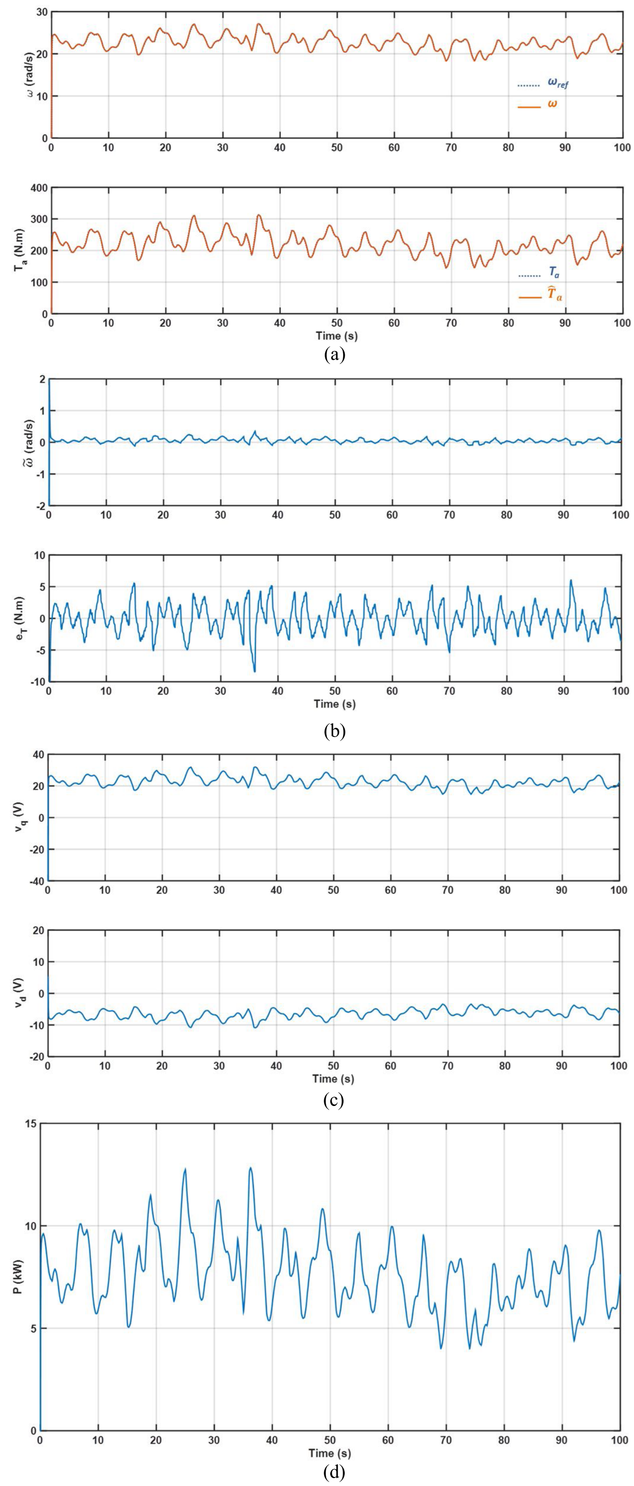

FIGURE 4. Simulation Results of the proposed DOB- based fuzzy SMC method. (a) Angular shaft speed reference (ω_{ref}), angular shaft speed response (ω), aerodynamic torque (T_a), and aerodynamic torque estimation ($\hat{T}_a$). (b) Tracking error ($\tilde{\omega}$) and estimation error ($e_T = \hat{T}_a - T_a$). (c) q-axis voltage (v_d) and d-axis voltage (v_q). (d) Generated Power (P).

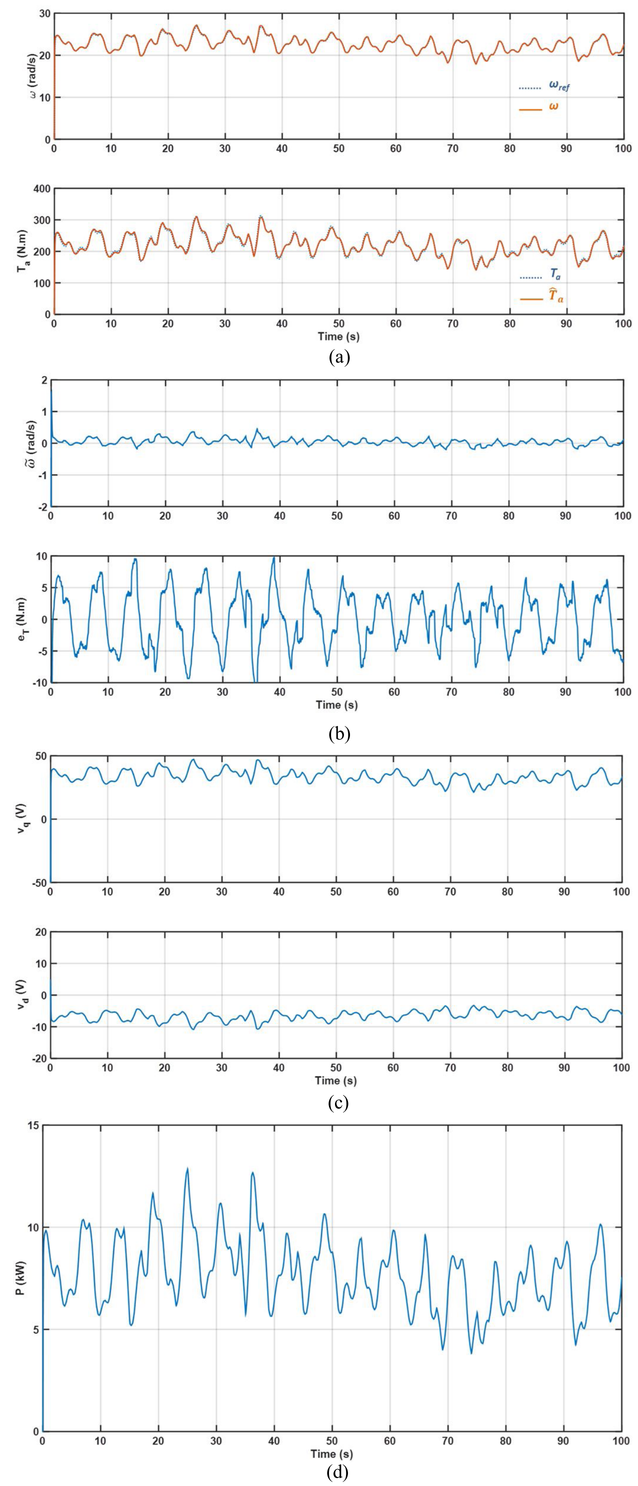

FIGURE 5. Simulation Results of the proposed DOB- based fuzzy SMC method under uncertainties. (a) Angular shaft speed reference (ω_{ref}), angular shaft speed response (ω), aerodynamic torque (T_a), and aerodynamic torque estimation ($\hat{T}_a$). (b) Tracking error ($\tilde{\omega}$) and estimation error ($e_T = \hat{T}_a - T_a$). (c) q-axis voltage (v_d) and d-axis voltage (v_q). (d) Generated Power (P).

dynamics. It means, the first equation of (5) now becomes

$$\frac{d\omega}{dt} = -\frac{B}{J}\omega - \frac{1}{J}T_e + \frac{1}{J}T_a + \tau_d \quad (34)$$

In simulation, the unstructured mechanical uncertainties are modeled with the signal $\tau_d = 5sin(t)$.

Fig. 5 illustrates the simulation results with parameter and unstructured uncertainties of the proposed DOB-based fuzzy

SMC scheme. Compared to nominal case in Fig, 4, although the estimation error is more highly oscillated (11.3 N · m), the tracking performance is retained in a small range (0.22 rad/s). It should be noted that, in this case, due to the effect of the uncertainties, the control signal v_q is higher.

V. CONCLUSION

In this paper, a DOB-based fuzzy SMC system is introduced for WECSs without the measuring of wind speed or aerodynamic torque. A nonlinear disturbance observer was used to estimate the angular shaft speed reference and aerodynamic torque. Based on this estimated information, the sliding surface was designed. Via this design, the disadvantages associated with robust controllers were avoided. Moreover, the fuzzy-based variable switching gain technique was introduced to remove the chattering. Simulation results under different conditions were shown to prove the feasibility of the proposed control system. Although the proposed control system was applied for PMSG, we believe that it is possible to extend the proposed controller to DFIG.

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TON DUC DO (S'12–M'14) received the B.S. and M.S. degrees in electrical engineering from the Hanoi University of Science and Technology, Hanoi, Vietnam, in 2007 and 2009, respectively, and the Ph.D. degree in electrical engineering from Dongguk University, Seoul, South Korea, in 2014.

From 2008 to 2009, he was a Lecturer with the Division of Electrical Engineering, Thuy Loi University, Hanoi. He was a Post-Doctoral Researcher with the Division of Electronics and Electrical Engineering, Dongguk University, in 2014. He was also a Senior Researcher with the Pioneer Research Center for Controlling Dementia by Converging Technology, Gyeongsang National University, Jinju, South Korea, from 2014 to 2015. Since 2015, he has been an Assistant Professor with the Department of Robotics And Mechatronics, Nazarbayev University, Astana, Kazakhstan. His research interests include the field of advanced control system design, electric machine drives, renewable energy conversion systems, uninterruptible power supplies, electromagnetic actuator systems, targeted drug delivery systems, and nanorobots.

Dr. Do authored or coauthored a number of well-known peer-reviewed journal publications, such as the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, the IEEE TRANSACTIONS ON POWER ELECTRONICS, the IEEE/ASME Transactions on Mechatronics, the IEEE TRANSACTIONS ON ENERGY CONVERSION, the Journal of Biomedical Nanotechnology. He received the best paper award from Dongguk University in 2014. He is currently an Associate Editor of the Vietnam Journal of Science.