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Observer-based single-phase robustness sliding mode controller for the pitch control of a variable speed wind turbine

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ABSTRACT

In this paper, a new observer-based single-phase robustness sliding mode controller (SPRSMC) is proposed for the pitch control of a variable speed wind turbine (VSWT) systems. The finding of this research includes two tasks: i) to ensure a global stability of the VSWT plant, the reaching phase in traditional sliding mode control (TSMC) technique is eliminated and ii) to guess the immeasurable variables of VSWT plants, a novel pitch angle output feedback controller is constructed based on the estimator tool and output information only. Firstly, a single-phase switching function is determined to eject the reaching phase in TSMC. Moreover, an immeasurable variable of the VSWT system is estimated by employing the suggested estimator tool. Next, a SPRSMC for VSWT plant is built based on the support of the estimator instrument and output data only. Furthermore, an appropriate requirement is founded by utilizing the linear matrix inequality (LMI) method for ensuring the robust stability of motion dynamics in sliding mode. Finally, the solution of the suggested control is confirmed the three-blade wind turbine with a 5-MW utilizing the wind turbine simulator fatigue, aerodynamics, structures, and turbulence (FAST) code and the National Renewable Energy Laboratory (NREL).

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1. INTRODUCTION

A popular renewable energy source is wind energy and has gotten enormous development at the past decade. Wind energy has crucial advantages such as environment-friendly, cleanness, and global accessibility [1]. Therefore, the stability of the wind turbine plant has been fascinating the attention of a great amount of quality studies issued in the most lately internationally well-known journals [2]-[6] and the associated references therein.

In the wind energy generation plant, the variable speed wind turbine (VSWT) plant with pitch control is often used to obtain an effective and trustworthy conversion of wind energy to electricity systems. There were numerous control techniques to establish pitch angle controllers (PAC) such as [7]-[12]. A proportional–integral (PI) controller was suggested to capture the maximum power for VSWT [7]. A PAC based on the proportional–integral–derivative (PID) was designed for VSWT at high wind speeds [8]. However, the efficiency of these controllers is less due to the effect of uncertainties. By using the linear matrix inequality (LMI) technique, a PAC was established in [9] to regulate the generator speed considering mode uncertainties and additional constraints. The LMI technique is computationally requiring and typically complex. Based on this approach, a PAC was designed using H_∞ control [10]. By applying the linear quadratic Gaussian (LQG) method, a pitch angle control scheme was synthesized as [11]. The fuzzy logic-based advanced PAC was investigated for the VSWT systems [12]. Unfortunately, these controllers are mostly responsive to parametric changes and model uncertainties. These external perturbations and uncertainties may harm and even abolish the pitch control plants considered on nominal models. It may offset the anticipated control performances or flop of the entire VSWT system.

To address these shortcomings, sliding mode control (SMC) approach is employed to control the VSWT system. The noticeable advantages of SMC comprise simplicity computation, strong robustness against disturbances and uncertainties, and fast response [13]-[15]. This approach has been effectively executed to many wind turbine plants in the researches [2]-[5]. An adaptive robust integral sliding mode PAC was investigated to precisely track the wanted pitch angle path and compensate for the exogenous perturbations and model uncertainties [2]. Based on adaptive second order sliding mode approach, a state feedback controller was built in [3] for a floating wind turbine plant. An adaptive robust controller was proposed for wind turbine pitch plant to invalidate the impacts of actuator and sensor faults, external perturbations [4]. An adaptive fractional-order non-singular fast terminal SMC signal was investigated for control wind turbine's pitch angle against external perturbations and uncertainties [5]. Unfortunately, these works have assumed that the VSWT system's state variables are accessible. This is invalid in the practical pitch angle control systems. In order to solve this drawback, the authors in the researches [6] or [16] have employed the output feedback technique. By using robust sliding mode technique, an output feedback controller was designed in [6] for wind turbines. An adaptive output feedback SMC signal was addressed in [16] to control the speed of the rotor and energy of a wind turbine when considering actuator faults and uncertainties. However, in the existing wind turbine research of the SMC, the plant is sensible to the uncertainties and external disturbances during the reaching phase and all the robust properties are valid during the sliding mode. In addition, motion dynamics is settled after the plant's state trajectories drive into the switching surface and the system's performance is unknown in the reaching phase. As a result, the overall stability of plant may not be assured or dangerously corrupted [13] or [17]-[19]. Consequently, it is crucial for wind turbine control systems to develop a novel sliding mode pitch angle controller eliminating the reaching phase that means reaching time is equal to zero.

Interested by all the published studies and the declared restrictions above, we will discourse an observer-based single-phase robustness sliding mode controller (SPRSMC) for control the pitch angle of a VSWT plant with exogenous perturbations. The goal of our research is to contribute to the advance of single-phase robustness SMC without reaching phase and performance analysis for the VSWT plant. Firstly, a single-phase switching surface is specifically proposed for VSWT systems such that the robustness performance against external disturbance is precisely guaranteed at the beginning of process. Secondly, an estimator is explored to guess the VSWT plant's states which are not measured. Thirdly, based on estimation of the observer, a robustness SMC signal is designed for VSWT plants with external disturbances without reaching phase. In addition, by using LMI technique and Razumikhin–Lyapunov approach, sufficient stipulation is given for guaranteeing the robust stability of motion dynamics in sliding mode. Finally, the solution of the suggested control is confirmed on a 5-MW three-blade wind turbine employing the National Renewable Energy Laboratory (NREL) and wind turbine simulator fatigue, aerodynamics, structures, and turbulence (FAST) code.

The rest of this research is arranged as follows: the considered turbine model and problem statement in this study is showed in section 2. The main achievements of the paper are represented in section 3, which comprises a new observer, the wind turbine system's asymptotic stability investigation and the strategy of a SPRSMC. The practicability of the anticipated scheme is illuminated in section 4 with simulation example of wind turbine benchmark model. To end this work, several concluding annotations are made in section 5.

2. TURBINE MODEL AND PROBLEM STATEMENT

In the VSWT system, when the pitch angle is controlled, it will affect the aerodynamics and rotate the rotor. The output power of the VSWT plant can be computed from the (1) [20]:

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

where $\rho, R, V,$ and $C_p(\lambda, \beta)$ are the density of air, the turbine blade's radius, the wind speed, and the power factor, respectively. The tip speed ratio $\lambda = \frac{\omega_r R}{V.}$ The power coefficient of the VSWT plant can be determined as (2) [21]:

$$C_p(\lambda, \beta) = 0.517\left[116\left(\frac{1}{\lambda_i}\right) - 0.4\beta - 5\right] e^{-21\left(\frac{1}{\lambda_i}\right)}, \tag{2}$$

where $\frac{1}{\lambda_i} = \frac{1}{(\lambda+0.08\beta}) - \frac{0.035}{(\beta^3+1)}$. Further, the rotor is affected by aerodynamic torque and the value of the torque is calculated as (3):

$$T_r(\omega_r(t), \beta(t), V(t)) = \frac{1}{2}\frac{\rho\pi R^3 V^2(t)}{\lambda} C_p(\lambda(t), \beta(t)). \tag{3}$$

Dynamics of drive train can be specified by the resulting (4) [22]:

$$\begin{aligned}
\dot{\omega}_r(t) &= \frac{1}{J_r}\left[T_r\big(\omega_r(t), \beta(t), V(t)\big) + \frac{B_{dt}}{N_g}\omega_g(t) - K_{dt}\theta_\Delta(t) - \omega_r(t)(B_r + B_{dt})\right], \\
\dot{\omega}_g(t) &= \frac{1}{J_g}\left[\theta_\Delta(t)\frac{K_{dt}\eta_{dt}}{N_g} + \frac{B_{dt}\eta_{dt}}{N_g}\omega_r(t) - \omega_g(t)\left(B_g + \frac{B_{dt}\eta_{dt}}{N_g^2}\right) - T_g(t)\right], \\
\dot{\theta}_\Delta(t) &= \omega_r(t) - \omega_g(t)\frac{1}{N_g},
\end{aligned} \tag{4}$$

where $\omega_r(t)$ is the rotor shaft speed, $\omega_g(t)$ is the generator shaft speed, N_g is the drive train gear ratio, K_{dt} is the rotation stiffness constant value of the drive train, $\theta_\Delta(t)$ is the drive train's rotation angle, η_{dt} is the drive train's efficiency, and $T_g(t)$ is the generator torque. The constants B_{dt}, B_r, B_g in the above equation are the torsion curbing constant value of the drive train, the friction damping constant of the rotor speed shaft, and friction damping constant of the generator speed shaft, respectively. Variable pitch operation is generally obtained by utilizing a hydraulic or electrical actuator. Actuator model portrays the dynamic behavior between the wanted pitch angle β_{ref} and the real pitch angle $\beta(t)$. The actuator dynamic is demonstrated as a first order plant [23]: $\tau\dot{\beta}(t) = \beta_{ref} - \beta(t)$ with $|\beta(t)| \leq C_\beta$ and $|\dot{\beta}(t)| \leq C_{\dot{\beta}}$, where τ is the pitch angle's time constant, $C_\beta, C_{\dot{\beta}}$ are positive scalars which define range and rate constraints, respectively. When the pitch actuator $\beta(t)$ is selected as input to the drive-train**,** the state space form of the linearized drive train is presented as (5):

$$\dot{x}(t) = Ax(t) + Bu(t) + B_d d(t), y(t) = Cx(t). \tag{5}$$

For pitch regulation at rated speed $\partial T_g(t) = 0$. Let $x_2(t) = \omega_g(t), x_1(t) = \theta_\Delta(t)$ and $x_3(t) = \omega_r(t)$ be the perturbed states of the system, $u(t) = \beta(t)$ is the perturbed input, $d(t) = v(t)$ is disturbance deviation from the operating point $(\omega_r^*, \beta^*, v^*)$, respectively. The parameter $y(t)$ is the output term of linearized model. The coefficient matrices details are listed as [24]:

$$A = \begin{bmatrix} 0 & -\frac{1}{N_g} & 1 \\ \frac{\eta_{dt}K_{dt}}{N_g J_g} & -\frac{(\eta_{dt}B_{dt} + N_g^2 B_g)}{J_g N_g^2} & \frac{\eta_{dt}B_{dt}}{J_g N_g} \\ -\frac{K_{dt}}{J_r} & \frac{B_{dt}}{N_g J_r} & -\frac{(B_{dt}+B_r)}{J_r} + \frac{1}{J_r}\gamma \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ \delta\frac{1}{J_r} \end{bmatrix}, B_d = \begin{bmatrix} 0 \\ 0 \\ \xi\frac{1}{J_r} \end{bmatrix}, C = [0 \;\; 0 \;\; 1],$$

where γ, ξ, and δ are described in [24]. The following assumptions are made for VSWT systems:

- Assumption 1: the sets (A, B) and (C, A) are fully controllable and observable, respectively.
- Assumption 2: the symbols B and C are the matrices with full rank and $\text{rank}(CB) = \text{rank}(B) = m$.
- Assumption 3: the sign $d(t)$ is exogenous perturbation bounded by $d(t) \leq \mu H(t)$, where constant $\mu > 0$ and $H(t)$ is a positive scalar or function which represents $\|x(t)\|$ upper limit ($\|x(t)\| \leq \|H(t)\|$).

3. MAIN RESULTS

In this section, a novel SMC law will be established by using new observer. A designed controller will keep the plant's states moving along the switching surface from the zero-reaching time as our key contribution. First, a new observer is designed.

3.1. Observer design

To get a better wind turbine control, the controllers investigated in previous publications essentially require that all parameter values are available for the measuring devices. This will produce a height cost. To solve this problem, a new estimator is presented in this section.

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L[y(t) - \hat{y}(t)], \hat{y}(t) = C\hat{x}(t), \qquad (6)$$

where $\hat{x}(t) \in R^n, \hat{y}(t) \in R^p, L \in R^{n \times p}$ are the estimation of the system states, the output of the estimator, the estimator's gain. The difference between the estimated and the actual variables be described by $e(t)$, i.e., $e(t) = x(t) - \hat{x}(t)$. Then, by combining first (5) and (6) lead to the estimator error as (7):

$$\dot{e}(t) = [A - LC]e(t) + B_d d(t). \qquad (7)$$

3.2. Stability analysis of the wind turbine system in sliding mode dynamics

To construct an output feedback pitch angle control signal, a novel single phase switching function is suggested such that the VSWT plant's state trajectories are entered the switching surface and stay on it. Now, the plant's robustness without reaching time in SMC technique is ensured by the following single-phase switching function.

$$\sigma[\hat{x}(t)] = B\hat{x}(t) - B^+ \int_0^t (A - BK)\hat{x}(\tau)d\tau - B^+\hat{x}(0) \times e^{-\varepsilon t}, \qquad (8)$$

where $\sigma[\hat{x}(t)]$ symbolizes the single phase sliding surface and $B^+ = (B^T B)^{-1} B^T \in R^{m \times n}$ is Moore-Penrose pseudo inverse of B. The design matrix $K \in R^{m \times n}$ is selected to satisfy the following inequality condition of the wind turbine system: $Re[\lambda(A - BK)_{max}[]]$ Now, by differentiating $\sigma[\hat{x}(t)]$ with respect to time combined with (6), we have:

$$\dot{\sigma}[\hat{x}(t)] = B^+BK\hat{x}(t) + B^+Bu(t) + B^+L[y(t) - \hat{y}(t)] + \varepsilon B^+\hat{x}(0)e^{-\varepsilon t} \qquad (9)$$

Thus, the equivalent control law in the sliding mode, $\sigma[\hat{x}(t)] = \dot{\sigma}[\hat{x}(t)] = 0$, is found by:

$$u_i^{eq}(t) = -(B^+B)^{-1} \times \{B^+BK\hat{x}(t) + B^+L[y(t) - \hat{y}(t)] + \varepsilon B^+\hat{x}(0)e^{-\varepsilon t}\} \qquad (10)$$

By replacing $u(t) = u_i^{eq}(t)$ to the wind turbine systems (5) yields the sliding motion:

$$\dot{x}(t) = [A - BK]x(t) + [BK - B(B^+B)^{-1}B^+LC]e(t) + B_d d(t) - \varepsilon B(B^+B)^{-1} \times B^+\hat{x}(0)e^{-\varepsilon t} \qquad (11)$$

Combining the (11) with the error estimation (7), the closed-loop VSWT plant is described as (12):

$$\begin{bmatrix} \dot{x}(t) \\ \dot{e}(t) \end{bmatrix} = \begin{bmatrix} A - BK & \Phi \\ 0 & A - LC \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} + \begin{bmatrix} I & \Omega \\ I & 0 \end{bmatrix} \begin{bmatrix} B_d d(t) \\ e^{-\varepsilon t} \end{bmatrix}, \qquad (12)$$

where $\Phi = BK - B(B^+B)^{-1}B^+LC, \Omega = -\varepsilon B(B^+B)^{-1}B^+\hat{x}(0)$.

The dynamic motion (11) offers the constraint that the wind turbine plant in the switching surface is stable if the (11) is stable and the observability constraint satisfies the assumption 2. Thus, the (11) is also built Hurwitz, so the dynamic error of the estimator $e(t)$ converges to zero when time approaches to infinity. To clarify the constraint, we suggest the following proposition.

- Theorem 1: if there exist symmetric positive definite matrices M, N and $\mu > 0, \bar{\mu} > 0, \tilde{\eta} > 0$ such that the LMI holds:

$$\begin{bmatrix} \Xi & M\Phi & MB_d & M\Omega & 0 \\ \Phi^T M & \Psi & 0 & 0 & NB_d \\ B_d^T M & 0 & -\mu^{-1} & 0 & 0 \\ \Omega^T M & 0 & 0 & -\tilde{\mu}^{-1} & 0 \\ B_d^T N & 0 & 0 & 0 & -\bar{\mu}^{-1} \end{bmatrix} < 0, \qquad (13)$$

where $\Xi = M(A - BK) + (A - BK)^T M$, $\Psi = N(A - LC) + (A - LC)^T N$, $\Phi = BK - B \times (B^+B)^{-1}B^+LC$, $\Omega = -\varepsilon B \times (B^+B)^{-1}B^+\hat{x}(0)$. Then, the VSWT plant (12) is asymptotically stable.

- Proof: to demonstrate the stability of the plant (12), we select the below Lyapunov function $V[x(t), e(t)] = \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} M & 0 \\ 0 & N \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$, where $M > 0$ and $N > 0$ satisfy (13). By getting the time derivative along the system state trajectory of wind turbine system and combining (12), we get:

$$\dot{V}[x(t), e(t)] = \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} M(A-BK)+(A-BK)^T M & M\Phi \\ \Phi^T M & N(A-LC)+(A-LC)^T N \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$$
$$+x^T(t)MB_d d(t) + B_d^T d^T(t) I^T M x(t) + e^T(t) N B_d d(t) + B_d^T d^T(t) I^T N e(t)$$
$$+ x^T(t) M \Omega e^{-\varepsilon t} + (e^{-\varepsilon t})^T \Omega^T M x(t) \tag{14}$$

By applying Lemma 12 in the paper [13] to the above equation and defining $\Xi = M(A-BK)+(A-BK)^T M$, $\Psi = N(A-LC)+(A-LC)^T N$, and $\tilde{\eta} = \mu^{-1} + \bar{\mu}^{-1}$, (14) can be characterized as (15):

$$\dot{V}[x(t), e(t)] \leq \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}^T \begin{bmatrix} \Xi + \mu M B_d B_d^T M + \tilde{\mu} M \Omega \Omega^T M & M\Phi \\ \Phi^T M & \Psi + \bar{\mu} N B_d B_d^T N \end{bmatrix} \begin{bmatrix} x(t) \\ e(t) \end{bmatrix}$$
$$+ \tilde{\eta} \|d(t)\|^2 + \tilde{\mu}^{-1} (e^{-\varepsilon t})^T e^{-\varepsilon t} \tag{15}$$

Moreover, employing the Schur complement in [13], the sufficient condition (13) can be rewritten as (16):

$$\Upsilon = -\begin{bmatrix} \Xi + \mu M B_d B_d^T M + \tilde{\mu} M \Omega \Omega^T M & M\Phi \\ \Phi^T M & \Psi + \bar{\mu} N B_d B_d^T N \end{bmatrix} > 0 \tag{16}$$

According to (15) and (16), we achieve $\dot{V}[x(t), e(t)] \leq -\lambda(\Upsilon) \left\| \widetilde{\begin{bmatrix} x(t) \\ e(t) \end{bmatrix}} \right\|^{2^2}_{min}$ where $\nu = \|d(t)\|$, $\delta(t) = \tilde{\mu}^{-1} (e^{-\varepsilon t})^T e^{-\varepsilon t}$, and the eigenvalue $\lambda(\Upsilon)_{min}$. The term $\delta(t)$ will hit to zero when the time approaches infinity. Hence, $\dot{V}[x(t), e(t)] \leq 0$ is obtained $\left\| \begin{bmatrix} x(t) \\ e(t) \end{bmatrix} \right\| > \sqrt{\frac{\tilde{\eta} \nu^2}{\lambda(\Upsilon)_{min}}}$. If $\dot{V}[x(t), e(t)] \leq 0$ show that the sufficient condition (13) satisfies, consequently, it further clarifies that the switching motion (12) is asymptotical stable.

3.3. New observer-based SPRSMC

In the previous section, we have designed the single-phase switching function, the state observer, and the proved whole system is asymptotically stable. In this section, we are going to determine the single phase SMC law such that the VSWT plant's state trajectories will be driven to the switching surface (8) from the instance time. The controller will be designed based on the proposed observer (6). As single phase switching function is defined in (8), the continuous SMC scheme which only uses the estimated states from the state estimator for the pitch angle of the wind turbine plant can be found as (17):

$$u(t) = -(B^+ B)^{-1} \{ \|B^+ BK\| \hat{x}(t) + \|B^+ L\| [\|y(t)\| - \|\hat{y}(t)\|] + \alpha \|\sigma(t)\| +$$
$$\varepsilon B^+ \hat{x}(0) e^{-\varepsilon t} \} sign(\sigma_i(t)). \tag{17}$$

To verify reachability of the system state variables to sliding surface, we suggest the following proposition as:

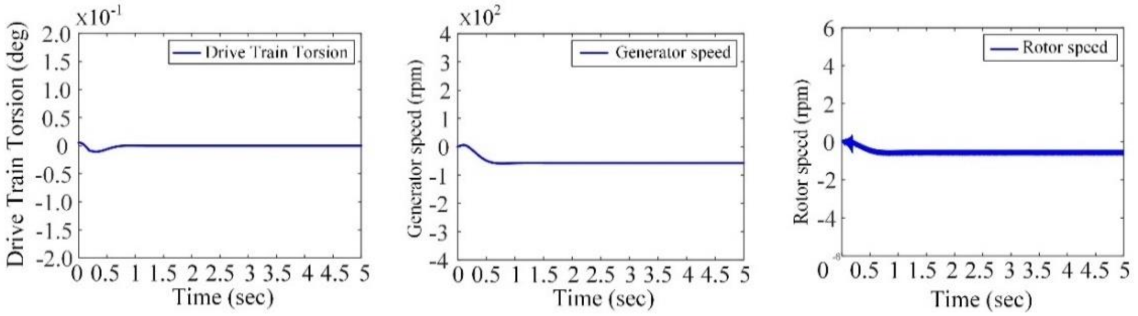
- Theorem 2: supposing that the LMI (13) has a solution $\mu > 0, \bar{\mu} > 0, \tilde{\eta} > 0$. Consider the wind turbine system (5) subject to Assumptions 1-3. If the switching surface (8), the observer (6), the output feedback SMC (17) are employed, then the plant's states (5) will asymptotically meet to zero from the occurrence time.
- Proof of Theorem 2: let us deliberate the Lyapunov function candidate $V(t) = \|\sigma(t)\|$, where $\sigma(t)$ is the switching function as the (8). Then, by using the (9), the time derivative of $V(t)$ is attained as (18):

$$\dot{V}(t) = \frac{\sigma^T(t)}{\|\sigma(t)\|} [B^+ BK \hat{x}(t) + B^+ B u(t) + B^+ L [y(t) - \hat{y}(t)] + \varepsilon B^+ \hat{x}(0) e^{-\varepsilon t}]. \tag{18}$$

By replacing the control signal (17) into (18), we have $\dot{V}(t) \leq -\alpha \|\sigma(t)\|$, where $\alpha > 0$ and $\hat{x}(t)$ is the state observer defined in the (6). Therefore, $\dot{V}(t)$ is less than zero which shows that the wind turbine system (5) is lead to the switching surface from zero reaching time.

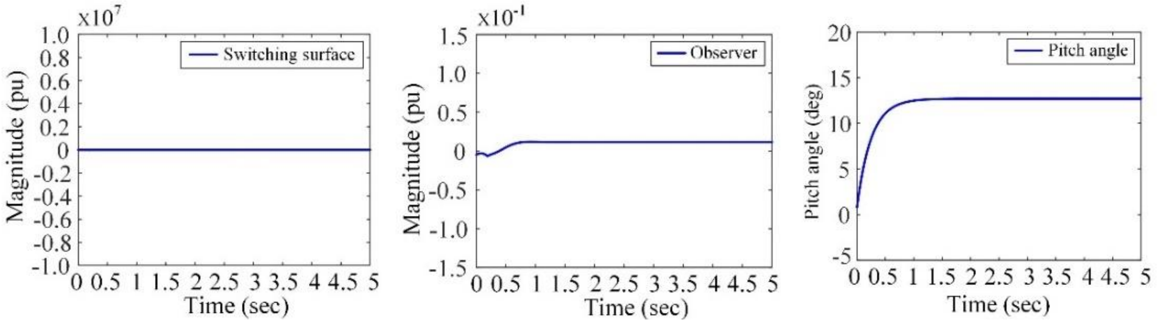
4. EXAMPLE AND SIMULATION

This section, the usefulness of suggested technique is carried out on the wind turbine standard model anticipated by a 5-MW three-blade wind turbine system with external perturbations [25]. Because the nonlinear in the FAST wind turbine model is high and changes with wind speed, we consider the effectiveness of the proposed control signal when the wind speed drift from the rated wind speed of 11.4 m/s. Figure 1(a) show drive train torsion, Figure 1(b) show the generator speed, and Figure 1(c) show the rotor speed of the VSWT plant. Figure 2(a) show the switching surface, Figure 2(b) show the observer, and Figure 2(c) show the pitch angle.



(a) (b) (c)

Figure 1. Time answer of: (a) the drive train torsion, (b) the generator speed, and (c) the rotor speed



(a) (b) (c)

Figure 2. Time reaction of: (a) the switching surface, (b) the observer, and (c) the pitch angle

From the aforementioned investigation of the attained simulation outcomes, it is clear to observe that the sliding mode occurs from the initial time moment (t=0). In addition, it can be indicated that the enhanced robustness and the wanted dynamic response of the VSWT systems are achieved by dismissing reaching phase that has reduced the limitations required in other researches [6] or [16]. Additionally, unlike the recent researches [4] or [5], the suggested technique does not require the accessibility of the state variables of the wind turbine systems. Thus, this technique is very valuable and more realistic, since it can be simply executed in many real-world VSWT plants.

5. CONCLUSION

This study represents the novel observer-based SPRSMC, which eliminates entirely the reaching phase and utilizes output information only, for a 5MW VSWT system. We have proposed the new switching surface such that the reaching time starts from zero and the VSWT plant is insensitive the external disturbance. The observer has been established to guess the immeasurable states for providing the controller strategy. The new SPRSMC for the VSWT systems has been built by utilizing the estimated states and output information only. Enhanced robustness and the anticipated dynamic response are attained by the elimination of the reaching phase that has reduced the restrictions required in other work. Moreover, the sufficient condition has been given by using the LMI technique such that the motion dynamics in sliding mode possess the property of asymptotical stability. Besides, the solution of suggested controller has been successfully implemented on a 5-MW three-blade wind turbine system with external perturbations. It is evident that the suggested technique is not only robust in the presence of exogenous disturbances but also can be applied to an actual wind turbine system.

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