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Estimator-based single phase second order variable structure controller for the pitch control of a variable speed wind turbine

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ABSTRACT

A novel single phase second order variable structure controller (SPSOVSC) based on estimated variables and output information only is presented for the variable speed wind turbine (VSWT) system. In contrast with a recent method, the output feedback and second order sliding mode control techniques are deliberated for the SPSOVSC design in the VSWT. The selection of an integral single-phase sliding surface is established such that the reaching phase required in the basic variable structure control (BVSC) scheme is removed since the plant's state trajectories always begin from the sliding surface. In addition, appropriate stability constraints by Lyapunov based novel linear matrix inequality (LMI) technique are acquired to guarantee the entire VSWT plant's steadiness. Using the proposed techniques, the SPSOVSC is developed to modify BVSC to advance the performance of VSWT plant in terms of overshoot and settling time. The results show the new scheme is highly robust in sliding variable's fast convergence to zero asymptotically. It is obvious that the robustness of the proposed controller in terms of steadiness and usefulness of the scheme.

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NOMENCLATURE

${A^{/}}^{T}$	:	Transpose of $A^{/}$ matrix	$\lVert z(t) \rVert$	:	Norm of state vector $z(t)$
${A^{/}}^{-1}$	:	Inverse of $A^{/}$ matrix	${B^{/}}^{\perp}$	:	Perpendicular complement of $B^{/}$ matrix
$z(t)$	:	States of the plant	${B^{/}}^{+}$	:	Moore-Penrose inverse of $B^{/}$ Matrix
$y(t)$	:	Output signal	λ_{min}	:	Minimum eigenvalue
$\eta(z,t)$	:	Lumped uncertainty	$u(t)$	:	Variable structure controller
$\sigma[\hat{z}(t)]$	:	Single phase switching surface	$\theta(t)$	:	Dynamics error of estimator
$s(t)$	:	Sliding manifold function	$\xi(z,t)$	:	Disturbance input signal
$\omega_g(t)$	:	Generator shaft speed	$\theta_{\Delta}(t)$	:	Drive train's torsion angle
$\omega_r(t)$	:	Rotor shaft speed	η_{dt}	:	Proficiency of the drive train
P_a	:	Aerodynamic power	$C_p(\lambda,\beta)$	:	Pitch angle function

1. INTRODUCTION

In the last decade, wind energy is one of the foremost renewable power sources. It leads to a growing insertion of this energy in the power system [1]. One of the most common uses of wind energy is a variable speed wind turbine (VSWT) plant, which converts the mechanical power of VSWT attained from wind into electrical power through a generator. Most VSWT systems provide for variable-speed procedure with the help of pitch control so that the wanted energy output can be attained [2]. Many pitch angle control approaches have been proposed by now. The traditional pitch angle controllers were established by proportional integral derivative (PID), particle-swarm-optimization (PSO), fuzzy logic procedure, and neural network techniques mostly [3]-[7]. These controllers have high reliability, good stability, and simple construction but it immoderately depends on model parameters of controlled objects and robustness is not so good. In addition, these controllers are mostly responsive to parametric changes and model uncertainties. These exterior trepidations and uncertainties may harm and even abolish the pitch control plants considered on nominal models. Consequently, the controller requests to have high robustness and strong dynamic quality.

To solve these disadvantages, sliding mode control (SMC) with sliding mode, also termed variable structure control (VSC), is an arresting and robust control technique for controlling dynamical systems containing uncertainties [8], [9]. Its benefits comprise high robustness, strong response, simple structure, and is easy to be appreciated in wind power plants, which has been effectively implemented in concentration and application [10], [11]. Zhang *et al.* [10] explained projection type adaptation laws and adaptive robust integral SMC were explored for electro-hydraulic servo pitch angle plant to increase the performance of pitch angle control for VSWT. An adaptive fractional-order non-singular fast terminal VSC signal was established for controlling the VSWT's pitch angle against exogenous perturbations and uncertainties [11]. However, these works could not reduce the undesirable high-frequency vibrations in signal input. This unwanted chattering is caused by the disjointed control signal and is identical hazardous to the electromechanical actuator of control systems [12]. One solution to cancel the chattering is to use the well-known second-order variable structure control (SOVSC) technique [13], [14]. Recently, a novel sliding mode controller was investigated in [15] for wind turbine pitch angle control. Nevertheless, these researches have supposed that the states of VSWT plant are available. This is worthless in the practical control plants. To overcome this drawback, the researchers in the recent investigates [16]-[18] have utilized the output feedback approach. Based on this technique, an adaptive SMC law was constructed in [18] to regulate rotor speed and wind turbine energy subject to uncertainties and actuator faults. By using sliding mode observer, a pitch angle controller was developed in [17] for wind turbine. Unfortunately, in the existing wind turbine researches of the SMC, the plant is sensible to the uncertainties and exogenous perturbations 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 hit to the switching surface and the system's performance is unknown in the reaching phase. Consequently, the global steadiness of plant may not be assured or dangerously despoiled [19]. Consequently, it is crucial for the VSWT's pitch angle control to develop a novel SOVSC eliminating the reaching phase and undesirable high-frequency vibrations input signal.

Interested by the aforementioned researches, in this paper, we effort to address an output feedback robustness variable structure controller for the VSWT system's pitch control with unmeasurable states and exogenous disturbances. For novel SOVSC based on estimated variables and output information only is presented for the VSWT plant. First, a one-phase switching surface is established such that the reaching phase required in the traditional VSC scheme is removed since the plant's states always beginning from the switching surface. Secondly, an estimator is proposed to conjecture the inestimable states of the VSWT plants. Then, a single-phase SOVSC, only employ output data, is constructed to guarantee not only the system's stability but also the undesirable high-frequency fluctuation removal. Additionally, appropriate LMI stability constraints by LMI technique and Razumikhin–Lyapunov approach are derived to certify the entire stability of the plant for all time. Lastly, a numerical illustration of 5-MW three-blade wind turbine is anticipated to demonstrate the usefulness of the suggested theoretical attainments.

2. MODEL OF WIND TURBINE SYSTEM IN STATE SPACE FORM

Generally, a variable speed wind turbine (VSWT) plant includes the following constituents i.e. aerodynamical, drive trains, generator, and pitch actuator models. The pitch angle control affects on the aerodynamic forces progressed on the rotor. Consequently, an inappropriate controller may induce the fluctuations and bends in the tower. The aerodynamic power exerted by wind to move the rotor. It relies on three main factors comprising the energy curve of the machine, the available power of wind, and the machine ability to react to wind fluctuations. Based on the results of [20], [21] drive train is transmission plant which converts low speed to high speed to drive the generator rotation. Table 1 shows the dynamics of drive train based on Newton's second law.

Table 1. Dynamics equation of drive train [18]

Parameters	Expression
Rotor shaft speed ($\dot{\omega}_r$)	$\frac{1}{J_r}\left[T_r(\omega_r(t),\beta(t),V(t))+\frac{B_{dt}}{N_g}\omega_g(t)-K_{dt}\theta_\Delta(t)-(B_{dt}+B_r)\omega_r(t)\right]$
Generator shaft speed ($\dot{\omega}_g$)	$\frac{1}{J_g}\left[\frac{\eta_{dt}K_{dt}}{N_g}\theta_\Delta(t)+\frac{\eta_{dt}B_{dt}}{N_g}\omega_r(t)-\left(\frac{\eta_{dt}B_{dt}}{N_g^2}+B_g\right)\omega_g(t)-T_g(t)\right]$
Torsion angle of the drive train ($\dot{\theta}_\Delta$)	$\omega_r(t)-\frac{1}{N_g}\omega_g(t)$

The constants B_{dt}, B_r, B_g in the above equation are the torsion hampering constants of the drive train, the abrasion damping constant of the low-speed (rotor) shaft, and the friction hampering constant of the high-speed (generator) shaft, respectively. The terms $V(t)$ and $\beta(t)$ are wind speed's cube and pitch angle functions, respectively. In addition, $K_{dt}, N_g, \theta_\Delta(t), \eta_{dt}$, are the torsion stiffness coefficient of the drive train, the drive train gear proportion, the spin angle of the drive train, and the efficiency of the drive train, respectively. And $T_g(t)$ is the generator torque. Variable pitch operation is mostly attained by employing a hydraulic or electrical actuator. The actuator model symbolizes the dynamic behavior between the pitch request β_{ref} from the pitch controller and the actuation of this request $\beta(t)$. The dynamics of pitch actuators is generally characterized by a first-order plant [22]:$\tau_c\dot{\beta}(t)=-\beta(t)+\beta_{ref}$ with $|\beta(t)|\le C_\beta$ and $|\dot{\beta}(t)|\le C_{\dot{\beta}}$, where τ_c is the time constant of pitch angle with $\tau_c=(0.2-0.25)$, $C_\beta, C_{\dot{\beta}}$ are positive scalars that define range and rate constraints, respectively. By choosing the pitch actuator $\beta(t)$ as input to the drive-train, the linearized model of the VSWT system is displayed as (1).

$$\begin{aligned}\dot{z}(t)&=[A^/+\Delta A^/(z,t)]z(t)+B^/[u(t)+\xi(z,t)]+B_d d(t)\\&=A^/z(t)+B^/u(t)+\eta(z,t), y=C^/z(t)\end{aligned} \tag{1}$$

Where $A^/, B^/, C^/$are the coefficient matrices; $\Delta A^/(z,t)$ is the parameter uncertainties; $B^/\xi(z,t)$ is the disturbance input signal; and the lumped uncertainty $\eta(z,t)$ is demarcated as follows: $\eta(z,t)=\Delta A^/(z,t)z(t)$ $+B^/\xi(z,t)+B_d d(t)$. In addition, the plant states $z(t)=[\theta_\Delta(t)\ \omega_g(t)\ \omega_r(t)]^T\in R^n$, $u(t)=\beta(t)\in R^m$ is the perturbed input, $d(t)=v(t)$ is perturbation deviation from the operating point (ω_r^*,β^*,v^*), respectively. The parameter $y(t)\in R^p$ is the output term of the linearized model. The matrices' details are listed as [23].

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

Where $\gamma,\ \xi,\ \delta$ are the specified coefficients in the work [23].

In the best conceivable solution, several assumptions are specified to show the reality and viability of the VSWT plants as well as the plant parameters-based pitch control approaches under certain constraints.

- Assumption 1. The pair (A,B) and (C,A) are fully controllable and observable, correspondingly.
- Assumption 2. The input matrices B and C have full rank, and $rank(CB)=rank(B)=m$.
- Assumption 3. The lumped uncertainties $\eta(z,t)$ and the derivative of $\dot{\eta}(z,t)$ are constrained, i.e., there exist acknowledged scalars γ and ρ such that $\|\dot{\eta}(z,t)\|\le\rho$ and $\|\eta(z,t)\|\le\gamma$, where $\|.\|$ is the matrix norm.

3. NEW ESTIMATOR-BASED SECOND ORDER-VARIABLE STRUCTURE CONTROLLER

3.1. Design of novel estimator

In the existing research, all parameters associated with the controller are supposed to be measured by sensors. However, it is costly or difficult to measure all plant variables in practical systems. To explain this problem, we utilize a linearized model of the VSWT to propose the estimator, and it is described as (2).

$$\dot{\hat{z}}(t)=A^/\hat{z}(t)+B^/u(t)+R[y(t)-\hat{y}(t)], \hat{y}=C^/\hat{z}(t) \tag{2}$$

Where $\hat{z}(t) \in R^n$ is the approximation vector of $z(t)$, $\hat{y}(t) \in R^p$ is the estimator's yield, $R \in R^{n\times p}$is the gain of the estimator. The dynamics of its error $\theta(t) = z(t) - \hat{z}(t)$ is governed by the form.

$$\begin{aligned}\dot{\theta}(t) &= A^/ z(t) + B^/ u(t) + \eta(z,t) - \{A^/ \hat{z}(t) + B^/ u(t) + R[y(t) - \hat{y}(t)]\} \\ &= [A^/ - RC^/]\theta(t) + \eta(z,t), \end{aligned} \tag{3}$$

3.2. Stability analysis of the wind turbine system by LMI theory

In this part, the build of the suggested controller comprises two steps. Initially, the strategy of new single phase switching surface (SPSS) which the trajectories of the plant in the SPSS can asymptotically meet to zero. Secondly, a novel SPSOVSC is constructed for the VSWT plant which its state trajectories are forced forward the switching surface and stay on it. By proposing an SPSS and taking time derivative of its, and merged with (2), we get (4).

$$\begin{aligned}\sigma[\hat{z}(t)] &= B^{/+}\hat{z}(t) - B^{/+}\int_0^t (A^/ - B^/ S)\hat{z}(\tau)d\tau - B^{/+}\hat{z}(0)e^{-\varepsilon t} \quad \dot{\sigma}[\hat{z}(t)] \\ &= B^{/+}B^/ S\hat{z}(t) + B^{/+}B^/ u(t) + B^{/+}R[y(t) - \hat{y}(t)] + \varepsilon B^{/+}\hat{z}(0)e^{-\varepsilon t}\end{aligned} \tag{4}$$

Where the Moore-Penrose pseudo inverse of $B^/$ is $B^{/+} = (B^{/T}B^/)^{-1}B^{/T} \in R^{m\times n}$, and S is the design matrix. The design matrix $S \in R^{m\times n}$ is chosen to indulge the inequality condition of the wind turbine system: $Re[\lambda /^/{}_{max}$ setting $\sigma[\hat{x}(t)] = \dot{\sigma}[\hat{x}(t)] = 0$, we can infer that the equivalent control is rewritten as (5).

$$u_{eq}(t) = -(B^{/+}B^/)^{-1}\{B^{/+}B^/ S\hat{z}(t) + B^{/+}R[y(t) - \hat{y}(t)] + \varepsilon B^{/+}\hat{z}(0)e^{-\varepsilon t}\} \tag{5}$$

Replacing $u(t)$ with $u_i^{eq}(t)$ into the second of (4) produces the sliding motion, as (6).

$$\dot{z}(t) = [A^/ - B^/ S]z + [B^/ S - B^/(B^{/+}B^/)^{-1}B^{/+}RC^/]\theta - B^/(B^{/+}B^/)^{-1}\varepsilon B^{/+}\hat{z}(0)e^{-\varepsilon t} + \eta(z,t) \tag{6}$$

From (3) and (6), the sliding motion can be represented as (7).

$$\begin{bmatrix}\dot{z}(t)\\ \dot{\theta}(t)\end{bmatrix} = \begin{bmatrix}A^/ - B^/ S & \Omega\\ 0 & A^/ - RC^/\end{bmatrix}\begin{bmatrix}z(t)\\ \theta(t)\end{bmatrix} + \begin{bmatrix}I & \Xi\\ I & 0\end{bmatrix}\begin{bmatrix}\eta(z,t)\\ e^{-\varepsilon t}\end{bmatrix}, \tag{7}$$

Where $\Omega = B^/ S - B^/(B^{/+}B^/)^{-1}B^{/+}RC^/$, $\Xi = -B^/(B^{/+}B^/)^{-1}\varepsilon B^{/+}\hat{z}(0)$.

The dynamic motion in (7) offers the constraint that the wind turbine plant in the SPSS is stable if the sliding dynamics in (7) is stable and the observability constraint embraces assumption 1. Thus, the sliding dynamics in (7) is also finished Hurwitz, so the estimator error $\theta(t)$ tends 0 when $t \to \infty$. To clarify the above constraint, the steadiness of VSWT plant can be itemized as follows.

Theorem 1. The sliding gesticulation dynamics as designated in (6) is asymptotically steady, if there exist positive definite matrices $P > 0, Q > 0$, and $\mu > 0, \bar{\mu} > 0, \tilde{\eta} > 0$ such that resulting LMI constraint satisfies.

$$\begin{bmatrix}P(A^/ - B^/ S) + (A^/ - B^/ S)^T P & P\Omega & P & P\Xi & 0\\ \Omega^T P & Q(A^/ - RC^/) + (A^/ - RC^/)^T Q & 0 & 0 & Q\\ P & 0 & -\mu^{-1} & 0 & 0\\ \Xi^T P & 0 & 0 & -\tilde{\mu}^{-1} & 0\\ Q & 0 & 0 & 0 & -\bar{\mu}^{-1}\end{bmatrix} < 0 \tag{8}$$

Proof: To demonstrate the steadiness of the of the plant dynamics, we indicate the Lyapunov formal $V[z(t),.\theta(t)] = \begin{bmatrix}z(t)\\ \theta(t)\end{bmatrix}^T \begin{bmatrix}P & 0\\ 0 & Q\end{bmatrix}\begin{bmatrix}z(t)\\ \theta(t)\end{bmatrix}$, where $P > 0$ and $Q > 0$ satisfy (8). By receiving the time derivative along the VSWT's state trajectory, combining the (7), and applying Lemma 12 in the paper [24], and by defining $\tilde{\nu} = \|\eta(z,t)\|$ and $\tilde{\delta}(t) = \tilde{\mu}^{-1}(e^{-\varepsilon t})^T e^{-\varepsilon t}$, we have (9).

$$\begin{aligned}\dot{V} \le &\begin{bmatrix}z(t)\\ \theta(t)\end{bmatrix}^T \begin{bmatrix}P(A^/ - B^/ S) + (A^/ - B^/ S)^T P + \mu PP + \tilde{\mu}P\Xi\Xi^T P & P\Omega\\ \Omega^T P & Q(A^/ - RC^/) + (A^/ - RC^/)^T Q + \bar{\mu}QQ\end{bmatrix}\begin{bmatrix}z(t)\\ \theta(t)\end{bmatrix}\\ &+(\mu^{-1} + \bar{\mu}^{-1})\tilde{\nu}^2 + \tilde{\delta}(t)\end{aligned} \tag{9}$$

By employing the Schur complement in [24], the LMI (8) is corresponding to (10).

$$\Theta = \begin{bmatrix} P(A^{/} - B^{/}S) + (A^{/} - B^{/}S)^{T}P + \mu PP + \tilde{\mu} P \Xi \Xi^{T} P & P\Omega \\ \Omega^{T}P & Q(A^{/} - RC^{/}) + (A^{/} - RC^{/})^{T}Q + \bar{\mu} QQ \end{bmatrix} > 0 \tag{10}$$

By utilizing in (9) and (10), we achieve $\dot{V}[z(t),\theta(t)] \le -\lambda_{\min}(\Theta)\|\hat{z}(t)\|^2 + (\mu^{-1} + \bar{\mu}^{-1})\tilde{v}^2 + \tilde{\delta}(t),$ where the eigen value $\lambda_{\min}(\Theta) > 0$ and the term $\tilde{\delta}(t)$ will hit to zero when the time approaches infinity. Hence, $\dot{V}[z(t),\theta(t)] \le 0$ is obtained by using (10). If $\dot{V}[z(t),\theta(t)] \le 0$ show that the LMI (8) embraces, hence, it further clarifies that the sliding motion (7) is asymptotical stable. We can rewrite as: $\dot{V}[z(t),\ \theta(t)] \le -\lambda_{\min}(\Theta)\|\hat{z}(t)\|^2 + (\mu^{-1} + \bar{\mu}^{-1})\tilde{v}^2,$ where the constant $(\mu^{-1} + \bar{\mu}^{-1})\tilde{v}^2$ and the eigenvalue $\lambda_{\min}(\Theta) > 0$. Hence, $\dot{V}[z(t),\ \theta(t)] \le 0$ is obtained with $\|\hat{z}(t)\| > \sqrt{\frac{(\mu^{-1}+\bar{\mu}^{-1})\tilde{v}^2}{\lambda_{min}(\Theta)}}$ Thus, the (7) is asymptotically stable.

3.3. Output feedback second-order variable structure control law design

In the above section, we have constructed the new SPSS based on a state estimator. Theorem 1 has been established for proving the whole stability of the VSWT system. In this step, we are going to establish a new SPSOVSC such that the state paths of the VSWT plant will be driven to the switching manifold from the zero-reaching time. The vital impression of the second order VSC procedure is to implement the second order sliding variable's derivative (11), rather than the primary derivative as in traditional sliding mode. Firstly, the second order derivative of the sliding variable is considered as (11).

$$\ddot{\sigma}(t) = B^{/+}B^{/}S\dot{\hat{z}}(t) + B^{/+}B^{/}\dot{u}(t) + B^{/+}R[\dot{y}(t) - \dot{\hat{y}}(t)] - \varepsilon^2 B^{/+}\hat{z}(0)e^{-\varepsilon t} \tag{11}$$

The sliding manifold is showed as $s(t) = \dot{\sigma}(t) + \bar{X}\sigma(t).$ Using the second of (4), (11), its derivative is calculated as (12).

$$\begin{aligned}\dot{s}(t) = \ddot{\sigma}(t) + \bar{X}\ \dot{\sigma}(t) = B^{/+}B^{/}S\dot{\hat{z}}(t) + B^{/+}B^{/}\dot{u}(t) + B^{/+}R[\dot{y}(t) - \dot{\hat{y}}(t)] + \\ \bar{X}\ \dot{\sigma}(t) - \varepsilon^2 B^{/+}\hat{z}(0)e^{-\varepsilon t}\end{aligned} \tag{12}$$

Where $\bar{X} > 0$ is a positive constant. Now, a novel following output feedback control signal is designed based on the suggested estimator and sliding manifold above for neglecting the high frequency oscillation in control input and alleviating the VSWT (1). This is main attainment of this research.

$$\begin{aligned}\dot{u}(t) = -(B^{/+}B^{/})^{-1}\{\|B^{/+}B^{/}S\|\|\dot{\hat{z}}(t)\| + \|B^{/+}R\|[\|\dot{y}(t)\| - \|\dot{\hat{y}}(t)\|] + \|X^{-}\|\|\dot{\sigma}(t)\| - \\ \varepsilon^2\|B^{/+}\|\|\hat{z}(0)\|e^{-\varepsilon t} + \alpha\|s(t)\|\}sign(s(t)).\end{aligned} \tag{13}$$

To prove the reachability of the VSWT plant's states to the sliding manifold, the resulting theorem is specified as Theorem 2. Presume that the LMI (8) has a result $\mu > 0,\ \bar{\mu} > 0,\ \tilde{\eta} > 0.$ Consider the VSWT plant with external agitations (1), and advocate that the assumptions 1-2 are gratified**.** If the sliding manifold (12)**,** the estimator (2), and the output feedback variable structure controller (13) are used, then the plant's states (1) will asymptotically meet to zero from the instance time.

Proof of Theorem 2: The Lyapunov formal is described as $V(t) = \|s(t)\|,$ where $s(t)$ is the switching manifold functions as the (12). Then, by using the (12), enchanting the derivative of $V(t)$, and by means of the control signal (13) yields.

$$\begin{aligned}\dot{V} \le \|B^{/+}B^{/}S\|\|\dot{\hat{z}}\| + \|B^{/+}R\|[\|\dot{y}\| - \|\dot{\hat{y}}\|] + \|\bar{X}\|\|\dot{\sigma}\| - \\ -\varepsilon^2\|B^{/+}\|\|\hat{z}(0)\|e^{-\varepsilon t} + \frac{s^T}{\|s\|}B^{/+}B^{/}\dot{u}(t) \le -\alpha\|s(t)\|\end{aligned} \tag{14}$$

Where $\alpha > 0$ and $\hat{z}(t)$ is the state observer demarcated in the (2). Consequently, $\dot{V}(t)$ is less than zero which shows that the VSWT system (1) hits to the switching manifold surface from zero reaching time. Resulting that, Figure 1 describes the flowchart of the suggested estimator-based SPSOVSC.

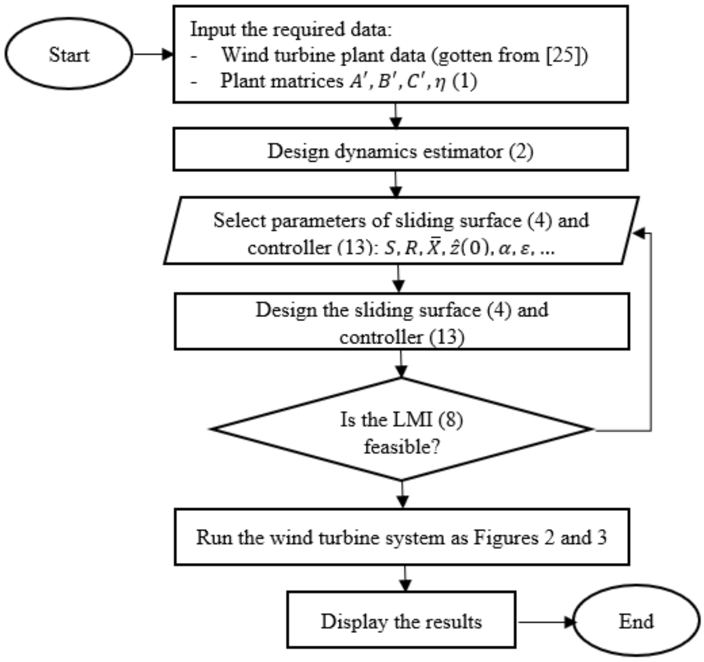


Figure 1. The flowchart of the suggested estimator-based SPSOVSC

4. EXAMPLE AND SIMULATION

In this section, simulations of the proposed technique have been replicated in a MATLAB environment to verify the results. All of the VSWT plant benchmark model parameters are specified which are utilized in Table 2. Because the VSWT plant model in the wind turbine benchmark model is decidedly nonlinear and reliant on wind speed, we consider the effectiveness of the controller when the wind speed drifts from the speed of nominal wind of 11.4 (m/s). The initial condition assumed is $z(0)$ = [-0.05 0.05 0.01]. By utilizing the MATLAB package, we have attained noteworthy marks in Figures 2 and 3.

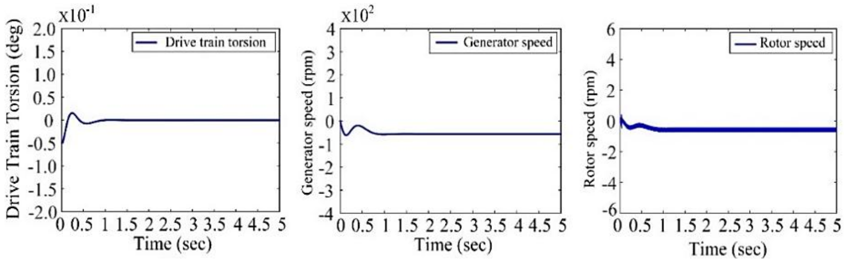
Remark 1. The time answer of the drive train torsion, the generator speed, and the rotor speed are displayed in Figures 2(a)-2(c). We can see that their responses asymptotically approach zero after about 0,7 seconds. In other words, the generator and rotor speed are much lesser by using the suggested attenuated-chattering SOVSC signal (13) considering the unknown external perturbations (1) as compared to [14], [17], [4], which reduces the loading effect and increases the life of the equipment.

Table 2. Properties of the NREL 5-MW wind turbine [25]

Parameters	Value
Rating	5 MW
Rotor orientation, configuration	Upwind, 3 blades
Control	Variable speed, collective pitch
Drivetrain	High speed, multiple-stage gearbox
Rotor, Hub diameter	126 m, 3 m
Hub height	90 m
Cut-in, rated, cut-out wind speed	3 (m/s), 11.4 (m/s), 25 (m/s)
Cut-in, rated rotor speed	6.9 rpm, 12.1 rpm
Rated tip speed	80 (m/s)
Overhang, shaft tilt, precone	5 m, 5°, 25°
Rotor mass	110,000 kg
Nacelle mass	240,000 kg
Tower mass	347,460 kg

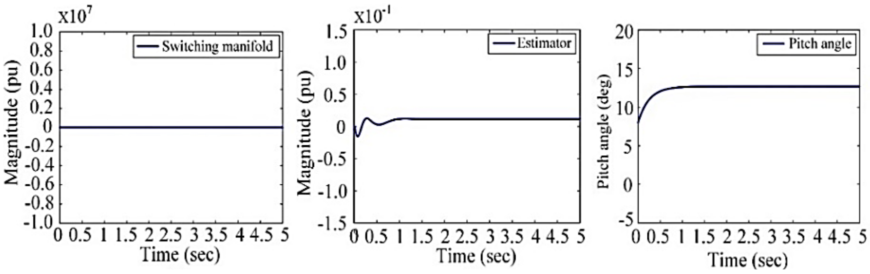
Remark 2. The switching manifold's time history (12), the estimator's error (3), and the pitch angle are displayed in Figures 3(a)-3(c). From Figure 3(a), it is palpable that the sliding variables of VSWT system hits zero from the commencement time ($t \geq 0$) which is implied the removal of the reaching phase in the BVSC. That is, the VSWT system's paths always initiate from the switching surface and the plant's anticipated comeback is certified from the beginning of its gesticulation. Consequently, the total system's forcefulness and recital have been improved. In addition, the undesired chattering is reduced by using second order VSV

technique. From Figure 3(b), the reply time of the estimator error dynamics of the VSWT system rapidly tends to zero. Figure 3(c) displays the pitch angle of a turbine. The attainments explain that when the wind speed fluctuates, the ability to set and stabilize the VSWT system is also better. Thus, this method stretches better performance than the other methods issued in [5], [15], [16]. From the above obtained achievements, we can deduce that the anticipated method is effective for answering the unwanted chattering phenomenon and makes stable for the VSWT systems even at the presence of external distractions.



(a) (b) (c)

Figure 2. Time history of (a) the drive train torsion, (b) the generator speed, and (c) the rotor speed



(a) (b) (c)

Figure 3. Time response of (a) the switching manifold, (b) the estimator, and (c) the pitch angle

5. CONCLUSION

To solve the problem of the chattering removal and unmeasurable plant states in the variable speed wind turbine (VSWT) plant due to lack of sensor, a new single phase second order variable structure controller (SPSOVSC) based on state predictor and output data only is proposed in this paper. The predictor has been proposed to guess the VSWT's inestimable variables for serving the controller approach. Furthermore, a new sufficient constraint in terms of LMIs has been given to guarantee the sliding mode asymptotical steadiness of the VSWT plant. The obtained achievements point out that the SPSOVSC-based second-order VSC technique diminishes the undesired high-frequency fluctuation and advances the system dynamics answer to fast response in setting time and to diminish over or undershoots in the VSWT plant. It is obvious that the suggested controller's robustness is in terms of steadiness and usefulness of the scheme.

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