Control of variable speed variable pitch wind turbine based on a disturbance observer

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Abstract. In this paper, a novel sliding mode controller based on disturbance observer (DOB) to optimize the efficiency of variable speed variable pitch (VSVP) wind turbine is developed and analyzed. Due to the highly nonlinearity of the VSVP system, the model is linearly processed to obtain the state space model of the system. Then, a conventional sliding mode controller is designed and a DOB is added to estimate wind speed. The proposed control strategy can successfully deal with the random nature of wind speed, the nonlinearity of VSVP system, the uncertainty of parameters and external disturbance. Via adding the observer to the sliding mode controller, it can greatly reduce the chattering produced by the sliding mode switching gain. The simulation results show that the proposed control system has the effectiveness and robustness.

1. Introduction
Renewable energy sources play a vital role in energy market because of the increasingly global environmental pollution and significant depletion of fossil fuel sources. Among renewable energy sources, wind energy is one of the most reliable and environment friendly energy source. Therefore, as a way of exploiting wind energy in an efficient way, the wind power generation technology has become the focus of people’s research [1-2]. Due to the highly nonlinear with strongly external disturbances and parameter uncertainties of wind energy conversion system, control technology is the key to keep the system safe and efficient. However, traditional linear controllers cannot achieve good performance. As a result, many nonlinear control theory and linearization methods are used to the VSVP wind turbines.

Sliding mode control (SMC) is also called variable structure control, which is a kind of special nonlinear control essentially. Several types of SMCs were successfully applied to wind turbine pitch system such as a novel adaptive second-order SMC in [3] and high-order SMC in [4-5]. Despite the good performance of the control method, these SMCs still need the information of the boundary function which cannot be calculated.

In this paper, a disturbance observer based on SMC (DOB-SMC) is designed for VSVP wind turbine system. As the aerodynamic torque is a highly nonlinear function, which is linearized at the rated power operating point of wind turbine, and then the dynamic equation of the system is deduced. After transforming the equation to appropriate form, the DOB-SMC is designed. Compared to the control methods in recent years [6-8], the advantages of the proposed DOB-SMC include: the switching gain only depend on the disturbance estimation rather than that of the disturbance; the switching gain is reduced by designing DOB-SMC, which is proposed to solve the chattering problem. Finally, the performance of the controller is analyzed through simulation and conclusions are presented. Compared to conventional control methods, the proposed controller has good robustness and stability.
2. The VSVP wind turbine model

2.1 Aerodynamics model

According to the Betz momentum theory, the aerodynamic power and torque that the wind turbine captures from the wind is expressed as follows,

\[ T_r = \frac{P_r}{\omega_r} = \frac{1}{2} \rho \pi R^2 \frac{v^3}{\omega_r} C_p(\lambda, \beta) \]  

where \( P_r, T_r \) are the aerodynamic power and torque, respectively; \( \rho \) is the air density, \( R \) is the wind turbine rotor radius, \( v \) is the wind speed, \( \omega_r \) is the optimum reference of rotor speed, and the power coefficient \( C_p(\lambda, \beta) \) represent the efficiency of wind turbine to convert the wind energy into electric energy, which is a non-linear function related to the tip-speed ratio \( \lambda \) and the pitch angle \( \beta \).

2.2 The model of drive-train and generator

In the current research, this paper uses a two-quality wind turbine drive-train model, as shown in Fig.2. The low speed shaft connected to the wind turbine is the main drive shaft, and the high-speed shaft connected with the generator is the secondary drive shaft, and both are connected through gearbox. For easy of study, it is assumed that the drive shaft is rigid and free of friction.

![Wind turbine drive-train diagram](image)

The equivalent rotary inertia \( J_r \) of the drive system is defined as

\[ J_r = J_r + N_g J_g \]  

where \( J_r \) is rotor inertia, \( J_g \) is generator inertia.

The gearbox ratio is

\[ N_g = \frac{T_{ls}}{T_{hs}} = \frac{\omega_g}{\omega_r} \]  

where \( T_{ls} \) is the low speed shaft torque, \( T_{hs} \) is the high speed shaft torque, and \( \omega_g \) is generator speed.

As this paper focuses on the control performance of the pitch angel controller, the generator electromagnetic torque \( T_e \) is assumed to maintain constant.

Linearized VSVP wind turbine model

The aerodynamic torque of the wind turbine is also a nonlinear function with respect to the variable \( (\omega_r, \beta, v) \) from equation (1). It’s necessary to linearize the aerodynamic torque \( T_r \) along the constant power operating point \( (\omega_r^*, \beta^*, v^*) \). Equation (5) can be obtained through Taylor expansion to \( T_r \).

\[ \Delta T_r = a \Delta \omega_r + b \Delta \beta + c \Delta v \]  

In order to simplify the model, the mathematical model of the pitch angle actuator is equivalent to the first-order inertia.

\[ \beta = \frac{\beta_r - \beta_i}{\tau} \]  

where \( \tau \) is the time constant, \( \beta_r \) is the input pitch angle of the pitch angle actuator.

The following time-varying linear model describes the local dynamics

\[ x(t) = A x(t) + B u(t) + H \Delta v(t) \]  

where \( x = [\Delta \omega, \Delta \omega_r]^T \in \mathbb{R}^2 \), \( u = \Delta \beta_r - \Delta \beta \) are the state variable and the control input, respectively.
3. Control strategy

In order to observe the change of the rotor speed and the external disturbance effectively, \( d(t) = H \Delta v(t) \) is defined, then the system (7) becomes

\[
x'(t) = A_1 x(t) + Bu(t) + d(t)
\]

The disturbance observer is designed

\[
\hat{\Delta} = A_2 \hat{\Delta} + Bu + K (x_2 - \hat{x}_2)
\]

where \( \hat{\Delta} = [\hat{\Delta}_1 \hat{\Delta}_2]^T \), \( A_2 = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}, K = [k_1 \ k_2]^T \); \( \hat{\Delta}_1 \) and \( \hat{\Delta}_2 \) are the estimated value of \( d(t) \) and \( \Delta \omega_r \), respectively. \( k_1 \) and \( k_2 \) satisfy the condition \( k_1 > 0, \ k_2 > 0 \).

The goal of variable pitch control is to adjust the pitch angle when the wind speed is above the rated wind speed, so that the generator speed is maintain at rated speed. The block diagram of the control system is shown in Fig.2. Sliding mode control has strong robustness to the nonlinear system. The design steps mainly include two aspects: (1) determining the switching function \( s(x) \); (2) designing the sliding mode control law \( u \).

![Fig.2 The block diagram of sliding mode pitch control base on disturbance observer.](image)

For equation (8), define the following sliding surface

\[
s = cx_1 + x_2 \tag{10}
\]

where \( c \) must satisfy the Hurwitz condition, i.e. \( c > 0 \).

The control law of conventional sliding mode control (SMC) is designed as

\[
u_s = \frac{1}{b} (-c x_2 - \frac{a}{f_v} x_2 - d - \eta \text{sgn}(s) - k s) \tag{11}
\]

where \( \eta \) represents the switching gain.

The control law of sliding mode controller based on disturbance observer is designed as

\[
u = \frac{1}{b} (-c x_2 - \frac{a}{f_v} x_2 - \hat{\Delta} - \eta \text{sgn}(s)) \tag{12}
\]

where \( \hat{\Delta} = d - \hat{\Delta} \) is the estimation error and satisfies \( |\hat{\Delta}| \leq \eta \).

Consider the following Lyapunov function,

\[
V = \frac{1}{2} s^2 \tag{13}
\]

From (10), (12) and (13), the time derivative of Lyapunov function can be achieved as

\[
\dot{V} = ss\dot{s} = s (d - \hat{\Delta} - \eta \text{sgn}(s)) = \dot{s}s - \eta |s| \leq 0 \tag{14}
\]

The Lyapunov function satisfies the condition \( \dot{V} \leq 0 \). Based on Lyapunov stability theory, the control law can satisfy the condition that the system arrive the sliding surface rapidly within a limited time.

In order to reduce the chattering, the saturation function \( sat(s) \) is used to take place of the sign function \( \text{sgn}(s) \).

\[
sat(s) = \begin{cases} \frac{s}{L} & |s| < L \\ \text{sgn}(s) & |s| \geq L \end{cases} \tag{15}
\]

Where \( L \) represents the width of the boundary layer.
4. Numerical simulation

In this paper, the model of VSVP wind turbine is established by MATLAB/Simulink simulation tool, and the control strategy and control performance of the system are verified by simulation analysis. The main parameters of the wind turbine used in the simulation are shown in Table 1. The values of observer gain are chosen as $k_1 = 15000, k_2 = 50$.

| Parameter       | Value and Unit | Parameter       | Value and Unit |
|-----------------|----------------|-----------------|----------------|
| Rotor radius    | 47.5 m         | Generator inertia | 15 kg · m$^2$ |
| Rated wind speed| 13 m/s         | Gearbox ratio   | 80             |
| Rated rotor speed| 1.81 rad/s    | Air density     | 1.20 kg/m$^3$ |
| Rotor inertia   | 6250000 kg · m$^2$ | Time constant | 0.2 s          |

The wind speed signal uses Gaussian white noise to produce random wind speed, and its variation range is between 12 m/s and 14 m/s. Compared with SMC and DOB-SMC in Fig.3 and Fig.4, DOB-SMC achieves a higher stability. Via adding a disturbance observer to the sliding mode controller, the rotor speed and the output power can be maintained at the rated value. However, the conventional sliding mode controller has large fluctuations around the rated value. So it is concluded that the proposed DOB-SMC has better dynamic performance in the VSVP wind turbine system.

![Fig.3 Rotor speed for SMC and DOB-SMC](image1.png)

![Fig.4 Output power for SMC and DOB-SMC](image2.png)

5. Conclusion

This paper presents a sliding mode controller based on DOB for VSVP wind turbine. A disturbance observer is used to estimate the wind speed. Based on the estimated information, the sliding mode control law is designed. The switching gain is reduced by designing DOB-SMC, which was proposed to solve the chattering problem. Simulation results show the feasibility of the proposed control strategy. Although the proposed control strategy is used to VSVP wind turbine, we think that it is possible to extend the proposed controller.

Acknowledgments

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