

Load Reduction Pitch Control for Large Scale Wind Turbines based on Sliding Mode

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Abstract

With the wind turbines being produced toward to large scale and light weight, the flexibility of blade, drive mechanism and tower increase apparently. Loads suffered by wind turbines during operation become increasingly intricate. Some control approaches could be used to cut down these loads in order to expand life cycle of generating sets. Aiming at the full load operation zone above rated wind speed, conventional control target is only considering rotating speed of wind turbine and without considering the loads, such that these loads could not be restrained effectively. This paper proposes a multi-objective sliding mode pitch control approach based on a new double-power reaching law. It can control rotating speed of wind turbine and decrease balanced loads of tower, blade and drive mechanism. Simulation is implemented under Matlab/Simulink and the results verified effectiveness of the designed control scheme.

Keywords: *wind power generation system, variable pitch, balanced loads, double-power sliding mode reaching law*

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1. Introduction

In recent years, wind power is one of the most hopeful renewable energy. More and more scholars studies wind turbine technologies [1-3]. Enhancing unit capacity is an effective way to lower generating cost, and it compels rotor diameter to increase continually and makes flexibility of blade, drive mechanism and tower increase, such that loads become intricate and increase mechanical stress which can influence life cycle of wind turbines immediately. Both load and power/rotating speed of wind turbine could not be ignored [4]. Loads are mainly triggered by aerodynamic force which could be whittled by adjusting blade pitch angle and in the end enhance economic benefit.

Variable pitch control approaches are divided into collective pitch control and individual pitch control. Collective pitch control scheme is effective for balanced loads and the latter can restrain unbalanced loads. Both the pitch controllers can be designed independently [5]. This paper studies collective pitch control which includes single objective and multiobjective control. The former can only adjust power/rotating speed while the latter also decrease vibration of mechanical parts.

Recently, many scholars study loads reduction of wind turbines. Paper [6] proposes a novel logic controller for loads caused by inertia and float wind turbines, yet it is only designed for offshore wind turbines. Ekelund T [7] brings in yaw to decrease dynamic loads and structural vibration. Blade's displacement and tower's side bend are suppressed, but the rotating speed of wind turbine is not controlled effectively. A gain scheduling predictive control for decrease vibration of transmission shaft is proposed in [8], but the approach is obscure and difficult to achieve. Laser radar is employed in [9, 10] to forecast wind speed and then to carry out feedforward control in the light of the wind speed, but radar technique measuring wind speed is immaturity and high cost. Bossanyi EA's means [11] is to measure loads on the blade root and convert loads from rotational coordinate to vertical coordinate frame.

Uncertainties of dynamical parameters in wind turbines make it difficult to design the controller. Considering robustness of sliding mode for parameter perturbation, this paper proposes a multiobjective collective pitch control strategy to reduce loads. Pole placement is employed to design parameters of sliding mode surface. According to system linear model, the controller is designed using double power reaching law. Simulation results indicate that the

designed controller could not only adjust rotating speed of wind turbine but also damp vibration of blade and tower.

2. Modeling

With regard to onshore horizontal axis wind turbines with three blades, a part of degrees of freedom are chosen during modeling for reducing complexity of control method. Given that dynamic response of pitch control is slow and collective pitch control could only reduce balanced loads, three degrees of freedom are chosen. The three degrees of freedom include vibration mode of first-order tower, average mode of first-order blade and rotation angle of generator. Average mode of first-order blade is the average component of three blades. Unbalanced loads take no account of here could only be decreased by individual pitch control.

The system nonlinear model with the three degrees of freedom could be expressed as:

$$\ddot{z} = f(\dot{z}, z, u, u_w, t) \quad (1)$$

Where u, u_w denote pitch angle and wind speed input, $z = (z_1, z_2, z_3)^T$, z_1, z_2, z_3 respectively represents tower tip displacement, rotation angle of generator and blade tip displacement.

The object of study is a horizontal axis 1.5MW wind turbine with three blades. The parameters are as follow: rated speed 20r/min, rated power 1.5MW, rated wind speed 12m/s, cut-in wind speed 3m/s, cut-out wind speed 25m/s, blade radius 35m, tower height 82.39m, rotational inertia of rotor is $2962.44 \times 10^3 \text{ kg}\cdot\text{m}^2$, rotational inertia of generator is $53.036 \text{ kg}\cdot\text{m}^2$, gear ratio 87.965.

Generally, Electromagnetic torque of generator keeps constant for full load operation zone, such that it could not be regard as control input. It is such difficult to design controller based on nonlinear system model that literature [12] worked out the average linear model around a steady operating point by FAST software.

$$\dot{x} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} & \alpha_{34} & \alpha_{35} \\ \alpha_{41} & \alpha_{42} & \alpha_{43} & \alpha_{44} & \alpha_{45} \\ \alpha_{51} & \alpha_{52} & \alpha_{53} & \alpha_{54} & \alpha_{55} \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ \beta_{31} \\ \beta_{32} \\ \beta_{33} \end{bmatrix} \Delta u + \begin{bmatrix} 0 \\ 0 \\ \beta_{w31} \\ \beta_{w32} \\ \beta_{w33} \end{bmatrix} \Delta u_w \quad (2)$$

Where $x = [x_1 \ x_2 \ x_3 \ x_4 \ x_5]^T = [\Delta z_1 \ \Delta z_3 \ \Delta \dot{z}_1 \ \Delta \dot{z}_2 \ \Delta \dot{z}_3]^T$, Δ represents increment, namely, the error between true value and the value on steady operating point.

For improving control performance, actuator dynamic of variable pitch blade must be considered which can be simplified to first-order inertial element. The equation is:

$$\Delta \dot{u} = -\frac{1}{Te} \Delta u + \frac{1}{Te} \Delta u^* \quad (3)$$

Where Te is time constant and Δu^* represents command value of control output. $x_p = \Delta u$ is regard as a state variable.

Moreover, in order to improve regulation performance of rotating speed and eliminate steady state error, integral of rotating speed error is added as a state variable which is:

$$x_s = \int x_4 dt \quad (4)$$

The variable could be get directly by intergral of rotating speed error. Now the system model can be represented as (5).

$$\dot{x} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ \alpha_{31} & 0 & \alpha_{32} & \alpha_{33} & \alpha_{34} & \alpha_{35} & \beta_{31} \\ \alpha_{41} & 0 & \alpha_{42} & \alpha_{43} & \alpha_{44} & \alpha_{45} & \beta_{32} \\ \alpha_{51} & 0 & \alpha_{52} & \alpha_{53} & \alpha_{54} & \alpha_{55} & \beta_{33} \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{Te} \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ \frac{1}{Te} \end{bmatrix} \Delta u^* + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \beta_{w31} \\ \beta_{w32} \\ \beta_{w33} \\ 0 \end{bmatrix} \Delta u_w \quad (5)$$

Where $x = [x_1 \ x_p \ x_2 \ x_3 \ x_4 \ x_5 \ x_s]^T$. This linear model is used to design sliding mode controller in section 3.

3. Pitch Sliding Mode Controller

3.1. Characteristic of Double Power Reaching Law

Sliding mode dynamic consists of reaching phase and sliding process. The reachability condition can only guarantee that system states reach sliding mode surface in finite time, but concrete trajectory of reaching process is not restrained at all. Dynamic quality of reaching phase could be improved by reaching law methods.

Double power reaching law is as [13]:

$$\dot{\sigma} = -a |\sigma|^{k_1} \text{sign}(\sigma) - b |\sigma|^{k_2} \text{sign}(\sigma) \quad (6)$$

Where $k_1 > 1, 0 < k_2 < 1, a > 0, b > 0$. The first item of (6) plays a leading role when system states is far away from sliding mode ($|\sigma| > 1$), while the latter item makes greater contribution when $|\sigma| < 1$. Dynamic quality is guaranteed by combing the two items.

Theorem 1. double power reaching law possesses second order sliding mode characteristic, that is, $\dot{\sigma} = \sigma = 0$ in finite time.

Proof. According to the reachability of sliding mode, considering (6) and $k_1 > 1, 0 < k_2 < 1, a > 0, b > 0$.

$$\sigma \dot{\sigma} = \sigma (-a |\sigma|^{k_1} \text{sign}(\sigma) - b |\sigma|^{k_2} \text{sign}(\sigma)) = -a |\sigma|^{1+k_1} - b |\sigma|^{1+k_2} < 0 \quad (7)$$

Such that sliding mode can reach equilibrium origin in finite time. Suppose the original state $\sigma(0) > 1$, let's caculate the finite time t on the basis of two stages.

(1) $\sigma(0) \rightarrow \sigma = 1$. The effect of the first item in (6) is far greater than that of the second item for $k_1 > 1, 0 < k_2 < 1$, such that influence of the second item can be neglected. From (6):

$$\dot{\sigma} = -a |\sigma|^{k_1} \text{sign}(\sigma) \quad (8)$$

Integrate (6), and then:

$$\sigma^{1-k_1} = -(1-k_1)at + \sigma(0)^{1-k_1} \quad (9)$$

The time that makes $\sigma(0) \rightarrow \sigma = 1$ is:

$$t_1 = \frac{1 - \sigma(0)^{1-k_1}}{a(k_1 - 1)} \quad (10)$$

(2) $\sigma(0) = 1 \rightarrow \sigma = 0$. Similarly, the effect of the second item in (6) is far greater than that of the first item because of $k_1 > 1$, $0 < k_2 < 1$, such that influence of the first item can be neglected. From (6):

$$\dot{\sigma} = -b |\sigma|^{k_2} \text{sign}(\sigma) \quad (11)$$

Integrate (11), such that:

$$\sigma^{1-k_2} = -(1-k_2)bt + 1 \quad (12)$$

The time that propels $\sigma(0) = 1 \rightarrow \sigma = 0$ can be calculated as:

$$t_2 = \frac{1}{b(1-k_2)} \quad (13)$$

So the total convergence time is as:

$$t = t_1 + t_2 = \frac{1 - \sigma(0)^{1-k_1}}{a(k_1-1)} + \frac{1}{b(1-k_2)} \quad (14)$$

It is similar as $\sigma(0) > 1$ when $\sigma(0) < -1$. The total convergence time is:

$$t = t_1 + t_2 = \frac{1 + \sigma(0)^{1-k_1}}{a(k_1-1)} + \frac{1}{b(1-k_2)} \quad (15)$$

Furthermore, $\dot{\sigma}$ is zero when σ vanish, such that the velocity of sliding variable decrease to zero when reaching sliding mode surface. System states move smoothly and system chattering is greatly whittled.

It is obvious that convergence time t is continuous function with regard to original state. The actual value t is smaller than (14) or (15) considering the secondary factors are overlooked.

3.2. Controller Design

System model (5) has a single input form, such that it needs only one linear sliding switching function $\sigma = Cx$. Matrix C can be got by pole placement or quadratic performance index optimization method. Pole placement is employed here. Formula (5) is already a reduced form and without considering disturbance, the system model could be represented as:

$$\begin{cases} \dot{\tilde{x}}_1 = A_{11}\tilde{x}_1 + A_{12}\tilde{x}_2 \\ \dot{\tilde{x}}_2 = A_{21}\tilde{x}_1 + A_{22}\tilde{x}_2 + B_2\Delta u^* \\ \sigma(x) = C_1\tilde{x}_1 + C_2\tilde{x}_2 \end{cases} \quad (16)$$

Where $\tilde{x}_1 = [x_1 \ x_p \ x_2 \ x_3 \ x_4 \ x_5]^T$, $\tilde{x}_2 = x_s$.

Sliding mode of the system is:

$$\dot{\tilde{x}}_1 = (A_{11} - A_{12}C_2^{-1}C_1)\tilde{x}_1 \quad (17)$$

Poles of Matrix $A_{11} - K A_{12}$ can be allocated arbitrarily by a feedback gain K if matrix $(A_{11} A_{12})$ is controllable. K can be obtained according to expected poles, then make $C_2^{-1} C_1 = K$. Thus:

$$C = [C_1 \ C_2] = [C_2 K \ C_2] = C_2 [K \ I] \tag{18}$$

C_2 can be chosen arbitrarily and if chosen as $C_2=I$, then:

$$C = [K \ I] \tag{19}$$

From formula (6), (16), the control law is:

$$\Delta u^* = (C_2 B_2)^{-1} (-(C_1 A_{11} + C_2 A_{21}) \tilde{x}_1 - (C_1 A_{12} + C_2 A_{22}) \tilde{x}_2 - a |\sigma|^{k_1} \text{sign}(\sigma) - b |\sigma|^{k_2} \text{sign}(\sigma)) \tag{20}$$

Now the sliding mode controller is completed.

Remark 1. system stability is guaranteed because that double power reaching law satisfies sliding mode reaching condition. Stability and robustness can also be guaranteed by suitable a, b, k_1, k_2 when existing external disturbance or inner uncertainty.

4. Simulation Results

System linearization is carried out based on wind speed 18m/s. T_e is arranged as 0.2s, then from (5) system linear model is:

$$\dot{x} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ -6.932 & 0 & 1.26 & -0.096 & 0.347 & 0.052 & 1.207 \\ -0.102 & 0 & 0.461 & 0.008 & 0.131 & 0.027 & 1.762 \\ 18.021 & 0 & 0.452 & 0.007 & 0.116 & 0.027 & 1.832 \\ 0 & 0 & 0 & 0 & 0 & 0 & -5 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 5 \end{bmatrix} \Delta u^* + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.035 \\ -0.006 \\ 11.819 \\ 0 \end{bmatrix} \Delta u_w \tag{21}$$

So as to improve capacity of speed adjustment, increase vibration damp of tower and blade, state eigenvalues are arranged as $-4.6 \pm 7.821i, -2 \pm 2.618i, -2.3, -2.1$. By pole placement method, matrix $C = [-1.591 \ -2.921 \ -0.113 \ -0.033 \ -3.931 \ -0.021 \ 1]$.

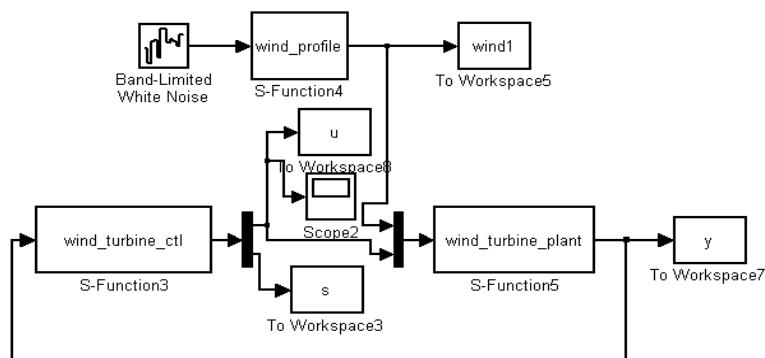


Figure 1. Simulation Block Diagram

Figure 1 is simulation block diagram. The parameters in (20) are chosen as $a=2, b=13, k_1=2, k_2=0.3$. In order to highlight the advantages of the proposed control approach, a comparative study of exponential reaching law is carried out. exponential reaching constant is 5 and uniform speed reaching constant is set as 4.5. Simulation time and step size are respectively arranged as 120s, 0.001s. Simulation results between 50s and 55s are shown as Figure 2-Figure 6 so as to make a comparison intuitively and clearly.

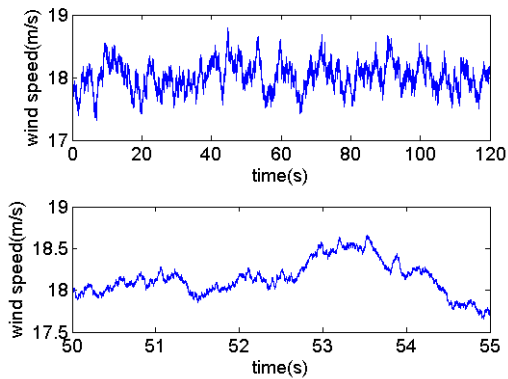


Figure 2. Wind Speed Profile

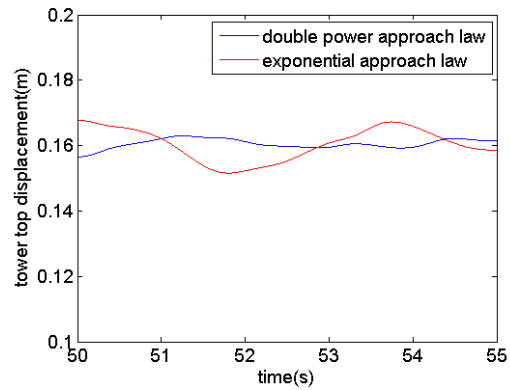


Figure 3. Tower Tip Displacement

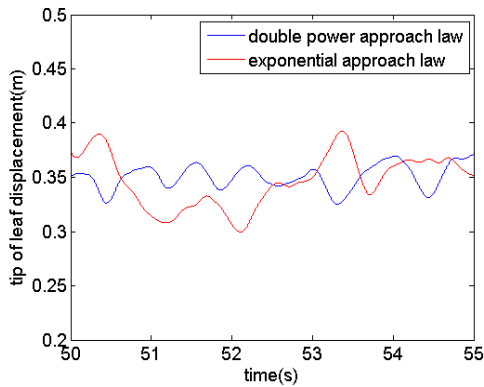


Figure 4. Blade Tip Displacement

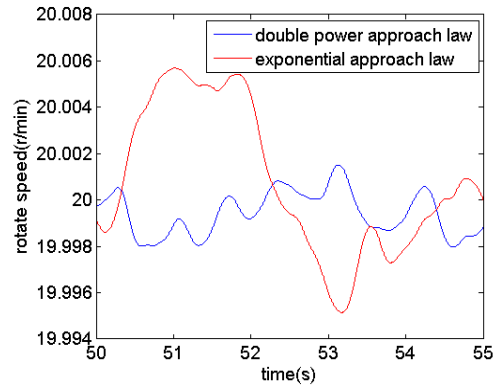


Figure 5. Rotate Speed

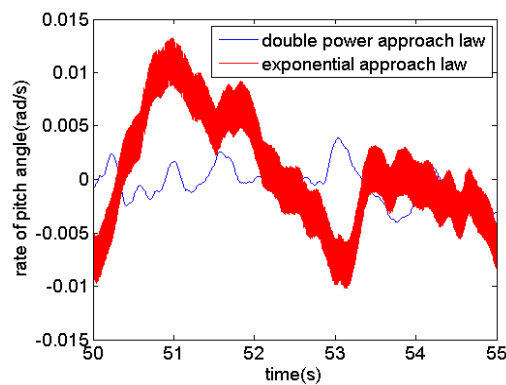


Figure 6. Rate of Pitch Angle

As is shown in Figure 2–Figure 6, both the control strategies can achieve better rotating speed keeping ability and enhance vibration damp, especially the damp of tower tip vibration. Control ability of tower tip displacement is better when based on double power reaching law, what's more, rate of pitch angle change is rather smooth which means the control chattering is greatly reduced.

5. Conclusion

A multiobjective variable pitch sliding mode control strategy which can reduce loads of wind turbines is proposed in this paper. Multivariable linear model around working point is adopted. Coefficients of sliding switching function is designed based on pole placement. Second order sliding characteristic of double power reaching law is analyzed and sliding mode controller is designed. Comparing with normal exponential reaching law, simulation results show the improvement in both regulation performance of rotating speed and vibration damp of tower and blade. Furthermore, the proposed scheme is easy to implement.

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