# The Robust $H_{\infty}$ Control for Inhibition of Load on Offshore Wind Turbines Variable Pitch Control

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Abstract. Offshore wind power industry develop rapidly in recent years. Offshore wind has many advantages compared with onshore wind turbine. For example, it do not take up land and can make better use of the sea wind resources. However, the flexible components of wind turbines violent vibration will cause the fatigue damage and increase the cost of the maintenance and reduce the service life. Pitch variable is an effective means of control to prevent the sea wind of the interference. In recent years, robust control has won a bigger development. In the paper a multi-objective pitch control strategy based on robust theory is proposed for large wind turbines. The experimental results shows that the robust  $H_{\infty}$  control has a good effect on the wind turbines variable pitch control.

## 1. Introduction

Human is facing the problem of environmental pollution, resources shortage and the ecological deterioration. Wind power industry, especially for offshore, has many advantages such as widely distributed, renewable, safety, reliability and so on. Therefore, the development of offshore wind power has become a global trend. However, offshore wind need to overcome more complicated and more severe natural environment conditions. With the improvement of wind power technology, the size and weight of the wind turbines growth rapidly. Wind turbines need to bear a lot of pressure because of its great body shape. Mechanical parts of the weight increasing will lead to rising costs. Many manufactures lower the system costs by reducing the weight of the wind turbines. The decrease of the parts weight often lead to changes in the structure of the wind power properties. It increasing the system flexible. At this time, the wind turbine can be regarded as the flexible systems with rigid modal. Meanwhile, the offshore wind turbine has long been under a random superposition of wind and ocean wave. It will bring strong dynamic load to the system. The biggest impact on the operation of wind turbines is random wind. Study on the suitable control strategies to reduce the dynamic load of offshore wind power is important for us.

The aerodynamic force is the main source of the system load. By changing the pitch angle of the blades, wind turbines can reduce the aerodynamic loads. For improving the economic benefits of wind turbines, we can increase the system reliability, prolonging the service life. Pitch control is divided into uniform pitch control and independent variable pitch control. Unified pitch control can suppressed unbalanced load. In this paper we only study uniform variable pitch control strategy. Uniform pitch control can be grouped into a single target control and mufti-objective control. Single target only consider speed control / power control, regardless of other factors. However, multi - objective control to adjust the pitch, it can suppressed the vibration of machine parts, when adjust the speed / power at the same time. The literature [1] sing the sliding mode variable structure control to adjust the pitch, it can suppressed the vibration of the tower and blades. The method has a certain degree of robustness. However, it improves the utilization rate of the implementing agencies, osts more energy consumption. He Bossanyi [6-7] installing the acceleration sensors in the top of the tower to prevent vibration around the tower, however, his method ignores the tower vibration coupling between the rotor speed. he literature[10]application the modern control

theory, design the disturbance attenuation controller(DAC) and linear quadratic regulator(LQR) from linear model of the system. But it bring the speed steady error, what's more, it requires a high precision of the system. The literature[10] design a predictive controller to reduce the vibration of drive shaft, but it is a complex method and difficult to realize. Literature[11] design a Model - based adaptive control strategy of dynamic load of the wind wheel, improving the wind turbine robustness, unfortunately, it is difficult to realize.

Dynamic model of wind turbine parameters have large uncertainties. It brings some difficulties to controller design. This paper presents a multi-objective control strategy which can reduce the load of wind turbine. Based on the state feedback theory and linear model of the system, using LMI approach to design a variable pitch controller. In the end of the paper, the simulation results shows that the control strategy can effectively reduce the tower and blade vibration and it has good robustness to parameter variations.

#### 2. Model of variable - pitch system

The wind turbine model was provided by literature[1]. This article does not consider unbalance load because the unbalancing load can only be carried out by the independent variable pitch control. The unified variable pitch can only control load balance and it response is slowly. This study selects only 3 degrees of freedom, it contains that: the tower vibration modes, average mode of blade flapping and generator angle. In this chapter, considering the above 3 degrees of freedom nonlinear model, so the linear system is written as:

$$q = f(q, q, u, u_d, t) \tag{1}$$

Where u is the control input(pitch angel),  $u_d$  disturbance input(wind speed); and t is the time.

 $q = (q_1, q_2, q_3)^T$ ,  $q_1$ : the wind turbine tower vibration modes.  $q_2$ : the Generator angle

 $q_3$ : the wind average mode of blade flapping.

In high wind ares, the wind turbine operating at the rated working point, generator electromagnetic torque remain constant, so the torque is treated as control inputs. We can obtain the model under the matching point as:

$$\mathbf{\dot{x}} = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{pmatrix} \mathbf{x} + \begin{pmatrix} 0 \\ 0 \\ b_{31} \\ b_{32} \\ b_{33} \end{pmatrix} \Delta u + \begin{pmatrix} 0 \\ 0 \\ b_{d31} \\ b_{d32} \\ b_{d33} \end{pmatrix} \Delta u_d$$
(2)

 $(x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5)^T = \left( \Delta q_1 \quad \Delta q_3 \quad \Delta \dot{q}_1 \quad \Delta \dot{q}_2 \quad \Delta \dot{q}_3 \right)^T$ ;  $\Delta$  is the state change, That is, the difference between

actual value and the balance point.

The mechanism of pitch variable is a huge inertia system. The linear model of pitch actuator can be simplified as a part of first inertia, the model can be described by:

$$G(s) = \frac{1}{\tau s + 1} \tag{3}$$

Turning it into state - space expression:

$$\overset{\bullet}{x_{\tau}} = -\frac{1}{\tau} x_{\tau} + \frac{1}{\tau} \Delta u^* \tag{4}$$

 $\tau$  is the pitch actuator time constant;  $x_a = \Delta u$ ;  $\Delta u^*$  is the controller output value. In order to improve the speed regulator performance and eliminate steady state error, we can add the speed of error integrals as the system state variables:

$$x_e = \int x_4 dt \tag{5}$$

After adding state variables, the model of the system can be written as:

$$\mathbf{\dot{x}} = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ a_{31} & 0 & a_{32} & a_{33} & a_{34} & a_{35} & b_{31} \\ a_{41} & 0 & a_{42} & a_{43} & a_{44} & a_{45} & b_{32} \\ a_{51} & 0 & a_{52} & a_{53} & a_{54} & a_{55} & b_{33} \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{1}{7} \end{pmatrix} \mathbf{x} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -\frac{1}{7} \end{pmatrix} \Delta u^* + \begin{pmatrix} 0 \\ 0 \\ 0 \\ b_{d_{31}} \\ b_{d_{32}} \\ b_{d_{33}} \\ 0 \end{pmatrix} \Delta u_d$$
(6)  
$$\mathbf{x} = \left( x_1 \quad x_e \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \right)^T$$

## 3. The $H_{\infty}$ Controller

The target of the  $H_{\infty}$  control is minimize the output energy. Assume that the generalized plant and controller are time-invariant and finite dimensional model. The most general block diagram of a control system is shown in fig.1.



Fig.1. The generalized plant

The general plant consists of everything that actuators which generate input to the plant, sensors measuring certain signals, etc. The controller consisted of the engineer's design part. The signals w,z,y and u are, in general, vector-valued functions of time. The components of w are all the exogenous inputs, references, disturbances, sensor noises and so on. The z contains all the signals we want to control: tracking errors between reference signals and plant outputs, etc. The vector y including the outputs of all sensors. Finally ,u contains all control inputs to the generalized plant.

The system can described in transfer function as:

$$G(s) = \begin{pmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{pmatrix}$$
(7)

It also can be written as:

$$x = Ax + B_1 w + B_2 u$$
  

$$z = C_1 x + D_{11} w + D_{12} u$$
  

$$y = C_2 x + D_{21} w + D_{22} u$$
(8)

The control objective is a closed - loop system stable and minimize the impact of interference on the output. The transfer function now can written as:

$$\|T_{w_{z}}\|_{\infty} = \left(G_{11} + G_{12}K(I - G_{22}K)^{-1}G_{21}\right) < \gamma$$
(9)

The optimal  $H_{\infty}$  control is :

$$\min_{K} \left\| T_{zw}(s) \right\|_{\infty} = \gamma_0 \tag{10}$$

The optimal  $H_{\infty}$  control problem is difficult to solve, so we always discuss the problem of the suboptimal control

$$\left\|T_{zw}(s)\right\|_{\infty} < \gamma \tag{11}$$

Infinite norm of the  $H_{\infty}$  transfer function can describe finite maximum gain of the input energy to the output power. There are many methods to solve  $H_{\infty}$  control problem[2,3].  $H_{\infty}$  control theory can be divided into the frequency domain and time domain method. State Space method, including the method of Riccati equation and LMI. But the Riccati method are often dependent on the adjustment of parameters. And cannot optimize the performance indicator  $\gamma$ . However, the Linear matrix inequality(LMI) approach can overcome the above shortcomings of the Riccati method. The Matlab has been developed LMI Toolbox. It provides a great help for simulation and design of control system.

Based on the Bounded real lemma[2], we can making the transfer function inequality(10) into linear matrix inequalities, it can be described as: min  $\rho$ 

$$\begin{bmatrix} AX + B_2W + (AX + B_2W) & B_1 & (C_1X + D_{12}W)^T \\ B_1^T & -I & D_{11}^T \\ C_1X + D_{12}W & D_{11} & -\rho I \end{bmatrix} < 0$$
(12)  
$$X > 0$$

The state feedback control law is:  $K = WX^{-1}$ 

 $H_{\infty}$  control is a kind of optimal control problems with state regulators. We can design the feedback control law to enable closed - loop system to stabilize and making the transfer function minimum.

This feedback is a convex optimization problem with linear matrix inequalities(LMI) constraints and linear objective function. By reference[2],the LMI Solver 'mincx' in the Toolbox can be applied to solve the optimization problem.

## 4. Simulation

The model data can be found in the literature[1]. The linear system's matching point based on 18m/s wind speed, variable pitch actuator's time constant  $\tau = 0.2$ s. Generalized model of the entire system is:

Based on this state equation, the block of state feedback method is shown in fig.2.



Fig.2. The block diagram of state feedback method

Using 'mincx' function to solve this problem. LMI is a good way to solve this problem. With the help of matlab software, we can get the results as follows:

K=[62.45 115.15 -1.31 -63.82 44.3 23.32 34.96]

Control performance is verified by simulation in the whole responses. The results are shown in fig.3-fig.6



Fig.3. the tower vibration displacement





0.6

0.4

Fig.5. the torque speed (20r/m)

Fig.6. the change of pitch angle

By the simulation results ,the  $H_{\infty}$  controller can make the system stable. As is seen in fig.3, When the tower deviating from the equilibrium position 0.8 meters by the interference wind, It will return to equilibrium in 12 seconds. The blades will come back to the working point in 10 seconds when it out of balance 0.4 meters. Meanwhile, the torque(fig.5) remains constant. However, it increase the efficiency of the variable pitch actuator(fig.6).

## 5. Conclusion

This paper design a controller to reduced the wind turbine load based on  $H_{\infty}$  theory. This control strategy can effectively restrain the vibration of tower and blades by increasing the usage of variable pitch. The algorithm has robustness and easy to realize, more importantly, it has a good restraining effect on wind disturbance.

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