Controlling Structural Vibration in Wind Turbine by $H_\infty$ Control

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Abstract. As wind turbine rated power increase, the potential danger of the vibration is bigger result of the rotor diameter and the hub height is longer and higher. Wind turbine vibrations will cause futile mechanical loads, such vibration loads maybe result to serious damage of wind turbine. In order to achieve vibration suppression, taking the uncertainty of turbulence which the operate environment of wind turbine into consider, control methods is utilized in wind turbine to achieve reduction of coupled load. The state space of wind turbine in cycle life is established. Effectiveness of controller based on the $H_\infty$ control in vibration control field is verified by GH-Bladed and Matlab. Simulation results and validation results show that the purposed control strategy is effective in terms of wind turbine tower vibration.

Introduction

The basic control requirements for a wind turbine are to regulate rotor speed and electric power aiming to reduce detrimental dynamic loads and to maximize efficiency on energy conversion [2]. In most wind turbine, the speed of generator must be controlled to restrict speed variations since the generator is directly connected to fixed-frequency electrical net. Another important control objective is to reduce the influence of wind fluctuation and ripple torque on wind at any rotation speed, whose introduce unavoidable vibrations along drive train line with detrimental effects on wind turbine. The vibration issues have become a key problem that cannot be ignored in the wind turbine’s life cycle. The advanced control system is considered as a promising way to improve wind turbine conversion system and to decrease wind turbine cost. Wind turbine is a nonlinear system, because of complex multi-body structure which is consists with the rigid structures like nacelle, hub, tower and the flexible structures like rotor. System analyze issue also is the fluid-structure interaction with high linearity.

The conventional approach to introducing additional damping is by adding separate single-input signal-output (SISO) control loops to the existing baseline control loop for each new control objective. Although the classical methods for wind turbine vibration control like tuned mass damper (TMD) for wind turbine has been applied in vibration control field, but the control method existed do not offer a completely satisfactory solution to decrease vibration, since they do not assure the robustness for both stability and performance, especially the stability fitting for various wind condition. Considering that wind turbine objectives can be easily specified in terms of maximum allowable gain in the disturbance to output transfer functions, $H_\infty$ and $H_2$ methodologies consist in good options to control design for wind turbine. Active control of $H_\infty$ control takes the vibration information, e.g. Velocity, acceleration, as the feedback to achieve vibration suppress. It is based on a modern multi-input multi-output (MIMO) controller described by the state function to design the controller. This approach has also been shown effective for reducing loads and suppressing vibration.

In this paper, $H_\infty$ control methodologies are utilized on feedback controller for a multivariable wind turbine. The section 2 shows the linearized wind turbine model, the section 3 presents the $H_\infty$ control methodologies design. Section 4 shows the dynamic response and the performance of close-loop system simulating results using a nonlinear model of a wind turbine. Section 5 presents some conclusions, which from simulation results the $H_\infty$ controllers can achieve vibration control of wind turbine.
Wind Turbine Model

Wind turbine model is a complex nonlinear model. In order to conduct the control analyses, the first is linearized the wind turbine model. The linear system is the system can be described as a linear differential equation. And it is should satisfy the superposition principle, that is,

\[ f(ax) = af(x) \]  \hspace{1cm} (1)

\[ f(x_1 + x_2) = f(x_1) + f(x_2) \]  \hspace{1cm} (2)

Wind turbine is consists of rotor, nacelle, tower, drive train, generator and foundation, Figure 1 shows the model of wind turbine.

The power of wind turbine \( P_r \), the aerodynamics torque \( T_{aero} \) and the thrust force \( F_{aero} \) are functions of the air density \( \rho \), the velocity \( V \), the rotational speed \( \omega_r \), the power coefficient \( C_p \), the thrust coefficients \( C_T \) and the torque coefficient \( C_Q \),

\[ P_r = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta)V^3 \]  \hspace{1cm} (3)

\[ T_{aero} = \frac{1}{2} \rho \pi R^2 C_Q \left( \frac{\omega R}{V_e}, \beta \right) V^2 \]  \hspace{1cm} (4)

\[ F_T = \frac{1}{2} \rho \pi R^2 C_T \left( \frac{\omega R}{V_e}, \beta \right) V^2 \]  \hspace{1cm} (5)

Where \( R \) is the radius of the rotor blades, \( V_e \) is the actual wind speed, and the tip speed ratio \( \lambda \), the ratio of the blade tip linear speed to the wind speed.

The drive train model of wind turbine can be described as,

\[ T_{aero} = J_r \frac{d\omega_r}{dt} + B_s(\omega_r - \omega_g) + K_s(\theta_r - \theta_g) \]  \hspace{1cm} (6)

\[ -T_g = J_g \frac{d\omega_g}{dt} + B_s(\omega_g - \omega_r) + K_s(\theta_g - \theta_r) \]  \hspace{1cm} (7)

Where \( J_r \) is the wind rotor inertia, \( J_g \) is the generator inertia, \( B_s \) is the transmission damping, \( K_s \) is the transmission stiffness. The pitch control in linearized aero is,

\[ \dot{\beta} = -\frac{1}{\tau_\beta} \beta + \frac{1}{\tau_\beta} \beta_r \]  \hspace{1cm} (8)

Where \( \tau_\beta \) the time is constant, usually equals 0.2s, \( \beta_r \) is the control input pitch angle. The nonlinear generator torque can be linearized as,
\[ T_e = -\frac{1}{\tau_e} T_g + \frac{1}{\tau_e} T_{g,\text{ref}} \]  

(9)

Where \( T_{g,\text{ref}} \) is the control input generator torque, \( \tau \) is the time constant, usually is a small value can be ignored in simulation. The absolute angular position of the drive chain, written as \( \theta_r \), \( \theta_g \) has little practical significance in the analysis of control. Therefore, substitute those parameters in the state equation of a single state variable torsion angle, defined by \( \theta_s = \theta_r - \theta_g \).

\[
\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Cx + Du
\end{align*}
\]

(10)

Where \( x \) is the state variable, \( u \) is the input variable, \( y \) is the output variable.

**H∞ Control Methodologies**

**Control Task**

Variable speed wind turbine operation can be divided into three operating regions,

Region I: Below cut-in wind speed. Region II: Between cut-in wind speed and rated wind speed. Region III: Between rated wind speed and cut-out wind speed. Region III is considered in the present work where the power available in the wind exceeds the limit for which the turbine mechanics has been designed. In the studied operating zone, the system has to operate at a fix rotational speed, the nominal speed of the generator and has to produce a fix electric power. Another controller objective is reducing fatigue load of the components, especially blades, shaft and tower. These two objectives are contradictory, and therefore a tradeoff between these two objectives has to be optimized.

**H∞ Control Synthesis**

Robust control methods are designed to function properly provided that uncertain parameters or disturbances are found within some (typically compact) set. Robust methods aim to achieve robust performance and/or stability in the presence of bounded modelling errors. It is not only applied in SISO system, but also in MIMO system. \( H\infty \) reflects the max energy ratio of output signal and input signal, which is the energy amplification ratio.

Propose of \( H\infty \) control is finding an optimal controller gain \( K \) for a generalize system \( G(s) \). The control system is designed from a linear parameter varying representation of the wind turbine. The model of the system is firstly linearized as the MIMO system, this paper considered model as two inputs including pitch angle, several outputs, the interrupt factor is wind speed, the control output is nacelle x-direction acceleration, the state function is given by,

\[
\begin{align*}
\dot{x} &= Ax + B_1 \omega + B_2 u \\
z &= C_1 x + D_{11} \omega + D_{12} u \\
y &= C_2 x + D_{21} \omega + D_{22} u
\end{align*}
\]

(11)

Where \( x \) is the state vector, \( u \) is the system inputs, \( \omega \) is the exogenous inputs, in this paper wind speed is chosen as the exogenous input, \( z \) is the control objectives outputs, \( y \) is the measured outputs. Such a problem is now well-understood if the linear system is detectable form \( \omega \) to \( z \). Propose of control is constructing feedback compensator to let the transfer function from \( \omega \) to \( z \),

\[
T_{\omega z}(s) = C(sI - A)^{-1} B + D
\]

(12)

In condition of suitable for closed feedback control system inner stability, transfer function eq. (12) satisfies the eq.

\[ \|T_{\omega z}(s)\|_\infty < \gamma \]

(13)

Where \( \gamma \) is the set constant. That is the energy amplification ratio from \( \omega \) to \( z \) is minimized.
The cancellation of the tower feedback loop via control has received a great deal of attention over recent years, essentially all methods involve a feedback of the tower speed, based on a measurement of tower acceleration.

**Simulation Results**

The proposed theory of vibration control in this paper has been tested by simulations. The linearized wind turbine model get from the GH-bladed, which is the software used to analysis wind turbine loads, modes, and the simulation in time and frequency domain. Paper uses the 1.5 MW wind turbine which is a variable-speed, variable pitch wind turbine. The rated wind speed is 12 m/s. The vibration issue increases amplitude with the wind speed, so 12 m/s and 18 m/s is chosen as the working points in this study.

Usually it is convenient to use the tower top longitudinal acceleration as the feedback signal. Different approaches have been investigated for control input signal, e.g. tower top displacement, tower top velocity and tower top acceleration, i.e. nacelle displacement, nacelle velocity, nacelle acceleration. The most direct method of exploiting the control capability to alleviate tower loads is to modify the blade angle in response to a measurement of tower acceleration.

Figure 2. The step and singular value curve response with different control algorithm.

Figure 2.left is the step response $H_\infty$ control with different control algorithm in time domain, and figure 2.right shows the singular values of the frequency response of a dynamic system. The grey line shows the frequency response of original system from the pitch angle to tower x-acceleration in the condition of 12m/s turbulence. The $H_\infty$ control 1 and the $H_\infty$ control 2 is the controller with different weighting function. From the figure, the $H_\infty$ control 1 has better effect, quicker response speed compared to $H_\infty$ control 2. So the weighting function in $H_\infty$ control 1 applied in wind turbine control.

Figure 3. The frequency and impulse response of the system control in 12m/s.

In figure 3.left and figure 4.left, the grey line is the bode response of the original system and the black line is the bode response with $H_\infty$ control. For the closed stable system, the phase $\gamma$ means if the open loop phase-frequency lagging $\gamma$, the system would be marginal stable. The magnitude $h$ means if the open loop phase-frequency amplifying $h$, the system would be marginal stable. So the system with $H_\infty$ control (the black line) is more stable compared with the original wind turbine control system. The magnitude and the phase has lower value, that is the system hard to arrival critical
stable. From figure 3.right and figure 4.right, the conclusion could be get is that with $H_\infty$ control the amplitude has been reduced obviously, and it is can seed from the figure that the peak value has been decreased from 17 to 10-4.

![Figure 4](image4.png)

Figure 4. The frequency and impulse response of the system control in 18m/s.

The $H_\infty$ controller added in the wind turbine control, and the simulation in time domain is simulated by GH-bladed. The displacement and the acceleration is the key factor which is analyzed.

![Figure 5](image5.png)

Figure 5. The frequency and impulse response of the system control in 18m/s and 12m/s.

Figure 5 shows the tower displacement and the acceleration in 12 and 18m/s. Form the figure, the vibration has been suppressed with $H_\infty$ control added into the control system, from the bode results that the stability clearly been enhanced. It is indicated that the robust $H_\infty$ control can be used in vibration control field.

**Conclusion**

This vibration control approach is analyzed using a linear model of the wind turbine. It is shown that the pitch angle has a central role in determining whether the tower feedback loop is stable or unstable. The analysis and the linear models are validated using simulation from a 1.5MW wind turbine. The $H\infty$ control is included in the feedback loop control. The results are summarized below.

1) The linear model of wind turbine has been established to analyze the character of wind turbine.

2) The transfer function of the linear model from the pitch angle to tower x-acceleration has been analyzed in matlab, getting the character in time domain and the frequency domain from control input to output.

3) The $H\infty$ control applied in wind turbine vibration control has been established, and the validation simulated by GH-bladed and matlab. The results shows that even operating in different turbulence, the vibration can be suppressed with $H\infty$ control.
Further research will take generator torque into consider and more field test data will be approved to validate the vibration control.

References
