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Implementation of internal model based control and individual pitch control to reduce fatigue loads and tower vibrations in wind turbines

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A B S T R A C T

Vibration control and fatigue loads reduction are important issues in large-scale wind turbines. Identifying the vibration frequencies and tuning dampers and controllers at these frequencies are major concerns in many control methods. In this paper, an internal model control (IMC) method with an adaptive algorithm is implemented to first identify the vibration frequency of the wind turbine tower and then to cancel the vibration signal. Standard individual pitch control (IPC) is also implemented to compare the performance of the controllers in term of fatigue loads reduction. Finally, the performance of the system when both controllers are implemented together is evaluated. Simulation results demonstrate that using only IMC or IPC alone has advantages and can reduce fatigue loads on specific components. IMC can identify and suppress tower vibrations in both fore-aft and side-to-side directions, whereas, IPC can reduce fatigue loads on blades, shaft and yaw bearings. When both IMC and IPC are implemented together, the advantages of both controllers can be used. The aforementioned analysis and comparisons were not studied in literature and this study fills this gap. FAST, AreoDyn and Simulink are used to simulate the mechanical, aerodynamic and electrical aspects of wind turbine.

1. Introduction

Renewable energy sources such as wind energy are cleaner than traditional fossil fuel sources and offer the potential of limitless energy. For wind energy systems, it is important to maximize the amount of power that can be captured from the wind at different speeds and this can be done with an appropriate control strategy, but as commercial wind turbines become larger, they experience more fatigue and structural loads. Fatigue loads can reduce the lifetime of turbine components and cause failure in the system. Asymmetric or unbalanced loads, which are the main cause of fatigue in turbine components, are generated by deterministic and stochastic phenomena. The deterministic phenomena include wind shear, tower shadow effect, yaw misalignment whereas the fast changes in wind speed and direction known as turbulence is stochastic. These fatigue loads have several undesirable effects on the main turbine components such as the blades, tower, and main drivetrain, which includes the shaft, gearbox and bearings. A literature review shows that vibration-based studies in wind turbines are

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mainly divided into three categories: the analysis of the vibration signals to diagnose the components faults [1–5], the development of control methodologies to suppress the vibrations [6,7], and the comprehensive study of fault tolerant controllers to reduce vibrations induced by the fault [8,9].

Different stationary and non-stationary methods have been used in Ref. [10] to model and analyze the random vibrations in a fixed speed operating wind turbine, considering the measured acceleration vibration signal. A new blade design and the use of active controllers were proposed in Ref. [6] to reduce blade edgewise vibrations, using a pair of actuators/active tendons mounted inside each blade. Roller dampers were used in Ref. [11] to mitigate the edgewise vibrations in wind turbine blades, where the mass ratio, frequency ratio, the coefficient of rolling friction and the position of damper in the blade were optimized. In Ref. [12], the authors studied the flapwise dynamic response of a rotating wind turbine blade in super-harmonic resonance, considering unsteady aerodynamic loads.

A wind turbine tower is a significant part of any wind turbine system and can be up to 30% of its cost. All parts of the turbine are located on the top of the tower and any damage in the tower structure may lead to damage to all parts. Appropriate control strategies should therefore be adopted to reduce fatigue loads and tower vibrations. The suppression of wind turbine tower vibrations in both fore-aft and side-to-side directions has been analyzed in various studies. In Ref. [13], the authors used a passive control method to reduce blade and tower vibrations by dissipating the energy with a tuned mass damper (TMD). Passive methods have also been considered in other studies including [14], in which it was proposed that a tuned rolling-ball damper be mounted on the top of turbine to suppress wind-induced vibrations. Significant attention has been paid recently to the application of active vibration control methods to mitigate vibration signals in wind turbines. The modeling and control of wind turbine vibrations were studied in Ref. [15]; in Ref. [15], the rotation speed was used as the control signal. An active controller to reduce the edgewise vibrations of the blades of a HAWT was presented in Ref. [16]; in this study, a separate actuator and separate sensors were used for each blade. Researchers in Refs. [17,18] used the tower acceleration signal as a feedback signal in the speed control loop to reduce fore-aft vibrations. The blade pitch angle was modified in response to the tower acceleration and an additional pitch demand signal was added to the signal determined by the speed control loop. A similar approach was used in Ref. [19] to reduce tower fore-aft vibrations along with a torque controller implemented with the H_∞ control method to damp side-to-side vibrations. In Ref. [20], an active generator torque was used to control the lateral vibrations of an offshore wind turbine; in this work, both mechanical and power electronics aspects were considered in the implementation of the proposed method. The authors in Ref. [21] used a semi-active control method to mitigate the tower vibrations in an offshore wind turbine, where TLCD was used with a controllable valve as an external damping device to suppress wind turbine vibrations due to wind load and earthquake excitations. In Ref. [22], magnetorheological dampers were used as semi-active controller to suppress the wind turbine vibrations of a scaled tower.

To reduce these fatigue loads, advanced control methodologies including IPC can be implemented [23]. In Ref. [24] IPC was used to mitigate the fatigue loads for a 5 MW offshore wind turbine. Two floating platforms were considered and the results were compared to each other. In Ref. [25], a feedforward blade pitch controller was added to the standard feedback control to mitigate fatigue loads. In this study, two feedforward designs, including collective-pitch model-inverse feedforward and individual pitch gain-scheduled shaped compensator designs, were considered. In Ref. [26], the implemented IPC used load estimation instead of load measurement; the results of the load estimation and load measurement methods were compared and found to be similar.

Although internal model control (IMC) and individual blade pitch control (IPC) have been discussed in the literature, suppressing tower vibrations in wind turbines using IMC is a new approach for wind turbines. With this approach, an adaptive algorithm is used to identify the vibration frequency of the tower based on the rotor speed signal. The pitch controller that is normally used to limit the rotational speed and generated power in wind turbines when the wind speed is above rated wind speed can also be used to suppress mechanical tower vibration. Since the vibration frequencies of a tower are not exactly specified in real turbines, the proposed method, which is based on the behaviour of an internal model in an error feedback system, uses an algorithm to identify the vibration frequency and then cancel the vibration signal.

The proposed control method has some advantages compared to other methods that require passive devices (such as TMD, TLDC) or/and extra sensors (e.g. acceleration sensors to measure tower accelerations, etc.) to suppress the vibrations. It uses the feedback of the rotor speed signal, which is applied for power control, and does not need passive devices or additional sensors that add cost to the system and may reduce its reliability. Moreover, IPC can be used to reduce fatigue loads on the turbine components. In the present study, standard IPC has been implemented for two purposes:

1) To compare the performance of IMC and IPC when used to reduce fatigue loads when they are used separately as supplementary controllers.
2) To analyze the performance of wind turbine and fatigue loads reduction when both IPC and IMC are used together.

Simulation results demonstrate that the proposed IMC with adaptive algorithm can properly identify the tower vibration frequency. This controller reduces the tower vibrations in both fore-aft and side to side directions, but does not have a significant effect on reducing the fatigue loads on other components such as blades, shaft and yaw bearings. On the other hand, when standard IPC is implemented, the fatigue loads on some parts such as the blades, shaft, and yaw bearings are reduced, but there is no significant reduction in the tower vibrations. According to simulation results, using IMC or IPC alone results in certain advantages and can reduce fatigue loads on special components. When both IMC and IPC are used together,