THESIS

Literature Review

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1 Introduction

2 Literature Review

2.1 Background

Since the advent of modern wind turbine design, the capacity and size of wind turbines has increased dramatically. From the first electricity-producing wind turbine with a rotor diameter of 17m, the design trend has shown huge growth in rotor size with a 180m rotor on the Adwen 8MW platform. As the size of wind turbines continues to increase, new challenges arise in terms of rotor aerodynamics, structural design and control. large rotors require slender, lighter blades to combat the increase in manufacturing costs and loads. This comes at the cost of exacerbated fluctuating loads as the blades sweep around the rotor.

It is well known in the wind industry that loads induced by gravity loads, tower shadow, wind shear, turbulence and gusts can cause significant damage to the blade roots, rotor shaft and the tower. By introducing a larger rotor, not only is the turbine more susceptible to this damage, but new instabilities can also be introduced such as aeroelastic flutter, whirling modes, and dynamic coupling such as tower tilt-yaw and blade flap-torsion coupling.

These problems are typically addressed in the aerodynamic and structural design of the wind turbine to ensure significant damage does not occur by introducing safety factors and increasing blade strength. It is becoming increasingly difficult to both predict the effect of these weaknesses and instabilities as well as effectively eliminate them in the design stage without incurring costs in other aspects of the design, such as increased blade mass. For this reason, the wind industry is focusing more attention on innovative methods for reducing loads. One method, which is the focus of this thesis, is the use of active control methods to actively mitigate fatigue loads in order to extend the lifespan of wind turbine components.

2.2 Fatigue Load Mitigation in Wind Turbine Control Systems

The concept of active load control is not a new concept in the wind industry. Tower and drivetrain loads can successfully be reduced by extending the basic speed control used in modern variable speed wind turbines.

2.2.1 Torque Control

Torque control is used to maintain optimal power output when the wind turbine is operating below rated wind speed. The idea is to balance the aerodynamic and generator torque to achieve a maximum power coefficient C_p. A common control strategy to achieve this is to use a proportionality relationship between demanded torque Q, and the square of the generator angular velocity ω_g

$$Q = \frac{\pi\rho R^5 C_p}{2\lambda^3 G^3}\omega_g^2$$

[3]

torque control has also been used to introduce side-side tower damping and mitigate drive train torsion vibration. WRITE MORE

2.2.2 Collective Pitch Control

Collective pitch control is the basis for turbine power control in modern wind turbines when operating above rated wind speed. Two common objectives are constant torque control or constant power control. Both control objectives are achieved by collectively pitching the turbine blades to control the aerodynamic torque of the rotor.

It is common to superimpose a high bandwidth controller over the the power/torque controller to decrease the fore-aft tower motion. This is achieved by introducing artificial damping into the tower motion dynamics, reduces fatigue loads in the tower root as well as providing a more stable power output. Control at these frequencies has a much higher bandwidth than the power control loop. Therefore the two controllers are generally be superimposed without noticeable interference [3]. SOMEONE ELSE SAYS, the tower fore-aft damping control is highly coupled with the speed control due to the change in axial wind speed. [5]

2.2.3 Individual Pitch Control

Although collective pitch and torque control methods can reduce oscillations in the tower and drive train, it is ineffective at reducing certain oscillations in the blades. The reason for this is due to azimuth angle dependent loads such as wind shear and tower shadow. Furthermore, each blade experiences different stresses due to variation in the turbulent structure of the wind field. This is the motivation for individual pitch control (IPC). IPC has shown promising results in literature and simulation, and has only recently been introduced into commercial wind turbines, such as the Vestas V164-9.5.

IPC in literature has shown great reductions in flapwise blade loads using a variety of controller designs. Trudnowski and LeMieux [11] achieved an 86% reduction in flapwise loads using only the rotor angle as an input signal, however the simulation neglected the effects of turbulence. Bossanyi [2] showed reductions in equivalent fatigue loads in the out-of-plane (OOP) blade root moments, as well as shaft and yaw bearing moments using IPC compared to CPC. Mirzaei et al. [8] compared model predictive control and PI control for an IPC system, and found comparable reductions in OOP blade root bending moments in stochastic wind speeds based on LIDAR measurements. Selvam et al. [9] compares IPC systems using PI control as well as LQG control. PI control achieved load reductions at low frequencies, and the LQG controller was able to achieve load reductions at a higher bandwidth, including 2P and 3P, therefore able to reduce loads on non-rotating parts such as the nacelle, yaw bearing and tower. IPC using $\mathcal{H}_\infty$ control was addressed in Lu et al. [7] and Geyler and Caselitz [5], showing not only reductions in OOP blade root bending moments, but also adequate robustness from unmodelled and stochastic behaviour in the system. In all the considered literature, and to the best of the authors knowledge, load reductions were best achieved in OOP blade root moments rather than in plane moments. The reason for the poor performance of edgewise oscillation control is due to the large magnitude of the gravity loading which can not avoided easily [11].

An issue with IPC is the pitch rate of the blades. Pitch rates required to achieve decent reductions in fatigue load are around ± 10 deg s$-^{1}$, which is considered quite high[3]. However, the required pitching rate decreases with rotor diameter due to the decrease in rotational frequency. This justifies the use of IPC for larger wind turbine models. Higher order harmonic control may not meet the limiting pitch rate requirements, which explains why most papers consider low frequency oscillations (usually up to 3P). [5]

There are also mechanical concerns regarding the use of IPC. An increase in wear is expected as the pitch must shift at each rotor rotation. Heat dissipation could also be a concern in the pitch actuators, and should be taken into account in the performance of the actuators at different operating temperatures.

2.2.4 Active Aerodynamic Load Control

Active aerodynamic load control (AALC) devices such as trailing edge flaps and micro tabs have also been an active area of research. The advantage of AALC devices is their high bandwidth, allowing for controllability of high frequency dynamics. Berg et al. [1] and Wilson et al. [14] have researched the effects of load reduction using trailing edge flaps, showing a 20-32% reduction in blade root stress, which can allow for a 10% increase in blade length wihtout exceeding the original equivalent fatigue damage. These papers use tip deflection and tip deflection rate as controller inputs, making them highly relevant to this the topic at hand. The research in this field is so far restricted to small scale wind turbine models and simulations due to the difficulty and cost of implementing and maintaining such a system on a full scale wind turbine.

2.3 Sensing methods

Real time measurements have become increasingly important for wind turbines and wind farms over recent years, allowing for sophisticated digital control. The stream of data is typically referred to as Supervisory control and data acquisition (SCADA), and can comprise of a variety of novel measurements from components of the turbine. A summary of sensors relevant to active load reduction is described in this section.

2.3.1 Rotor Azimuth measurement

[4] derives an analytica approximation for wind across a rotor taking into account wind shear and tower shadow using potential flow model, and shows how 3p loads can be reduced. Can be easily extended to include yaw misalignment, however, turbulence is not included in the model, and is a large driver of loads. [4] provides analytical expression for wind speed due to wind shear and tower shadow as a function of azimuth angle. Could potentially base a controller purely on azimuth angle, however this does not provide feedback of the stresses experienced in the blades, and it does not account for turbulence. suseptible to errors in these measurements. Could use lidar[3]

2.3.2 Wind measurements

It is worth noting that other sensors have been explored for control purposes. LiDAR measurements are becoming increasingly popular in wind energy applications. XX looks at this. Other papers assume high frequency readings of the wind speed without explicit mention of the method of

measurement. XX XX. Such a measurement could be achieved with sonic anemometers, explored in XX XX, or pitot tubes. XX shows that measurements from a cup anemometer downstream of the rotor is adequate for successfully making short term predictions in the wind speed. It is clear that many methods exist for wind speed measurement purposes. As this paper focuses on the use of tip deflection sensors, it is assumed that adequate wind speed readings can be obtained without regard to the specific method.
can use Lidars to get such measurements [8]. [9] Works around the need for turbulence measurements by modelling turbulence as a random walk /colored noise (which is it?). Provides proof for the use of random walk in paper. Easily integrated into a Kalman filter for linear control.

2.3.3 Tower Acceleration

2.3.4 Strain Gauges

2.3.5 Tip Deflection Sensors

Bossanyi mentions the possibility of using accelerometers in the blade tips, however also mentions the difficulty of maintaining such sensors and accessibility of the blade tips. [2] [**?**]. [1] [14] use tip deflection sensors in their turbine controller designs, however they focus on active flap control. A whitepaper on the cost benefits and basic implementation of the iRotor would be very nice in this section.

2.4 IPC Controller Design

2.4.1 Wind turbine Modelling

including aerodynamic and structural modeling methods. [12]

2.4.2 Observer design

Kalman filter [3], extended kalman filter [6]. Implementation, and inclusion of colored wind spectrum [9].

2.4.3 Controller design

In designing a controller using IPC, it should be noted that suppression of 1p fluctuations in the blades is equivalent to suppressing yaw and tilt moments in the tower and nacelle. This is clearly seen using the Coleman transformation, a special case of the the multi-blade coordinate transformation, and also known as the d-q transformation borrowed from electrical machine theory. The advantage of performing this transformation is that the dependence on azimuth angle in the system dynamics is removed. In other words, the nonlinear system is converted into a time invariant system. By linearizing the system about an operating point, standard linear control methods can be used[7]. Weaknesses due to yaw tilt coupling, and shift in frequency response. can address 3p loads, however higher order frequencies such as 6petc can also be reached by extending the transformation (I cant find this reference anymore).
the need for multivariable controllers, LQG [2] [9] is good because it can balance between different control inputs and objectives. Hinf is also used, is more robust, and nonlinear (?) [7] [6]
Model predictive control [8]

Neural networks and machine learning. [13] [10]. bad because black box, and does not add any benefits. the motivation is lacking [3]
Recently, research has been performed on reducing loads in the rotor blades. There are a number of similarities in the research performed in this field so far. Typically, an observer is designed using strain gauges at the root of the blades to measure both out of plane and in plane stresses. Additionally, the control system uses individual pitch control (IPC) as the source of the load fluctuations in turbine blades is highly dependent on the azimuthal angle of the blade. for example, wind shear, yaw misalignment, tower shadow, and gravity loads are all sources of oscillatory stress on the blades once per revolution (1P). For this reason, the research carried out in this paper will focus on IPC as a basis for the turbine controller. Like the tower fore-aft damping controller, an IPC controller, or other active aerodynamic load control devices operate at a much higher bandwidth than the generator torque control and can be reasonably be superimposed over the speed controller. This has been demonstrated by Berg et al. [1],

Particular loads have been successfully mitigated as the result of active control solutions. Out of plane blade root moments are decreased in Berg et al. [1], Trudnowski and LeMieux [11], Mirzaei et al. [8], Bossanyi [2]. Tower fore aft, Berg et al. [1]. Tower yaw, Berg et al. [1]. blade root edge moment was not able to be reduced in Berg et al. [1], Trudnowski and LeMieux [11]. also tower side side: Berg et al. [1].

The unique aspect of this paper is in the use of tip deflection sensors instead of a strain gauge at the blade roots. This has rarely been investigated in literature. Berg et al. [1] addresses the use of tip deflection readings as an input for a turbine control system using active flaps. DESCRIBE RESULTS. Although active flaps can provide a high frequency response for a turbine controller, they have yet to be used in commercial turbine models, and are typically reserved for academic research. Active flaps are expected to increase operating and maintenance costs due to the additional moving parts required. XX mentions the possibility of using tip deflection readings as an alternative input. Apart from these references, tip deflection sensors have not been largely considered in literature to the best of the author's knowledge. It follows that the use of tip deflection sensors in conjunction with IPC has not been explored, and will remain the focus of this paper.

Advantages, disadvantages of tip deflection sensor

A fundamental aspect of a wind turbine controller is the state observer. The state observer recreates the structural and aerodynamic state of the wind turbine system. A good observer is able to improve controller response by providing a short term prediction how the state will change. It is able to track the state precisely over different working conditions, and in the presence of noise, both from the measurements and from the system dynamics itself. A standard and highly effective observer design is typically the Kalman filter. A Kalman filter is able to DESCRIBE THE KALMAN FILTER. In linear control theory, a Kalman filter is straight forward to design if the process and measurement noise can be known. The Kalman filter can be extended to nonlinear systems by using an extended Kalman filter, which uses a linearized approximation of the current operating point. Something about the unscented Kalman filter. Something about a second order extended Kalman filter (augmented Kalman filter) (maybe not?).

An alternative and novel approach to state observation is using machine learning algorithms. WRITE ABOUT THIS

Earlier it was established that IPC would be the basis for the controller in this paper, however the control design method is still open. As the system is nonlinear, there does not exist a standard approach for designing a controller. For this reason, an abundance of different control strategies exist in literature regarding wind turbine control. An optimal linear controller is one of the simplest controllers which can be designed despite the highly nonlinear system. XX talks about this. LQR is another linear method which could be applied. A linear controller in this sense is typically coupled with gain scheduling, where the gain scheduling parameter is the wind speed. $\mathcal{H}_\infty$ loop shaping is commonly used. XXXX. adaptive control. robust control. model predictive control. THE THING I SAW AT WINDEUROPE!

Cyclic pitch control - Selvam. Higher harmonic control

NOTE SURE WHERE THIS FITS IN THE FLOW Two types of loads are typically considered in engineering design: fatigue load and ultimate load. Fatigue loads occur as a result of structural oscillations over a long period of time. Calculations relating to fatigue largely consider the magnitude of the loading rather than the frequency. The rainflow counting algorithm developed by XX, is commonplace in engineering in distinguishing the the number of cycles of different magnitudes in a timeseries. Using the rainflow counting results, a short term equivalent load can be determined using BLAH BLAH. An equivalent load is a way of representing the fatigue load, which may consist of various amplitude oscillations at different frequencies, as a single sinusoidal oscillation with a fixed frequency (typically 1Hz). One control objective could be to minimise the short term equivalent load of the wind turbine blades over the operating lifetime.

The second type of load that is considered is the ultimate load, which is the largest expected load to occur over a short period of time. Extreme loads which exceed the ultimate strength of a component can lead to instantaneous catastrophic failure of a wind turbine, and can occur due to extreme winds or gusts. IEC standards consider the most extreme load within a 10 minute period which is expected to occur over 50 year time period. Extreme analysis, such as the use of a Gumbel distribution is commonly used to predict the 50 year extreme load based on limited time series data.

something about predicting gust, and maybe doing a good job using TDS

Take into account torsion? Berg et al. [1] says flap bending - torsion coupling increases with rotor sizze. ignores torsion as impact is minor.
Is cyclic pitch control the same as IPC? Should I make a distinction?
Is a sensor to measure azimuth angle the same as the sensor used to measure rotor speed?
What are the benefits of using tip deflection sensors

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