ACTIVE WIND TURBINE CONTROL UTILIZING MEASUREMENTS FROM FIBRE OPTICAL LOAD SENSORS TO ADJUST INDIVIDUAL BLADE ANGLE INTEGRATED IN TO AN ELECTROMECHANICAL PITCH SYSTEM

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Summary

Individual blade pitch control utilizing rotor load feedback presents the potential for significant improvements in cost, performance and reliability for future WTGs benefiting both the onshore and offshore markets. This type of control requires a stable and cost effective measurement input from load sensors during operation of WTG. In addition to the performance requirements, the system must be reliable for the lifetime of the turbine, cost effective for volume deployment, and the system must not interfere or degrade the turbines' components or operation in any way. Individual blade pitch control also requires a pitch system capable of pitching each blade independently. Most new current wind turbine designs already incorporate such a system.

In this paper we present an FOS load measurement system that meets these requirements and has been successfully demonstrated to fulfill the acceptance criteria for advanced control inputs. Fiber Optical Sensors (FOS) have been tested successfully in composite blades on wind turbine generators (WTG), showing their capability to perform under both laboratory and field conditions.

We present strategies for processing and using the data in controls algorithms, and simulation results showing up to 30% load decrease due to individual blade pitch based on blade load feedback.

Further, we discuss system architecture with the loads measurement system integrated into a standard electromechanical wind turbine pitch system, with effects including lower system cost, simplified installation, and streamlined communication and data processing.

1. Introduction

Every day wind energy is being pushed to new limits; both in terms of operating conditions and in terms of size. To meet these challenges turbine designers and wind park developers need new tools to ensure their products will meet goals of operating cost and availability. Recent innovations in fiber optic load sensing have created such a tool, which will expand the options for advanced monitoring and control of turbines which are pushing the envelope, and open up possibilities for huge gains in availability and operating cost.

Today's turbines are being installed in more places, under more diverse conditions, than ever before. Most wind turbines are designed for a twenty year life. This life span is dependent on the cyclic load seen by the turbine's rotor, and as such, accurate assumptions and about the characteristics which influence this loading are critical to the design. However as the wind energy market expands and changes, many sites being used or considered for wind energy production present wind conditions which are further and further outside of well understood and defined wind regimes. There is a huge technical risk associated with putting even proven technology into poorly understood conditions.

FIBRADAPT™ uses new criteria and input from online load measurements during the turbine life time as innovative input into turbine controls to significantly decrease operational cost as the main driver for profit across the investment time.

2. Technology of FIBRADAPT™

FIBRADAPT™ provides data from optical fiber sensors based on Fiber Bragg Gratings (FBG) which are commonly used in fiber optic communication systems. Unlike most fiber optical sensors, this system employs a "cold written" FBG, which allows the fiber to retain its structural integrity thus remaining robust for handling and installation.

Fiber optical sensors have wide a range of advantages in comparison to strain gauges, especially under severe environmental conditions such as those found during wind turbine operations. The benefits and main features of fiber optical sensors as they apply to wind turbines are as follows.

- Small cross section, low weight, very low heat conduction
- Long signal transmission lines, with very low or negligible losses
- Long term stability under operation in hostile environments (EMI, weather, chemicals, high/low temperatures)
- Remote, electrically passive sensors, ideal galvanic separation
- Ideal to embed in GRP structures
- Multiple sensors (up to 100) linked on a single conductor with only one mechanical connection point.

2.1. Structure of the Fiber Optical Sensor

The optical fiber has a diameter of 0.25 mm which includes the core, the glass cladding and the coating. The FBG sensor consists of a small periodic variation in the refractive index of the optical fiber core. The periodic variation is made by a high powered ultraviolet laser. By irradiating the core material of photo sensitive quartz glass locally with UV-light, the refractive index is increased at certain locations along the fiber. These locations are spaced in equal distances, the entire sensor having a length of about 3 – 14 mm. [1]

2.2. Structure of the Measurement System

The main components are:

1. Fiber Sensor Interrogator (FSI) as source and receiver of light, data processor, communication interface, transformer, software
2. Interconnecting Fiber (IF) for data transfer between FSI and sensor arrays
3. Sensor Arrays embedded in the blade structure
4. Temperature compensation sensor
5. Support brackets (customized according to design requirements)

2.3. Function of the Fiber Optical Sensor

A light source provides a broadband input signal into the fiber. When passing an FBG, the light is reflected within the pre-selected narrow wavelength band around λ_B. When the sensor is exposed to a strain, the distances of the grating change, which also changes the wavelength of the reflected light. The analysis of the characteristic of the reflected light is used to measure the strain at the sensor location. Shifts in the reflected wavelength are proportional to change in elongation caused by temperature, or load induced strain which can be computed to stress based on the component geometry. [2]

Because the optical strain sensor is sensitive to temperature changes, the strain measurements must be temperature compensated.

One of the main advantages of the fiber optic sensor is the multiplexing feature using one single fiber with multiple FBGs without interference between the single measurement points. This system is based on time division multiplexing, which allows the interrogation unit to distinguish between individual strain sensors by using their physical position in the array as a reference. By measuring the time taken for the light to travel from the interrogation unit to the sensor and back, it is possible to calculate its physical distance from the interrogation unit, and therefore which sensor the signal originated at. [3]

3. Integration into the Pitch System

The optical fiber sensors are embedded into the blade root as shown in Figure 1. The measurement system can be integrated into the wind turbine pitch system for production systems, as shown in Figure 2. The FSI acquires the sensor signals and processes these values. The bending moment Mb in flapwise and edgewise direction will be transferred with a frequency of 25 Hz to the Pitch System Control Unit or to the Turbine Controller.

4. Individual Blade Pitch Control

With large wind turbines there is significant variation in load across the face of the rotor. This can be the result of wind variation including shear and upflow, or turbine design and control, including yaw misalignment or rotor imbalance. Active individual blade pitch control based on load feedback from the blades can result in drastic decreases in fatigue loads in the rotor, and in the entire wind turbine structure.

The wind speed variations across the rotor disc result in a large once-per-revolution, or 1*P*, component in the blade loads, together with harmonics of this frequency, i.e. 2*P*, 3*P*, 4*P.* [4] The 1*P* frequencies are particularly significant and these can be reduced by individual blade pitch control at the 1*P* frequency, 120° out of phase at the three blades. [4]

To achieve active control, bending moment in the flapwise and edgewise directions from each blade are required at a scan frequency of 10 to 20 Hz. [4] FIBRADAPT™ provides this input by means of four blade root sensors in each blade (a pair of flapwise sensors and a pair of edgewise sensors), with a scan frequency of 25 Hz, which is more than adequate to perform the active control algorithms.

4.1. Control Strategies

In the control scheme, described in more detail in [4], the three blade root out of plane bending moment signals (derived from the flapwise and edgewise signals resolved through the pitch angle) are transformed into two orthogonal d- and q- axes (which can be thought of as the horizontal and vertical axes) by means of a special transformation, essentially Park's transformation originally used for 3-phase electrical machines [5]. A controller for each axis generates a pitch demand for that axis, and the two d- and q- axis pitch demands are converted by the reverse transformation to give pitch demand increments for each blade. These are each summed with the collective pitch demand (which controls torque and thrust, and hence rotational speed, tower vibration etc.) to give a total pitch demand for each blade.

The previous work has shown that the d- and q- axis controllers can be treated independently of each other, and also independently of the collective pitch controller. The d- and q- axis controllers are basically PI controllers, which can be thought of as controlling the horizontal and vertical components of the out of plane rotor asymmetrical loading to a zero set-point. A non-zero set-point can be used, for example to generate a yawing moment in the case that individual pitch control is required to yaw the turbine instead of a yaw motor. A notch filter in series with each PI controller removes the 3P component, and additional filters may be useful to shape the frequency response, for example to prevent excitation of out of plane blade vibrations.

This scheme effectively removes the 1P out of plane load component which drives the fatigue of rotating components likes blades, hub and low speed shaft, so that fatigue loads on these components are reduced by typically 20 - 40%. In the non-rotating frame, this 1P loading translates into 0P or low-frequency load variation, for example of the tower top nodding and yawing moments. Therefore the peak operational values of these loads are much reduced; however the fatigue of these non-rotating components is usually driven by the 3P blade passing frequency which is not greatly affected. However, if the rotational transformations are used at 2P instead of 1P, the resulting 2P pitch action does significantly reduce the 3P loads in the fixed frame. Thus significant further load reduction can be achieved by using two controllers in parallel, one operating at 1P and one at 2P.

4.2. Simulation Results

Some sample simulation results for a generic turbine are presented in Figure 3 for the rotating loads. These simulations are for a generic 2MW turbine, and show the effect of introducing the 1P individual pitch controller. Similar results are obtained at all above-rated wind speeds, leading to lifetime reductions in fatigue loading of around 20% at the blade roots and almost 40% for the hub and shaft. For the fixed frame loads the large reduction in peak operating loads is apparent, which is of benefit to the yaw motor for example, although the fatigue loading, being dominated by the 3P peak in this case, is reduced by less than 10%. Addition of the parallel 2P loop can achieve a significant further reduction in this 3P loading.

These load reductions are achieved at the expense of additional pitch activity, with each blade typically describing near-sinusoidal motion around the collective pitch at a frequency of about 1P and with an amplitude of typically 2 – 3º, occasionally reaching 5º. This results in a lifetime increase in total pitch travel by a factor of about 2.5, so the implications for the pitch bearing design and the thermal rating of the actuators must be taken into account.

5. References

[1] *Fiber Bragg Gratings*, R. Kashyap, March 1999

[2] *Fiber Bragg Gratings Fundamentals and Applications in telecommunications and sensing,* A. Othonos, K. Kalli, June 1999

[3] *Novel resonant cavity TDM demodulation scheme for FBG sensing,* G.D. Lloyd and I. Bennion, L.A. Everall, K. Sugden

[4] *Developments in Individual Blade Pitch Control*, E.A. Bossanyi, Paper presented at the EWEA special topic conference "The Science of making Torque from Wind" DUWIND, Delft University of Technology, The Netherlands, April 19-21 2004

[5] *Two-reaction theory of synchronous machines*, R.H. Park, *Trans. AIEE,* 1929, 48.

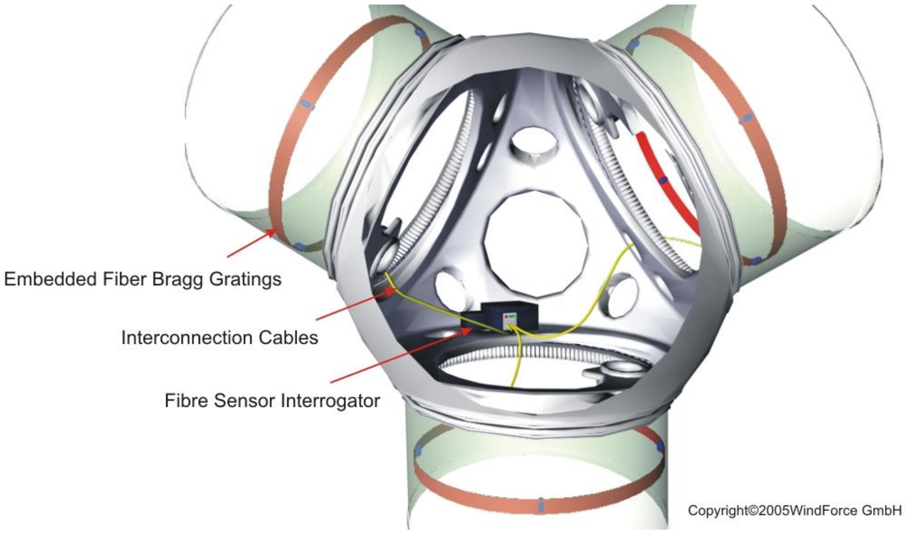

Figure 1: Structure of the Measurement System in a wind turbine

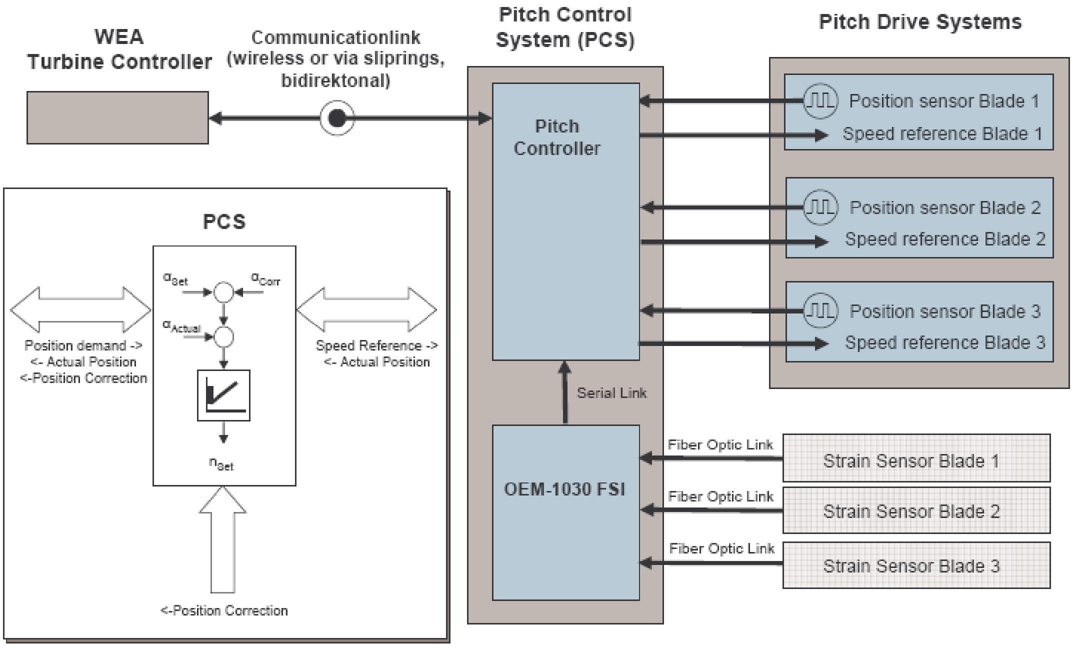

Figure 2: Integration into the Pitch System

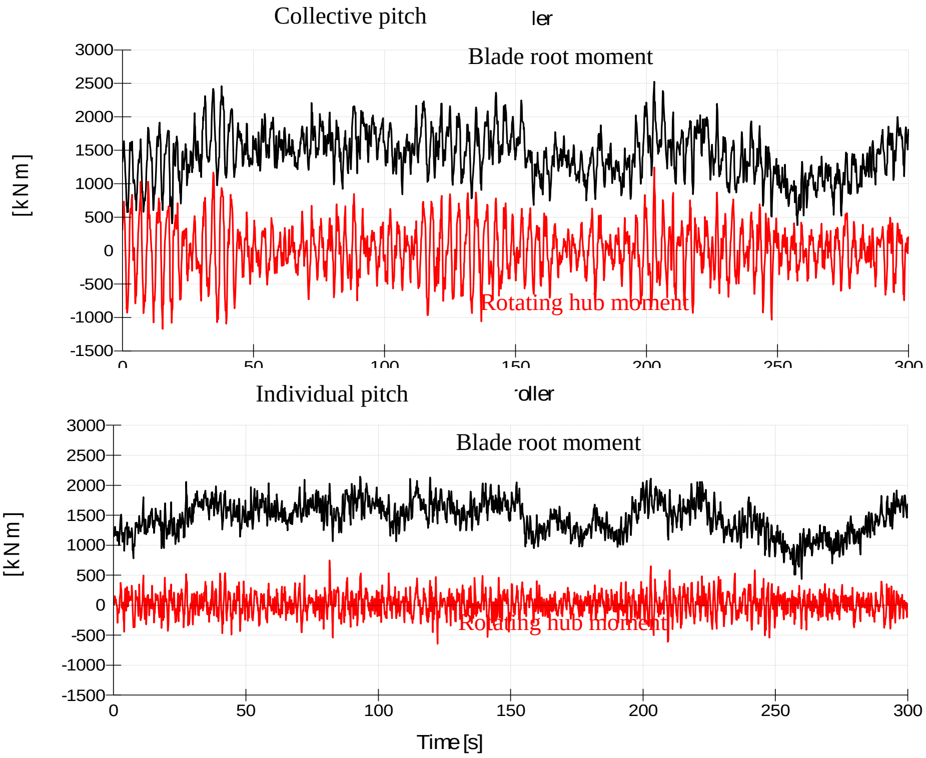

Figure 3: Reduction of rotating component loads