

Integrating Structural Health Management with Contingency Control for Wind Turbines

Susan A. Frost¹, Kai Goebel² and Léo Obrecht³

^{1,2}*NASA Ames Research Center, Moffett Field, CA, 94035, USA*

susan.frost@nasa.gov
kai.goebel@nasa.gov

³*FEMTO-ST Institute/ENSMM, Besançon, France*

leo.obrecht@ens2m.org

ABSTRACT

Maximizing turbine up-time and reducing maintenance costs are key technology drivers for wind turbine operators. Components within wind turbines are subject to considerable stresses due to unpredictable environmental conditions resulting from rapidly changing local dynamics. In that context, systems health management has the aim to assess the state-of-health of components within a wind turbine, to estimate remaining life, and to aid in autonomous decision-making to minimize damage to the turbine. Advanced contingency control is one way to enable autonomous decision-making by providing the mechanism to enable safe and efficient turbine operation. The work reported herein explores the integration of condition monitoring of wind turbine blades with contingency control to balance the trade-offs between maintaining system health and energy capture. Results are demonstrated using a high fidelity simulator of a utility-scale wind turbine.

1. INTRODUCTION

System health monitoring provides useful information on the current state of a system that can be used to improve many operational objectives of a wind turbine (Doebbling et al., 1996). Growing demand for improving the reliability and survivability of safety-critical systems (such as aerospace systems) has led to the accelerated development of prognostics and health management (PHM) and fault-tolerant control (FTC) systems. Active FTC techniques that are capable of retaining acceptable performance in the presence of faults are being developed for both inhabited and uninhabited air vehicles (Shore & Bodson, 2005 – Litt et al., 2003 – Zhang & Jiang, 2003) and researchers are

exploring new paradigms and approaches for integrating PHM with controls (Balaban et al., 2013 – Farrar & Lieven, 2007 – Tang et al., 2008). Typically, a decision-making component reasons over the system health and the objectives and constraints of the system and then determines (and sometimes enacts) the optimal course of action. For instance, a component could be identified as having a fault that would eventually lead to component failure and system shutdown. Decision making using prognostic information on the estimated remaining useful life (RUL) of the component along with operational objectives and constraints may result in enacting changes to the operational mode of the system or to the system's controller.

Wind turbines operate in highly turbulent environments sometimes resulting in large aerodynamic loads, potentially causing component fatigue and failure. Two key technology drivers for turbine manufacturers are increasing turbine up-time and reducing maintenance costs. What is desirable from an operator's and original equipment manufacturers (OEMs) perspective is a turbine controller that is capable of adapting to damage and remaining useful life predictions provided by condition or health monitoring systems. The objective would be for the turbine to continue operating and producing power without exceeding some damage threshold resulting in unscheduled downtime. Operating limits would be prescribed by the operator to the health monitoring system. This paper will propose an integrated framework that uses structural health information to inform a contingency controller to enable a damaged turbine to operate in a reduced capacity under some operating conditions to mitigate further damage.

Recent advances in structural health monitoring allow for more accurate assessment of the structural health of a wind turbine, including the blades, tower, and gearbox (Butterfield et al., 2009). In this paper, we develop an approach to integrate system health monitoring with contingency control to enable safe operation of a utility-

Susan A. Frost et al. This is an open-access article distributed under the terms of the Creative Commons Attribution 3.0 United States License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

scale wind turbine with blade damage. The approach is being demonstrated on a high fidelity simulation of a horizontal axis utility-scale wind turbine. A blade fault is modeled in the wind turbine simulation. Characteristics of the fault are identified to provide an elementary fault classifier. An observer is developed that predicts potentially damaging operating conditions. Using this information, the contingency controller is able to de-rate the turbine, that is, it reduces the generator operating set-point which results in lower loads on the turbine blades (Frost et al., 2012).

The paper is organized as follows: section 2 provides motivation for the problem, section 3 describes the wind turbine simulation, section 4 describes the blade damage model and classifier, section 5 describes the generator de-rating scheme and its affect on the wind turbine, and section 6 describes the contingency operation and gives simulation results.

2. MOTIVATION

A wind farm is an interconnected group of wind turbines that collectively act as a power plant, supplying electrical power to the transmission grid. The wind farm operator manages the complex problem of safely and efficiently operating the turbines and the power supplied to the grid, in addition to determining maintenance schedules and coordinating unplanned repairs of the turbines (Manwell et al., 2009).

Original equipment manufacturers are building turbines with dramatically longer blades than just a few years ago because wind power is proportional to the swept area of the rotor and the cube of wind speed. This increases the turbines' power generation capacity. Since wind speed increases with distance from the ground, large rotors on tall towers means more energy is captured. Even though modern turbines are much larger than previous generation turbines, advances in materials, design, and manufacturing techniques has enabled the dimensions to increase without a corresponding increase in material. Consequently, the cost for new turbines is not scaling with the cube of their size, which is helping to drive down the cost of wind energy generation. A decrease in the cost of energy is one important factor that will sustain the demand for new turbine installations.

However, the rapid pace of OEM development of ever larger turbines and the entry of new stakeholders into the market could result in unforeseen reliability issues, possibly impacting the cost of energy. For example, larger turbines are inherently more flexible than smaller ones, resulting in lower frequency resonant modes that are more easily excited and more destructive to the turbine components. Most utility-scale turbines are variable speed with a gearbox connecting the low speed shaft to the high-speed shaft, in essence connecting the rotor hub to the generator. The drive train and gearbox are especially vulnerable to fatigue and

failure loads. Most modern turbine blades are made from composite materials. Blades can be subject to destructive aerodynamic loads, cyclic loads, icing, insect and debris buildup (resulting in a roughness increase), and coupling of resonant modes. Any of these conditions can damage or contribute to damage progression of the composite material (Rumsey & Paquette, 2008). The power electronics of wind turbines are also vulnerable to several types of faults, especially if there is over-speeding of the generator. There are many other failure modes for turbines and their components not mentioned here (Lu et al., 2009). Even if turbines have a manufacturer's warranty, the timeliness of problem resolution can have a significant effect on operators' profits. In some cases, OEMs are providing contracts with turbine up-time guarantees, giving the operator more control over expected expenses and income. In any case, there is motivation for the manufacturer and the operator to monitor the health of the turbine and provide condition based maintenance.

Wind turbine operation is divided into several different *regions*, see Fig. (1). Region 1 represents the wind speeds below which the turbine does not operate. The wind speed at the start of region 2 is called the cut-in wind speed ($w_{\text{cut-in}}$). Rated wind speed (w_{rated}) is the velocity at which maximum power output, or rated power, of a wind turbine is achieved. Region 3 starts at the rated wind speed and extends to the cut-out wind speed ($w_{\text{cut-out}}$), above which the turbine is not allowed to operate. Turbines operating in region 2 use generator torque to maximize energy capture. In region 3, the turbine rotational speed is maintained constant at the rated speed by pitching the turbine blades. If a wind turbine were allowed to operate in an uncontrolled manner in region 3, the power output would increase in proportion to the cube of the wind speed, resulting in overheating of the generator and overstress of the power electronics system. An additional goal of operation in region 3 is to reduce the loads on the turbine due to aerodynamic forces. Multi-megawatt turbines typically have a control strategy for the transition region between region 2 and 3, also called region 2.5. In region 4, the turbine blades are locked down and the turbine is yawed out of the wind to prevent damage to the turbine and for safety.

The expected power output from a wind farm is a function of the installed name plate capacity of the turbines, e.g., a 2.5 MW turbine, and the expected capacity factor for the wind farm. The integration of system health monitoring of wind turbines with controls has the potential for significant payoff when applied to individual wind turbines and even more so when applied to large wind farms or wind parks. Contractual obligations to deliver power and the long lead time to replace a damaged turbine, requires wind farm operators to have contingency plans to manage the risk that one or more turbines will suffer damage between scheduled maintenance intervals. If a turbine suffers damage such as a blade delamination, it is crucial to be able to quickly detect

the presence of damage. Next, the proper response needs to be determined. The easiest solution would be to shut a damaged turbine down, but that leads to lost output and, potentially, additional costs for the operator due to unscheduled maintenance, amongst others. Unscheduled maintenance is a considerable cost driver for wind turbines since wind turbines are often times in remote locations and using a crane or other means to access the blades tends to be expensive. Alternatively, if the degree of damage is known and if the damage mechanisms are understood, the turbine could potentially continue to operate safely (until an orderly maintenance can be performed), albeit at a reduced capacity for some period of time without the danger of catastrophic failure.

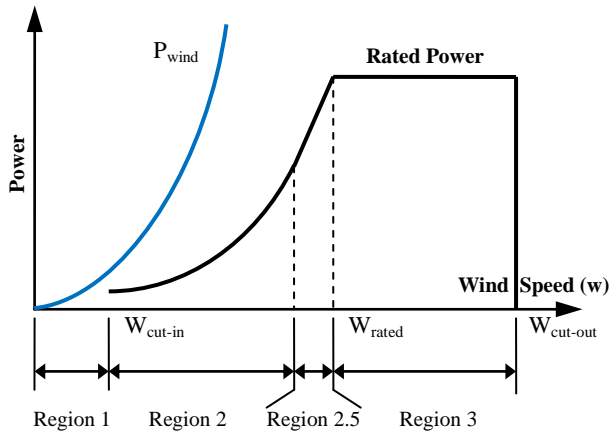


Figure 1. Regions of operation for a wind turbine.

that incorporates wind forecasts, historical data, contractual power output requirements, and maintenance schedules could be integrated with the health monitoring and controls. Such a system could allow the damaged turbine using contingency control to mitigate the blade stress to generate power under favorable wind conditions when the wind farm power requirements are the highest. The turbine health would be monitored to assess the damage and remaining useful life of the component, to ensure that, if the damage accelerated in an unexpected manner, the operating conditions would be further restricted. This includes a decision point where the turbine could no longer be operated safely and it would be shut down.

There is a continuum of solution techniques that include contingency controls, controller reconfiguration, planning and scheduling, and logistics optimization. This paper describes a contingency controller approach which acts on health information derived from blade strain gauge sensor data. It should be noted that in principle, the range of sensors is not limited to strain gauges. Accelerometers, thermo couples, or active piezoelectric sensors – to name a few – can all be part of a more comprehensive condition monitoring scheme that will allow to provide even more refined health information.

3. WIND TURBINE SIMULATION

3.1. Simulation overview

This study uses a nonlinear high-fidelity simulation of the 2-bladed Controls Advanced Research Turbine (CART2), an upwind, active-yaw, variable-speed horizontal axis wind turbine (HAWT) located at the National Renewable Energy Laboratory's (NREL) National Wind Technology Center (NWTC) in Golden, Colorado (Fingersh & Johnson, 2002 – Stol, 2004). CART2 is used as a test bed to study control algorithms for medium-scale turbines. The pitch system on the CART2 uses electromechanical servos that can pitch the blades up to ± 18 deg/s. In Region 3, the CART2 uses a conventional variable-speed approach to maintain rated electrical power, which is 600 kW at a low-speed shaft [LSS] speed of 41.7 rpm and a high-speed shaft [HSS] speed of 1800 rpm. Power electronics are used to command constant torque from the generator and full-span blade pitch controls the turbine rotational speed. The maximum rotor-speed for the CART2 is 43 rpm (on the low-speed side) or 1856.1 rpm on the generator side. Whenever the rotor-speed reaches this value the turbine shuts down due to an over-speed condition.

The CART2 has been modeled using the Fatigue, Aerodynamics, Structures, and Turbulence Codes (FAST), a well-accepted simulation environment for HAWTs (Jonkman & Buhl, 2005). The FAST code is a comprehensive aeroelastic simulator capable of predicting both the extreme loads and the fatigue loads of two- and three-bladed horizontal axis wind turbines. Wind turbines can be modeled with FAST as a combination of rigid and flexible bodies connected by several degrees of freedom (DOFs) that can be individually enabled or disabled for analysis purposes. Kane's method is used by FAST to set up equations of motion that are solved by numerical integration. FAST computes the nonlinear aerodynamic forces and moments along the turbine blade using the AeroDyn subroutine package (Laino & Hansen, 2001). The FAST code with AeroDyn incorporated in the simulator was evaluated in 2005 by Germanischer Lloyd WindEnergie and found suitable for 'the calculation of onshore wind turbine loads for design and certification' (Manjock, 2005).

The parametric information for the FAST simulator as configured herein is available from NWTC Design Code (2013). An example of some FAST configuration parameters can be found in Table 1. The control objective is to regulate generator speed at 1800 rpm and to reject wind disturbances using collective blade pitch. The inputs to the FAST plant are generator torque, blade pitch angle, and nacelle yaw. The FAST simulator can be configured to output many different states or measurements of the plant, such as generator speed and low speed shaft velocity. In this study, the yaw is assumed fixed, and the mean wind inflow is normal to the rotor. A baseline torque controller operates

to command the generator torque setting and a baseline pitch controller operates to command the blade pitch (Wright et al., 2006). These controllers will be described next.

Value	Variable	Description
True	FlapDOF1	First flapwise blade mode DOF
True	FlapDOF2	Second flapwise blade mode DOF
True	EdgeDOF	First edgewise blade mode DOF
False	TeetDOF	Rotor-teeter DOF
True	DrTrDOF	Drivetrain rotational-flexibility DOF
True	GenDOF	Generator DOF
False	YawDOF	Yaw DOF
True	TwFADOF1	First fore-aft tower bending-mode DOF
True	TwFADOF2	Second fore-aft tower bending-mode DOF
True	TwSSDOF1	First side-to-side tower bending-mode DOF
True	TwSSDOF2	Second side-to-side tower bending-mode DOF
True	CompAero	Compute aerodynamic forces
False	CompNoise	Compute aerodynamic noise

Table 1. FAST configuration parameters for CART2 simulations.

3.2. Torque controller design

The wind turbine simulation has independent generator torque control and collective pitch control. The purpose of the torque controller is to regulate the generator speed and torque to maximize the power capture below the rated generator speed. Once the turbine has reached rated speed, the torque controller commands constant generator torque and the pitch controller operates to maintain a constant rotational speed. If the turbine speed goes beyond a certain threshold, a shutdown procedure is commenced to protect the turbine.

To maximize the power capture, the relation between torque and speed is divided in four parts, called "Regions", that can be observed in Fig. (5). In region 1, the wind turbine does not operate. The start of region 2 is called the cut-in speed of the wind turbine. The generator torque versus wind speed curve of region 2 has a quadratic shape that is designed to track an optimal tip-speed ratio for maximum power

capture. The relation governing this region is given in Eq. (1).

$$T_{R2} = k_2 V_G^2 \quad (1)$$

where T_{R2} is the generator torque (Nm) in region 2, k_2 is a coefficient and V_G is the generator speed in rpm.

Region 2.5 is a linear transition allowing the generator to reach the rated generator torque quickly. Its relation is given in Eq (2).

$$T_{R2.5} = \frac{V_G - BSS}{k_{S2.5}} + k_{T2.5} \quad (2)$$

where $T_{R2.5}$ is the generator torque in region 2.5, BSS is the Beginning Slope Speed in rpm (i.e., the speed at which the generator switch from region 2 to region 2.5), $k_{S2.5}$ is the coefficient of the slope in region 2.5 and $k_{T2.5}$ is the torque value (N.m) at the BSS speed.

When the generator speed reaches the set-point, the generator torque is set to a constant value. The Controls Advanced Research Turbine (CART2) has a constant torque set by the manufacturer to $T_m = 3524.36$ N.m.

The following values are used in the CART2 controller for all the following simulations:

$$\begin{aligned} k_2 &= 0.0008992 \\ k_{S2.5} &= 10.557 \\ k_{T2.5} &= 2574.2265 \text{ N.m} \\ BSS &= 1690.98 \text{ rpm} \end{aligned}$$

3.3. Pitch controller design

During region 3 operation, the pitch controller collectively varies blade pitch (i.e., both turbine blades receive the same blade pitch command) to regulate rotor speed to the rated speed and to mitigate aerodynamic loads due to gusts. The pitch controller designed for the wind turbine simulation is a proportional integral (PI) feedback controller with a low pass filter on the plant output signal. It is assumed that the plant is well modeled by the linear time invariant (LTI) system:

$$\begin{cases} \dot{x}_p = A_p x_p + B_p u_p + \Gamma_p u_D \\ y_p = C_p x_p; x_p(0) = x_0 \end{cases} \quad (3)$$

where the plant state x_p is an N_p -dimensional vector, the control input vector u_p is M_p -dimensional, and the sensor output vector y_p is P_p -dimensional. The disturbance input vector u_D is M_D -dimensional. The system given by Eq. (3) is sometimes referred to as the triple (A, B, C) . The control objective will be to cause the plant output y_p to asymptotically track zero. Define the output error vector as:

$$e_y \equiv y_p - 0 \quad (4)$$

Hence, to achieve the desired control objective, the error must asymptotically approach zero:

$$e_y \xrightarrow[t \rightarrow \infty]{} 0 \quad (5)$$

Consider the plant given by Eq. (3). The control objective for this system is accomplished by a PI control law of the form:

$$u_p = G_P e_y + G_I \int e_y \quad (6)$$

where G_P and G_I are constant gains. It is well known that a system given by Eqs. (3)-(6) can achieve asymptotic stability if the plant given by Eq. (3) is controllable and observable and strict positive real (SPR). A system (A, B, C) is SPR when the matrix product CB is positive definite and the open-loop transfer function $P(s) = C(sI - A)^{-1}B$ is minimum phase, i.e., all of its zeros are in the left half of the complex plane.

In some cases the plant in Eq. (3) does not satisfy the controller's requirement of SPR. Instead, there may be a modal subsystem that inhibits this property during feedback control (Frost et al., June 2011). A low pass filter can be applied to the plant output to remove the effects of the modal subsystem.

The baseline pitch controller for the CART2 simulation was designed by researchers at NREL to regulate generator speed to the rated value of 1800 rpm and to alleviate aerodynamic loads on the turbine (Wright et al., 2006). The controller input is the generator operating speed and the controller output is the collective blade pitch. The baseline PI controller was designed for an operating point of 18 m/s wind inflow and has a proportional gain (G_P) of 0.38 and an integral gain (G_I) of 0.136.

The transfer function for the low pass filter used in this study is given by:

$$T(s) = \frac{10}{s + 10} \quad (7)$$

The low pass filter is placed in the feedback loop from the plant to the controller input in the Simulink™ turbine simulation. This has the effect of removing the modes from the plant output that inhibit the SPR property (Frost et al., 2011).

The baseline PI controller operating in turbulent winds is shown in Fig. (2). Simulation transients are removed from all results by omitting the first 60 seconds of the simulation. The generator speed set point is approximately 1800 rpm. Figure 2 shows the time series of average 18 m/s turbulent IEC 61400-1 class "C" wind in the direction normal to the

wind turbine rotor plane. This wind file or one generated with the same characteristics is used for all turbulent wind simulations reported in this paper.

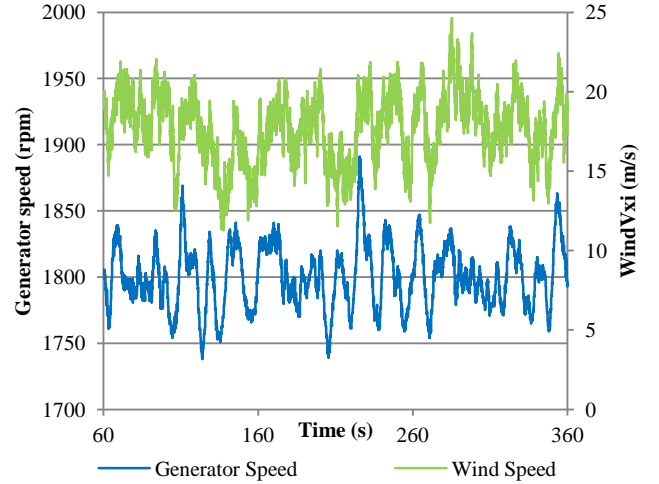


Figure 2. Time series of an 18m/s average turbulent wind (IEC 61400-1 class "C") and the generator speed.

Node (-)	BIFract (-)	BMassDen kg.m ⁻¹	FlpStff kN.m ⁻²	EdgStff kN.m ⁻²
1	0.000	282.92	165000	283000
2	0.022	290.24	161000	318000
3	0.053	261.88	142000	328000
4	0.114	201.28	98700	307000
5	0.175	186.52	78400	340000
6	0.236	169.10	59200	342000
7	0.299	149.28	45400	278000
8	0.364	133.19	34100	237000
9	0.427	111.74	25000	169000
10	0.491	96.86	17900	138000
11	0.555	78.57	12300	94000
12	0.618	65.03	8190	72500
13	0.682	49.68	5140	46700
14	0.745	37.59	3020	32600
15	0.809	25.01	1620	189000
16	0.873	16.01	868	13000
17	0.936	10.73	468	8850
18	1.000	6.02	209	6800

Table 2. Distributed nodes and properties for CART2 blades.

4. TURBINE BLADE DAMAGE

An objective of this study is to explore the response of a utility scale wind turbine to blade damage. The FAST simulation of the CART2 allows configuration of blade properties at distributed stations along the blade span, thereby enabling the properties to be modified to simulate blade damage. The total beam length of the CART2 blade is 19.995 meters. Table 2 gives relevant information on the 21 blade nodes used in the CART2 FAST simulation, including the node number, the fraction of the total beam length which determines the node position measured from the root (BIFract), the local blade mass density (BMassDen), and the local flapwise stiffness (FlpStff) and edgewise stiffness (EdgStff).

Additional distributed blade information used by the simulation includes aerodynamic center, chord length, and structural twist. The first and second blade flapwise bending modes and structural damping in percent of critical and the first blade edgewise bending mode and its structural damping in percent of critical are specified in configuration files. Blade mode shapes are represented by sixth-order polynomials that are a function of spanwise position with boundary conditions at the blade root of zero displacement and zero first derivative.

This study assumes that blade damage can be represented by a decrease in the spanwise and edgewise stiffness at a blade station and be reflected in corresponding changes in strain

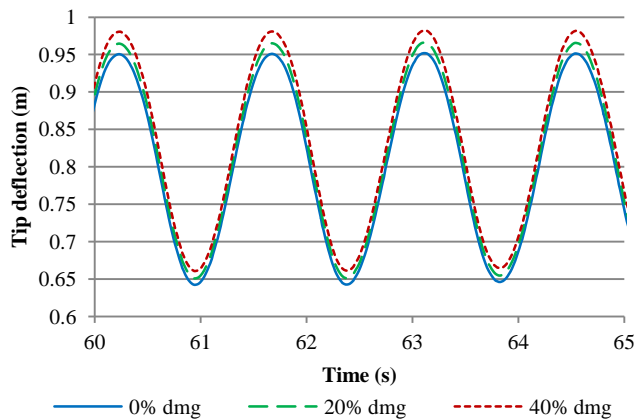


Figure 3. Tip deflection for simulation with blade having no damage, 20% and 40% reduction in stiffnesses at node 5, with constant 16 m/s wind inflow.

gauge data. Blade damage represented by local changes in stiffness includes cracks and delaminations (Nelson et al., 2011; Wahl et al., 2001; Yang et al., 1990). Simulations of the CART2 run with decreased blade stiffness and constant wind inflow show small changes in blade tip deflections. Figure (3) shows a plot of tip deflection for an undamaged turbine and a turbine with damage at node 5 consisting of a 20% and 40% reductions in stiffness in the edgewise and

flapwise directions. The wind inflow for the results in Fig. (3) was 16 m/s constant wind with 3 m/s vertical shear. Simulations with 14-24 m/s wind inflow with 3 m/s vertical shear were performed giving similar results to those seen in Fig. (3). Negligible changes in the power spectral density (PSD) of the blade bending moments and rotor thrust were observed for the various damage cases. This means that damage detection using PSD or tip deflection measurements will not be trivial.

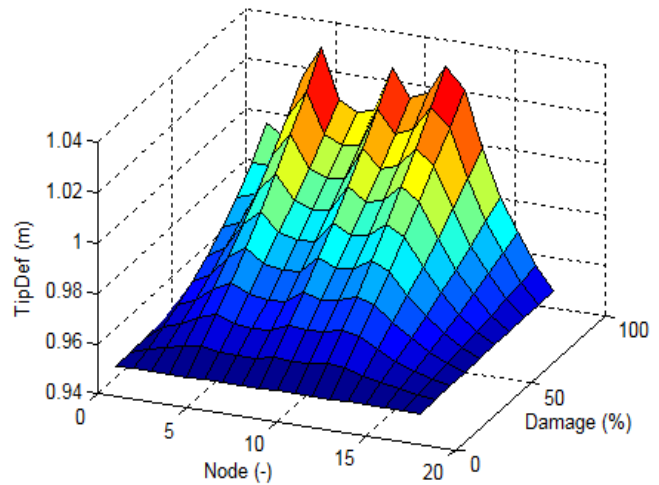


Figure 4. Tip Deflection with one damaged node, according to the node number and its damage level with a 16m/s steady wind.

Studies of the CART2 simulator are performed to investigate effects of changes in stiffness in the blades and to identify a possible feature for damage detection. A full factorial study with two parameters is performed to determine the spanwise blade point that is sensitive to changes in stiffness in the CART2 simulator. A Matlab program is developed to run multiple simulations, allowing one parameter to be modified at a time. For each simulation, a specific node of the blade is selected and its spanwise and edgewise stiffness are reduced by a damage coefficient expressed in percentage of the initial stiffness value.

The spanwise and edgewise tip deflections are recorded for each simulation. The norm of the two vectors is calculated to get the resultant tip deflection. The maximum value of the norm of each simulation is plotted according to the node and damage level. Figure 4 shows results of this study for wind inflow of 16 m/s with 3 m/s vertical shear.

This study shows that the most sensitive nodes to stiffness reduction, e.g., the nodes where stiffness reduction increases the tip deflection, are nodes 5, 12 and 9 (ordered by sensitivity). The same study was performed with different wind speeds and showed that these nodes were also the most sensitive.

In addition, it was observed that the minimum and maximum deflection of the damaged blade is a function of

wind speed and blade pitch. Deflection is also a function of the stiffness, which in turn is a measure for the blade's degree of damage. Changes in deflection due to pitch or wind speed dominate changes due to stiffness reduction. What this means is that a damage detection tool must factor out the impact of pitch and wind speed to make an inference on the presence of damage in a blade (Frost et al., 2012).

A structural health management system should be designed to monitor relevant subsystems to detect blade faults. Using appropriate fault mode models, damage propagation models, and continued monitoring of relevant measurements, inference on blade damage progression can be performed with the intent of determining remaining useful life of the blade.

For the purposes of the example described in this paper, a simple tip displacement threshold logic is employed as a damage classifier.

5. GENERATOR DE-RATING

In an earlier study (Frost et al., Mar. 2011), it was hypothesized that aerodynamic loads on the turbine blades could be lowered by *de-rating* the generator, e.g., by lowering the generator torque and speed set-point used by the controller to regulate turbine rotational speed (Fig. 5). A controller was designed allowing the user to choose the rating of the generator.

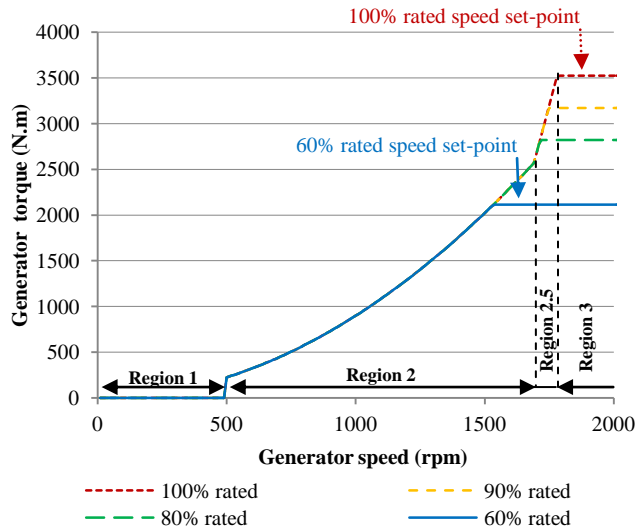


Figure 5. Correlation between generator torque and speed.

De-rating the generator means that the rated value of the generator speed set by the wind turbine manufacturer is reduced. When de-rating the generator, the value becomes the result of Eq. (8).

$$T_{R3} = T_m \times R \quad (8)$$

where T_{R3} is the generator torque (N.m) in region 3, T_m is the generator torque (N.m) set by the manufacturer and R is

the rating coefficient between 0 (0% rated) and 1 (100% rated).

To keep the laws governing region 2 and 2.5 operation consistent when de-rating, the speed set-point is also changed. The new set-point is calculated through Eq. (9).

$$V_{Sp} = \frac{T_{R3} - k_{T2.5}}{k_{S2.5}} + BSS + \Delta_{S3} \quad (9)$$

where V_{Sp} is the generator speed set-point in rpm and Δ_{S3} is a constant speed value (rpm) shifting the set-point to strive to keep the speed in region 3.

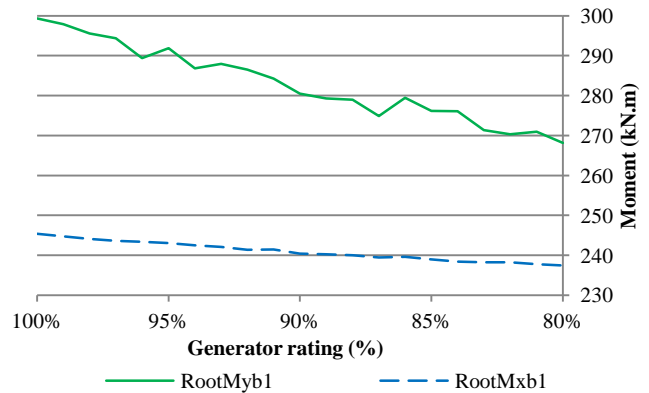


Figure 6. Effect of de-rating generator on damage equivalent loads at the root of the blade 1.

Simulations are run with de-rated generator values to see the effects on the blade root moments. Figure (6) shows the damage-equivalent loads of the root moments caused by flapwise and edgewise forces (RootMyb1 and RootMxb1, respectively), under an 18m/s average speed turbulent wind.

The results of this study show that de-rating the generator has a stronger impact on the damage-equivalent loads of the flapwise root moments. This can be explained by the fact that flapwise forces are mainly due to aerodynamic loads whereas edgewise forces are mainly due to gravity.

Simulations were run with the 18 m/s turbulent wind inflow resulting in primarily region 3 operation described in Section 3.3. The generator rating was constant during each simulation. Twenty simulations were run with rating between 100% and 80% with a 1% step. Each simulation ran for six minutes and the first minute was removed from results reported to avoid the transient period. The mean value of the root moment for each simulation and its single highest (extreme) value is reported.

To reduce the specific effects of a wind profile on the wind turbine, ten turbulent wind profiles were generated using TurbSim and the same study was repeated with each profile. TurbSim is a turbulent wind file generator for FAST available from NWTC Design Code (2012).

All the turbulent winds have a mean speed of 18 m/s and are following the third edition of the IEC 61400-1 standard. The turbulence characteristic is rated "C" in this standard.

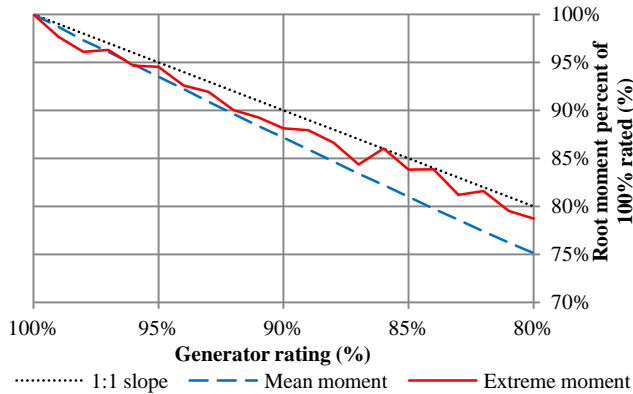


Figure 7. Effect of de-rating generator on blade 1 root moment

The mean values of the 10 studies were used to create Fig. (7). It represents the percentage of reduction of the root flapwise moment, i.e., the moment caused by flapwise forces, when de-rating the controller. The 1:1 slope shows

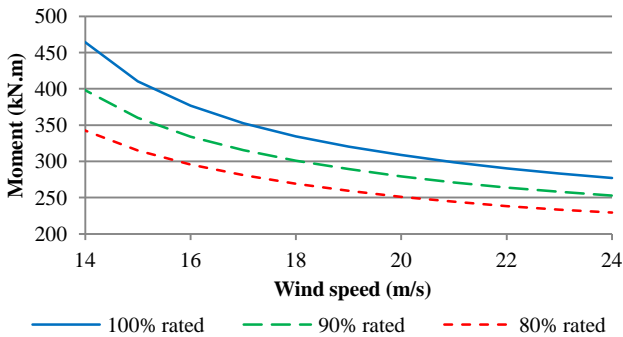


Figure 8. Extreme loads from flapwise root bending moment (RootMyb1) for various wind speeds and generator de-rating.

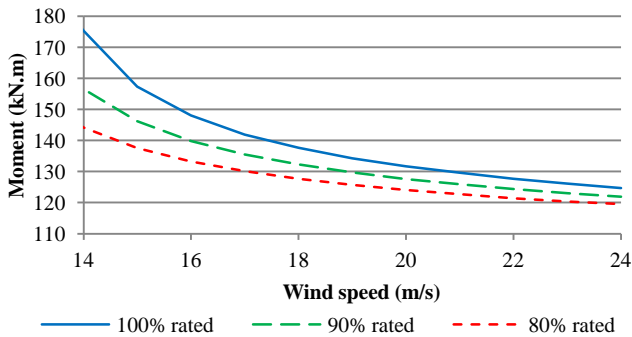


Figure 9. Extreme loads from edgewise root bending moment (RootMxb1) for various wind speeds and generator de-rating.

the threshold where the de-rating percentage is equal to percentage of reduction of the root moment. Values under the threshold show that root moments are reducing faster than controller rating.

In Fig. (7) it can be seen that de-rating the controller has a positive impact on the reduction of the mean and the extreme moments in the root of the blade. Since the values are under the threshold, the root moment is reducing faster than the controller rating. The extreme moments do not monotonically decrease with generator de-rating, this is due to the periodicity of the wind turbine blades and the time-varying nature of the wind. For instance, a gust hitting a turbine blade at a given point of time in the wind time series would hit the blade at a different time if the rotational speed of the blade differed, as it does when the turbine is de-rated.

Studies were run with constant wind having 3 m/s vertical shear. Data were analyzed after the wind turbine had reached a trim state and the start-up transients had died off. Figures (8) and (9) show the extreme loads of flapwise and edgewise root bending moments for an undamaged blade for 3 levels of generator settings: rated generator speed, generator set-point de-rated by 10%, and generator set-point de-rated by 20%. As can be seen in the figures, the damage equivalent loads of the blades decrease when the generator is de-rated. The de-rating of the turbine results in the blades being collectively pitched at a lower wind speed. This has the effect of reducing the flapwise aerodynamic loads on the blade and hence the flapwise blade root bending moments.

6. CONTINGENCY OPERATION

This section describes the contingency operation of a wind turbine to reduce loads on damaged blades under certain operating conditions. At times, it may be desirable to limit loads on a damaged turbine to ensure continued safe

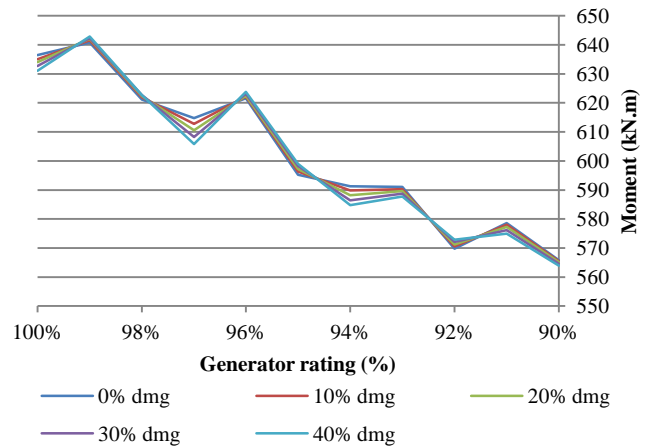


Figure 10. Extreme load for flapwise bending moment for blade with damage at node 5 for various damage levels and generator de-rating.

operation at a reduced level of energy capture from the turbine's nameplate generating capacity. In particular, controller operation might be modified when environmental or fault conditions exist that could result in high cyclic loads or extreme loads to the turbine blades resulting in a fault that causes the turbine to become disabled. As mentioned earlier, the success of wind energy depends on turbines being able to produce power whenever there is sufficient wind. Additionally, unscheduled turbine maintenance can be extremely expensive and disruptive, especially for blades, which require large, expensive cranes for access.

Figure 10 shows the resulting extreme loads in the flapwise direction for a blade with damage at node 5 under various generator de-rating values. It can be seen from the figure that de-rating the generator for a turbine with blade damage does lead to lower extreme loads on the damaged blade as was observed for undamaged blades. The mean loads were not included here since they were virtually unchanged across damage levels for the same generator rating.

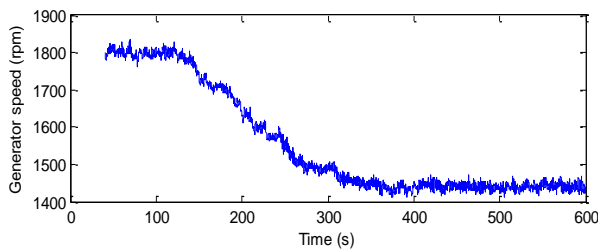


Figure 11. Measured generator speed for contingency controller.

The contingency controller has an observer or estimator of highly turbulent operating conditions. The observer uses measurements of the turbine rotor speed to estimate gusty conditions or conditions that cause rapid rotor accelerations suggesting extreme operating conditions that would not cause the turbine to shut down. For the illustrative example presented here, the generator was de-rated to 90% after a number of turbulent events were detected. It is assumed that the operating conditions transition from normal conditions to the turbulent wind conditions shown in Fig. (2). Furthermore, for this illustrative example, it is assumed that the operating conditions created by the turbulent wind are such that continued operation at rated speed could contribute to further damage of the turbine. The generator set-point is smoothly reduced by the contingency controller from rated speed to 90% of rated speed, thereby reducing transient behavior.

Figure 11 shows the generator speed for this illustrative example. Above-rated turbulent wind with IEC turbulence model C and a mean wind speed of 18 m/s is used to test the adaptive contingency controller. In practice, the operating conditions under which the turbine would be de-rated would be a design consideration depending on many factors, such

as the wind resource at the turbine site, the desired capacity factor for the turbine, and the location of the turbine within a wind farm. The type and degree of damage and remaining useful life predictions from the PHM system would inform the contingency controller, enabling it to adjust turbine operation to achieve desired objectives.

7. CONCLUSION

We report here on first steps towards integrating structural health monitoring and contingency control for wind turbines to reduce loads on damaged blades. Ultimately, a trade-off between power capture and potential turbine damage must be made. In the study described in this paper, information about blade health, operator goals, and operating conditions, are linked in parametric form to determine when the contingency controller will de-rate the generator to mitigate further damage to turbine blades. A method for representing blade damage in a high fidelity simulation of a wind turbine is presented. Generator de-rating is employed in simulation with a contingency controller to show the integration of controls and structural health monitoring to reduce loads on damaged turbine blades.

ACKNOWLEDGEMENT

The authors would like to acknowledge the SSAT project under NASA's Aviation Safety Program and the University of Wyoming Wind Energy Research Center for their support of this work.

REFERENCES

- Balaban E., Narasimhan S., Daigle M., Roychoudhury I., Sweet A., Bond C. & Gorospe G. (2013), Development of a Mobile Robot Test Platform and Methods for Validation of Prognostics-Enabled Decision Making Algorithms, *International Journal of Prognostics and Health Management*, Vol4(1) 006.
- Butterfield, A Sheng, S, & Oyague, F. (Sept. 9-11, 2009), Wind Energy's New Role in Supplying the World's Energy: What Role will Structural Health Monitoring Play?, 7th International Workshop on Structural Health Monitoring, Stanford, CA.
- Doebling, S.W., Farrar, C.R., Prime, M.B. & Shevitz, D.W. (May 1996), Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: A literature review, Technical Report LA--13070-MS, Los Alamos National Lab., NM,.
- Farrar, C.R. & Lieven (2007), N.A.J., Damage prognosis: the future of structural health monitoring, *Phil. Trans. R. Soc. A*, 365, pp. 623-632.
- Fingersh, L.J. & Johnson, K.E. (Oct. 2002), Controls Advanced Research Turbine (CART) Commissioning and baseline data collection. National Renewable Energy Laboratory, NREL/TP-500-32879, Golden, CO.

- Frost, S.A., Balas, M.J., Goebel, K., & Wright, A.D. (Jan. 2012), Adaptive contingency control: Wind turbine operation integrated with blade condition monitoring, Proceedings AIAA Aerospace Science Meeting, Wind Energy Symposium, Nashville, TN.
- Frost, S.A., Balas, M.J., & Wright, A.D. (June 2011), Generator speed regulation in the presence of structural modes through adaptive control using residual mode filters, *Mechatronics*, 21(4): 660-667.
- Frost, S.A., Goebel, K., Trinh, K.V., Balas, M.J., & Frost, A.M. (Mar. 2011), Integrating Systems Health Management with Adaptive Controls for a Utility-scale Wind Turbine, Proceedings AIAA Infotech@Aerospace Conference, St. Louis, MO.
- Jonkman, J.M. & Buhl, M.L. (Aug. 2005), FAST user's guide, National Renewable Energy Laboratory, NREL/EL-500-38230, Golden, Colorado.
- Laino, D.J. & Hansen, A.C. (Sept. 2001), User's guide to the computer software routines AeroDyn interface for ADAMS®. Salt Lake City, Utah: Windward Engineering, LC.
- Litt, J.S., Parker, K.J., & Chatterjee, S. (2003), Adaptive Gas Turbine Engine Control for Deterioration Compensation due to Aging, Technical Report TM 2003-212607, NASA Glenn, Lewis, OH.
- Lu, B., Li, Y., Wu, X., & Yang, Z. (June 24-26 2009), A review of recent advances in wind turbine condition monitoring and fault diagnosis, Proceedings IEEE Power Electronics and Machines in Wind Applications.
- Manjock, A. (May 25, 2005), Evaluation report: Design codes FAST and ADAMS for load calculations of onshore wind turbines, Report No. 72042, Germanischer Lloyd WindEnergie GmbH, Hamburg, Germany.
- Manwell, J.F., McGowan, J. G., & Rogers, A.L. (2009), *Wind Energy Explained: Theory, Design and Application*, 2nd ed., John Wiley & Sons Ltd.
- Nelson, J.W., Cairns, D.S., & Riddle, T.W. (Jan. 2011), Manufacturing Defects Common to Composite Wind Turbine Blades: Effects of Defects, Proceedings AIAA Aerospace Science Meeting, Wind Energy Symposium, Orlando, FL.
- NWTC Design Codes, FAST (2013) and TurbSim (2012), <http://wind.nrel.gov/designcodes/simulators/fast/>, <http://wind.nrel.gov/designcodes/preprocessors/turbsim/>, National Renewable Energy Lab., Golden, CO.
- Rumsey, M.A. & Paquette, J.A. (2008), Structural health monitoring of wind turbine blades, in Proc. SPIE, vol. 6933, Smart Sensor Phenomena, Technology, Networks, and Systems, p. 69330E.
- Shore, D. & Bodson, M. (2005), Flight Testing of a Reconfigurable Control System on an Unmanned Aircraft, *AIAA Journal of Guidance, Control, and Dynamics*, vol. 28, no. 4, pp. 696-707.
- Stol K.A. (Sept. 2004), Geometry and structural properties for the Controls Advanced Research Turbine (CART) from model tuning. National Renewable Energy Laboratory, NREL/SR-500-32087, Golden, Colorado.
- Tang, L., Kacprzynski, G.J., Goebel, K., Saxena, A., Saha, B., & Vachtsevanos, G. (Oct. 6-9, 2008), Prognostics-enhanced Automated Contingency Management for Advanced Autonomous Systems, International Conference on Prognostics and Health Management, Denver, CO.
- Wahl, N.K., Mandell, J.F., & Samborsky, D.D. (2001), Spectrum fatigue lifetime and residual strength for fiberglass laminates, Doctoral dissertation, Montana State University, Bozeman.
- Wright, A.D., Balas, M.J. & Fingersh, L.J. (2006), Testing state-space controls for the controls advanced research turbine, *Transactions of the ASME. Journal of Solar Energy Engineering*; 128(4): 506-515.
- Yang, J. N., Jones, D. L., Yang, S. H. & Meskini, A. (July 1990), A Stiffness Degradation Model for Graphite /Epoxy Laminates, *Journal of Composite Materials*, Vol. 24, pp. 753-769.
- Zhang, Y.M. & Jiang, J. (June 9-11, 2003), Bibliographical Review on Reconfigurable Fault-Tolerant Control Systems, in Proc. of the 5th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes, Washington, D.C., USA, pp. 265-276.