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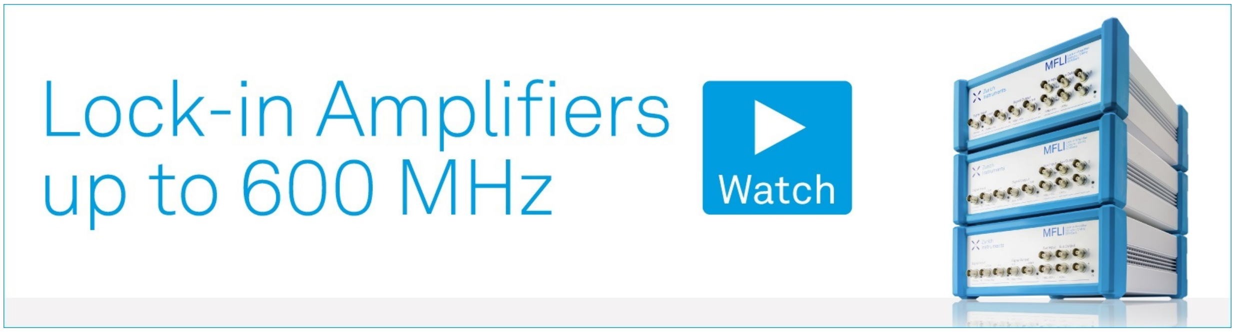

Economics of Online Structural Health Monitoring of Wind Turbines: Cost Benefit Analysis

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Abstract. Operations and maintenance (O&M) costs have an average share over the lifetime of the turbine of approximately 20%-25% of the total levelized cost per kWh of electricity produced. Online structural health monitoring (OSHM) and condition-based maintenance (CBM) of wind turbine blades has the potential to reduce O&M costs and hence reduce the overall cost of wind energy. OSHM and CBM offer the potential to improve turbine blade life cycle management, limit the number of physical inspections, and reduce the potential for missed significant defects. An OSHM system would reduce the need for physical inspections, and have inspections occur only after problem detection takes place. In the economics of wind energy, failures and unplanned outages can cause significant downtime, particularly while waiting for the manufacturing and shipping of major parts. This paper will report a review and assessment of SHM technologies and a cost benefit analysis, which will examine whether the added costs associated with an OSHM system will give an adequate return on the investment. One method in which OSHM reduces costs is, in part, by converting corrective maintenance to preventative maintenance. This paper shows that under both best and worse conditions implementing an OSHM system is cost effective in more than 50% of the trials, which have been performed. Opportunities appear to exist to improve the economic justification for implementing OSHM.

INTRODUCTION

Clean renewable energy is increasing in demand as the public and the scientific communities' desire a shift away from carbon intensive electricity generation. Wind power is increasingly becoming an economical alternative to traditional fuel sources, natural gas, coal, and nuclear, especially in areas with strong wind resources. A September 2014 report by Lazard has wind energy listed with the lowest levelized cost of energy (LCOE) [1]. The costs required to keep wind turbines working in extreme temperatures and weather conditions contribute to the high operation and maintenance (O&M) expenses, which contribute as much as 20% to the cost of wind power [2]. These O&M/operational-costs will continue to grow as wind energy use expands to more remote locations, including offshore.

Ropeworks, a blade maintenance provider, recommends blade inspections occur annually or every 2-3 years and are physical examinations in which technicians must either repel down the blades or be supported by a platform attached to the outside of the tower [3]. World Wind Energy Association (WWEA) highlights the three principle types of maintenance strategies, reactive, preventative, and predictive and states the economic benefit in terms of percentage of each [4]. Reactive maintenance is repairing or replacing components after defects become significant or replacement is necessary. Preventative maintenance, 24% better than reactive maintenance, is the process of servicing on a schedule or after a set amount of time. Lastly, predictive maintenance, 47% better than reactive maintenance, is repairing or replacing components based on the remaining useful life. Online structural health monitoring (OSHM) are technologies that can allow adoption of condition based maintenance (CBM) strategies to replace reactive and preventative maintenance.

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Adding an OSHM system to a wind turbine blade has the potential to offer many benefits to a wind energy plant. Active load monitoring performed with strain gauges allows the individual pitching systems of each blade to avoid or at least mitigate severe loads. Not only will active monitoring increase blade life by managing loads, but it can also increase the aerodynamic efficiency of the blades, hence increasing power output. With respect to maintenance, OSHM has the potential to decrease costs by avoiding unnecessary inspections and detecting early defects. Preventative maintenance reduces costs by redirecting replacement costs to major repair costs and major repair costs to minor repair costs. Further savings are possible because early detection allows lead times for scheduling maintenance during low wind periods and ordering necessary replacement components.

The following sections of this paper will review the present state of OSHM and then perform a cost benefit analysis implementing a system. The review of OSHM technologies will highlight the three primary systems (optical fiber, modal analysis, and acoustic emission sensing) and give an overview of the advantages and disadvantages of each. The cost analysis section of the paper will compare the life cycle costs of blades with OSHM installed and blades without. Blades that contain monitoring systems have the ability to be repaired earlier due to the online monitoring system, thus reducing repair costs. The analysis will determine if the repair cost mitigations are enough to cover the costs of the system.

STRUCTURAL HEALTH MONITORING TECHNOLOGY REVIEW

Condition based maintenance offers many economic benefits, but these are only available if a system can accurately predict failures. The primary systems used for online monitoring are optical fiber, modal analysis, and acoustic emission (AE). A recent survey of commercial structural health monitoring systems for wind turbines showed that there are 36 different systems and five of these apply to blade monitoring [5]. Three of the systems (IGUS ITS GmbH, Gram & Juhl, and SKF) use accelerometers and two use fiber optics (FiberSensing and Moog Insensys Ltd.); SCAIME is a company not included in the survey that develops fiber optic systems for wind turbine blades. Accelerometers monitor operating conditions and seek anomalies in the data that may be the result of damage or other changes in the condition of the blade. Fiber optic systems employ fiber Bragg grating sensors to monitor acceleration, tilt, displacement, strain, temperature, and pressure. No commercial AE system appears to have been deployed in the field for blade OSHM, but blade fatigue testing commonly uses AE [6].

Optical Fiber System

When considering fiber optic sensors the most common type is Fiber Bragg Grating (FBG). Photosensitivity in optical fibers was discovered by Hill et al. in 1978 [7], and in 1989 Meltz et al. [8] demonstrated the transverse writing of Bragg gratings. Three major equations govern FBG sensors, and the primary equation defines the fiber Bragg wavelengths [9].

$$\lambda_B = 2n_{eff}\Lambda \qquad (1)$$

In this equation, λ_B is the Bragg wavelength; n_{eff} is the effective refractive index of the fundamental mode, and Λ is the spatial period of the grating. The next two equations are associated with the change in wavelength due to temperature and strain.

$$\Delta\lambda_B = (1 - p_e) * \lambda_B \varepsilon \qquad (2)$$

where $\Delta\lambda_B$ is the change in Bragg wavelength, p_e is an effective strain-constant based on the strain-optic tensor and Poisson's ratio, λ_B is the given Bragg wavelength, and ε is the applied strain. The following equation defines temperature sensitivity.

$$\Delta\lambda_B = \lambda_B(\alpha - \zeta)\Delta T \qquad (3)$$

where α is the thermal expansion coefficient of the fiber (typically 0.55×10^{-6} m/(m*K)) and ζ is the thermo-optic coefficient of the refractive index of the fiber (typically 8.6×10^{-6} K^{-1}). Within a single sensor, both temperature and strain will affect the change in Bragg wavelength causing uninterpretable data. By eliminating temperature change or isolating a sensor, the individual affects can be determined allowing for the calculation of the contribution of the other factor.

An optical fiber system (OFS) can detect the strain in the blades and as such is able to monitor the forces exerted on the blades. Commercial systems have the capabilities of detecting resolutions down to 1με with a dynamic range of ±5000 με [9]. The capabilities of OFS's extend to monitoring various aspects of the blade including impacts, curvature, and bending. FBGs as bending sensors are not preferred due to fragility and sensitivity to mechanical fatigue.

Testing performed with FBGs has shown the usefulness of the system. A comparison of standard electrical strain gauges and FBGs performed on a small wind turbine blade revealed that the Fourier spectrum of electrical strain gauges and FBGs are similar [9]. Schroeder et al. [10] performed load monitoring and concluded that an OFS successfully monitored the loading on a blade for 2 years during field-testing. Park et al. [11] performed a load-monitoring test of a 2MW wind turbine using FBG sensors. Different operating conditions were experienced by the wind turbine and the system accurately monitored the loading in real-time.

Many benefits are available by adding an OFS including weight optimization, increased power production due to actively optimizing the wind-turbine-blade angle based on feedback from the system [9]. Further benefits include reducing maintenance costs by avoiding failures and detecting blade defects earlier, than would otherwise be possible. Glavind et al. [9] and Schubel et al. [12] highlight the important advantages and disadvantages of implementing an OFS.

Advantages

1. Small size for direct embedding with low risk of delamination
2. Multipoint sensors in the same fiber
3. Good material compatibility for embedding with glass fiber blades
4. Nonconductive and immune to electrical interferences
5. No risk of corrosion – more robust than conventional electrical sensors
6. Conduct a direct transformation of the sensed parameters to wavelengths
7. Independent of light level
8. Can be applied to the surface or embedded into the structure
9. More resonance peaks found in the Fourier spectrum of FBGs than electrical strain gauges
10. Monitor the curing process in blades

Disadvantages

1. Thermal sensitivity
2. Limited number of suppliers and relatively high costs (Cheaper solutions may be possible through detection based on wavelength division (de)-multiplexing (WDM) filters)
3. Grating reflectivity decays over time (20 yr. lifetime ensured with annealing treatment)

Modal Analysis System

Frequencies, mode shapes, and modal damping are functions of the physical properties of the structure, and thus detectable changes in the modal properties will reveal changes in the physical properties. Vibration frequencies change as the structural properties change and this allows the performance of health monitoring. Detecting shifts in the natural frequencies is a common and well-documented method of damage detection [13]. Yang and Sun give a review of modal analysis [14]. Surendra et al. [15] used modal analysis for detecting cracks in wind turbine blades and concluded that a crack affects the modes of the blade significantly and severe cracks cause changes that are more significant.

Accelerometers perform vibration analysis and provide information on the movement of the blades during operation. Rexroth Bosch Group, who developed the BLADEcontrol system, claim that they can detect damage, icing, loss of ductility, or material fatigue early by monitoring the changes in the natural oscillations of the blade. Rexroth also claims the ability to detect aerodynamic imbalances, loose parts, and incorrect pitch settings [16].

Some of the issues associated with modal analysis include interpreting the type and location of the damage. Many different factors can cause shifts in frequencies and modes and determining the specific cause is important for health monitoring. Secondly, modal properties are global properties, which results in difficulty in narrowing where the damage has taken place. A further issue can arise when multiple local frequencies shift resulting in difficulties determining the primary frequency change and its cause [13].

Acoustic Emission System

Acoustic Emission (AE) sensing is the process of detecting elastic waves emitted by dynamic structural events. Within fiber glass blades the main causes of AEs are crack initiation and propagation, breaking of fibers, and matrix cracking and fretting between surfaces at de-bonds or de-laminations [12]. Acoustic emissions result from local stress redistribution and any micro-mechanisms that cause stress release. Strain rate relates directly to the magnitude of the AE signal. Highly ductile materials may have undetectably low signals during events, because the strain rate is low. Microstructure controls the velocity and distances that dislocations and cracks propagate [17].

AE systems typically use piezoelectric sensors to detect waves in the structure. Despite the sensitivity of the system, it is unable to detect passive (non-growing) defects. The system detects and records the amplitude, energy, counts, duration, rise time, counts to peak, and average length of the wave signal and based on thresholds will indicate a defect. Characteristics of the wave signal correlate to characteristics of the defect or AE source. Another benefit of AE sensing is location determination through use of multiple sensors and triangulation, which is possible using knowledge of wave speeds and sensor coordinates.

AE systems perform well during controlled static and dynamic testing, but during operation, the high sensitivity leads to the detection of “noise”. High numbers of events and the level of background noise make extracting significant information difficult. Two other issues associated with AE systems are the complex of electronics for a sensor network and the propensity for blades to suffer lightning strikes. Despite the ability to potentially monitor the entire blade with few sensors, the system requires a high level of calibration for each blade design and low loads and signals will go unrecorded [12]. Data analysis typically implements thresholds to separate actual signals from the noise. High thresholds will not detect significant signals, and low thresholds will detect a high number of false calls.

Further capabilities associated with AE sensing are cure monitoring and acoustic-ultrasonic systems. First, vibrations and waves emitted and detected during the curing process can allow for cure monitoring, but the low signal to noise ratio may limit the feasibility. Second, integrating an AE and active ultrasonic system, using the same sensor network, enables the detection of passive defects as well as active defects. Adding appropriate transducers can convert the AE system to an acoustic-ultrasonic system capable of both AE and ultrasonic sensing [14].

COST ANALYSIS

Online monitoring can reduce O&M costs by detecting defects before they become serious and this can be done without the need for manual inspections. A primary cost reduction is converting corrective maintenance programs into preventative maintenance programs. Corrective maintenance is the cost associated with replacing the entire blade, and preventative maintenance is the cost associated with repairing the blade and bringing it back to full health. Preventative maintenance costs can vary depending when the monitoring system or inspection detects the damage [18].

Introduction to Economic Analysis

The principle benefit of a predictive maintenance system is the avoidance of catastrophic failures, which result in significant expense. Examples of the benefits of condition-based maintenance (CBM) in industry include the work by Bond et al. with nuclear power plants [19] and DLI Engineering’s research into fleet maintenance [20]. With respect to wind energy, the World Wind Energy Association (WWEA) collected case studies on online monitoring of wind turbine components [4]. Many of the benefits seen in other industries can also apply to the wind industry namely increased production, avoided failures, and decreased O&M costs.

Bond et al. show the benefits of employing online monitoring to reduce O&M costs and to increase the life expectancy of nuclear power plants. The paper stresses the importance of online monitoring in increasing capacity factor, lifetime operation, and safety. Public policy and plant owners have emphasized safety in nuclear power plants, especially after the accident in Fukushima. The paper highlights a return on investment of 200 sensors is 6 years. The methods of cost recovery are through reduced outage duration ($1-4M per cycle), avoided significant degradation ($600M), received insurance credits, and increased lifetime operation [19]. Online monitoring offers the potential to decrease O&M costs and to increase the overall plant life management and operation.

Cleven [20] wrote a report discussing the benefits of CBM over time based maintenance (TBM) methods with regard to the navy aircraft carrier fleet. The project conducted 5,754 machine tests during the FY 2008 and calculated a benefit cost ratio of 14.5/1. The highest full year benefit/cost ratio from 2000 to 2008 was in 2003 with 23.0/1 and the lowest was in 2007 with 12.4/1. The report gives seven ways in which CBM improved on TBM.

1. Prevention of progressive machine damage
2. Improved selection of machines for overhaul
3. Identification of specific repairs needed
4. Reduction in post-availability repairs
5. Prioritization of machinery operation
6. Finding recurring problems
7. Support of repair parts procurement and work force scheduling

Despite the difficulty in calculating the exact value of the benefits that result from using CBM verses TBM, the report shows a consistent benefit/cost ratio greater than 12/1.

WWEA [21] gives a series of case studies that show the benefits of CBM in wind energy. The first example is from the National Wind Coordinating Committee, who conclude that maintenance costs are due to three categories: unscheduled maintenance (75%), preventive visits (20%), and major planned overhauls (5%). The next two case studies are from a wind farm in Canada. The first examines the effect of having OSHM of the gearbox and employing forecasting for maintenance. A bearing break can force complete gearbox a replacement, and poor weather can create unsafe working conditions and disallow the use of the maintenance crane. Accelerometers or oil analysis monitoring systems can reveal the bearing defect early, and weather forecasting can allow repair scheduling during good weather and operation until repair. The second case study re-enforces the importance of proactive measures with respect to weather. An ice storm destroyed a wind turbine, because the emergency brake system failed in the beginning of the storm. Shutting the turbines down before the storm starts would avoid the failure that occurred.

With regard to wind turbine blades, OSHM has the potential to decrease the number of significant failures and downtime. Similar to nuclear power plants predictive maintenance can increase the safety of wind plants and reduce downtimes associated with blade failures. The same benefits that the Navy aircraft carrier fleet reported are also available to wind plant operators. OSHM will signal which blades need replacement, the type of repair needed, and scheduling of repairs/replacements. CBM is dependent on having a system that accurately predicts when failures will occur, the types of failures, and the remaining useful life.

Examples of Economics

The first case study of OSHM by Besnard and Bertling [22] compares three different maintenance strategies, visual inspection, nondestructive inspection, and online condition monitoring. The study considers two different factors when modeling the maintenance strategies, failure rate and time to failure. Two types of failure rate are defined. Instant failure rate is the occurrence of events such as lightning strikes and other events that require immediate replacement of the blade to occur. Defect initiation rate is that for the occurrence of minor defects. Time to failure describes the time needed for an initiated crack to evolve into a blade failure. Online CBM is best suited for blades that experience high failure rates and short times to failure. When failure rates lower and time to failure increases, nondestructive inspection becomes the best method for detection.

Besnard et al. [18] also performed another study to determine the life cycle costs of implementing condition monitoring on blades, generators, and gearboxes, as compared to the life cycle costs without online monitoring. The final analysis showed that using CBM cost on average $252,130 less than not using CBM. Earlier and cheaper repairs and increased production due to shorter lead times and these create the savings.

A third study, by Nilsson and Bertling [23], performs a life cycle cost analysis for two different wind plants and examines the necessary requirements for a condition monitoring system to be economical. When considering a 30-wind turbine plant, 47% of corrective maintenance needs to convert to preventative maintenance or availability would need to increase by 0.43%. Unique to this study, the authors examined the reduction of person-hours and savings possible by replacing two components at a single time rather than individually. Significant savings are possible, but this would not alone cover the costs of the monitoring systems.

Sorenson et al. [24] created a pre-project report considering the installation and use of online monitoring systems, which included the estimated return on investment. The return on investment considers three cases, best, worst, and most likely case. Based on the model used, the most likely case has a return on investment of three years, due to the ability to catch failures early. The best case assumes a low cost sensor system that provides returns almost immediately, and the worst case is the opposite assuming a high cost system that requires constant repairs and provides returns in year 19.

Each of the studies supports the economics of online condition monitoring and provides methods in which the system will provide a return on the initial investment. OSHM offers the ability to detect damage early, thus converting costly corrective maintenance into cost effective preventative maintenance. It can reduce the downtimes and increase availability by allowing scheduled repairs during low wind periods or multiple repairs during the same service trip.

Life Cycle Cost (LCC)

The cost analysis consists of four cases:

1. Best case Condition Based Maintenance
2. Best case Visual Inspection
3. Worst case Condition Based Maintenance
4. Worst case Visual Inspection

Best and worst case is with regard to the scenarios that will create the best/worst case conditions for CBM. Comparing the LCC of cases 1 to 2 and cases 2 to 4 determines if CBM is better economically than visual inspection. The CBM cases of LCC examine the costs over the life of a wind turbine blade including the condition monitoring system, repair costs, and blade replacement costs. The visual inspection LCC cases examine the costs over the life of a blade without an OSHM system, but with added inspection costs. If the CBM cases (1 & 3) are lower cost than the visual inspection cases (2 & 4) installing OSHM is economical.

$$LCC = C_{inv} + C_{ins} + C_{pm1} + C_{pm2} + C_{cm} \tag{4}$$

LCC = Life Cycle Costs
C_{inv} = Investment Costs
C_{ins} = Inspection Costs
C_{pm1} = Minor Preventative Maintenance Cost
C_{pm2} = Major Preventative Maintenance Cost
C_{cm} = Corrective Maintenance Cost

Equation 4 provides the framework for calculating the life cycle costs. The detection rates and the type of maintenance determine the impact that each term in the LCC equation has. In the CBM case, investment costs are equivalent to the cost of the system (Table 1), but in the visual inspection case, investment costs are zero. The reverse is true for the inspection costs. The visual inspection case incurs an inspection cost every 6 months, but the CBM case does not. Preventative Maintenance costs vary, because each system has a different probability of detecting minor and major failures. Corrective maintenance costs differ in for each case, because in the CBM case the investment costs are included in the blade replacement costs as well.

Many items contribute to the overall capital cost of an OSHM system including electronics, installation, and sensors. Sorensen et al. [24] gives a cost breakdown in Table 1 and estimates it will cost \$25,329 to install an AE system and \$13,152 to install an optical fiber displacement system per wind turbine. Further data from Cleven [22] and Nilsson and Bertling [23] shows system costs of \$20,670 and \$30,360, respectively. The different numbers show the wide range of estimates used for the cost analysis of condition monitoring systems. The visual inspection case has inspection costs instead of the initial capital costs. Inspections occur every 6 months and have a cost of \$276 [22] per blade inspection.

TABLE 1. Component Cost Breakdown.

	20 AE Transducer System (2014USD)	40 Sensor Displacement Fiber System (2014USD)
Transducers	2923	1948
Electronics in Blade	9742	0
Electronics in Hub	2923	3897
Communication	1948	1948
Central Processor	2435	2435
Installation	4871	2435
Wiring/Cabling	487	487
Total	25329	13152

The second cost incurred in the cost analysis is the repair costs. Repair costs split into two levels; the first level is for repairs made during the first 4 months of defect growth and the second level is for defects detected after the initial 4 months. Repair costs come from Besnard [18] and Sorenson et al. [20], and are $4,823 for minor repair and $48,230 for major repair and $4,554 for minor repair and $6,072 for major repair, respectively. The blade is unrepairable in the twelfth month after defect initiation. If detection fails, the blade fails in the twelfth month after defect initiation and requires replacement. During operation, blades can potentially fail immediately due to extreme weather and lightning strikes. The analysis includes the possibility of immediate failures, which require replacement. In the CBM cases, after failure the OSHM system and the blade require replacement adding to the overall costs.

TABLE 2. Primary Life Cycle Costs from different references.

	Costs (2014USD) [22]	Costs (2014USD) [23]
Inspection	276	-
Minor Repair	4823	4554
Major Repair	48230	6072
Blade Replacement	537240	303600
OSHM System	20670	30360

Because the failures occur randomly, the model randomly generates defects on a monthly basis. At the beginning of each month there is a 1% chance that a defect will be initiated and a 1% chance that an instant failure will occur. An instant failure requires corrective maintenance action and the blade is replaced. When defect initiation begins each system has a probability of detecting it. Online CBM has a 50% chance of detecting minor flaws and visual inspection has 0% chance. Online CBM has a 90% chance of detecting major flaws and visual inspection has an 80% chance. When a flaw is discovered the blade is repaired and returned to like-new condition. If neither methods detect the damage in 11 months, the blade fails in the 12th.

TABLE 3. Detection of Damage Rates [22].

Rate of Detection	CBM	Visual Inspection
Minor Flaw	50%	00%
Major Flaw	90%	80%
Critical Failure	100%	100%

The random nature of defects and the probability of detection creates situations in which either method can be more economical. Figure 1 shows a scenario in which visual inspection is more economical than CBM. Critical failures force replacement of both the blade and monitoring system, before the system has a chance to recover any costs. OSHM has the possibility of detecting failures early and drastically reducing repair costs and completely avoiding replacement costs as seen in figure 2. The system was able to detect the minor defects early adding only repair costs instead of full replacement costs.

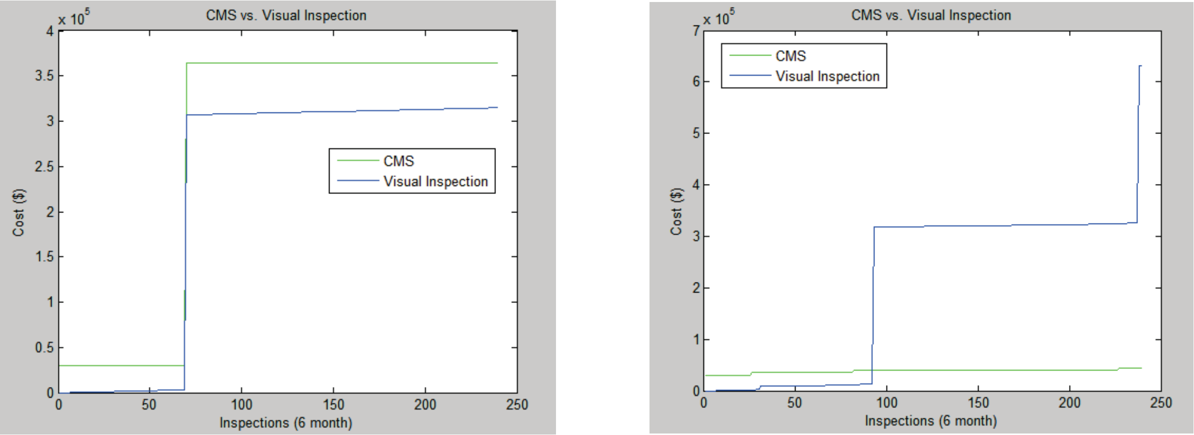

FIGURE 1 (Left) & **FIGURE 2** (Right) - Two possible scenarios over the life of a blade.

RESULTS

The distribution plots show the frequency in which CBM has a lower LCC than visual inspection under the two different cases. Figure 3 shows the worst-case scenario in which online CBM is more economical 55% of the time. Under the best conditions, figure 4, online CBM is more economical 70% of the time.

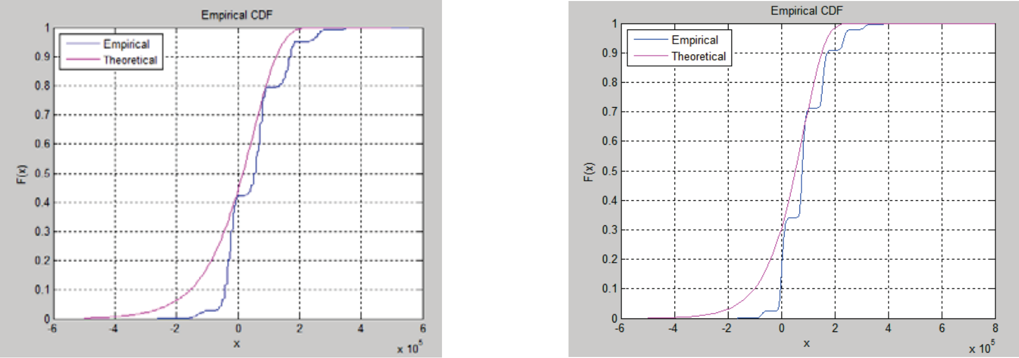

FIGURE 3 (Left) & **FIGURE 4** (Right) – Distribution of visual inspection and online condition monitoring cost differential – Worst Case (3) Best Case (4).

CONCLUSIONS

Online condition monitoring has the potential to reduce the O&M costs associated with wind turbine blades by detecting defects before they propagate into larger defects and eventual failures. Fiber optic strain gauges, acoustic emission detection, and vibration sensors have the capabilities to detect the initiation and growth of defects within the blade, which allows for cheaper repairs. Wind plant operators can reduce costs by scheduling repairs on days with low wind to reduce downtime losses. Stopping turbines with suspected defects during high winds can reduce the risk of increasing damage to the blade. Under both economic conditions considered in the study, online CBM is more economical than visual inspection more than 50% of the trials.

The risk associated with online CBM is that it will not be able to detect the damage or pending immediate catastrophic failure that will render the generating system useless. The model accounts for the possibility of immediate failure and missed defects and it shows that the systems will still be economical, but wind plant owners should consider the severe weather in an area before installing online CBM systems. The model assumes a six month inspection interval, industry standard is between once and twice a year. Increasing the inspections per year will decrease the economics of online CBM, because it will allow detection of failures before failure. Lower repair costs for major failures will also decrease the economics benefits of online CBM, because it reduces the importance of early detection.

The study only accounts for the benefits that would result from converting corrective maintenance to two levels of preventative maintenance. Online monitoring systems can supply other benefits other than just converting maintenance types. Installing the system during manufacturing adds to the value, because it allows detection of defects created during manufacturing. Avoiding installing defective blades can create significant savings. Preventative maintenance has a shorter downtime than corrective maintenance leading to increased income by reducing downtimes. Coordinating and scheduling repairs during low wind periods are other benefits of online monitoring.

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REFERENCES

1. Lazard, "Lazard's Levelized Cost of Energy Analysis - Version 8.0," Lazard, 2014.
2. R. Wiser and M. Bolinger, "2012 Wind Technologies Market Report," U.S. Department of Energy: Energy Efficiency & Renewable Energy, Berkeley, LBLN-6356E, 2013.
3. MISTRAS Group, Inc, "Wind Turbine Blade Repair and Maintenance Services," MISTRAS Group, Inc, 2013. [Online]. Available: http://www.ropeworks.com/service_wind_blade.htm. [Accessed 15 August 2014].
4. S. Barber and P. Golbeck, "WIND ENERGY - Technology and Planning," World Wind Energy Association, 2006. [Online]. Available: http://wwindea.org/technology/ch03/estructura-en.htm. [Accessed 19 June 2014].
5. C. Crabtree, D. Zappala and P. Tavner, "Survey of commercially available condition monitoring systems for wind turbines," Technical Report November, SUPERGEN, Durham, 2010.
6. A. Beattie, "Acoustic Emission Monitoring of a Wind Turbine Blade During a Fatigue Test," in *35th Aerospace Science Meeting*, Reno, NV, Jan. 1997.
7. K. O. Hill, Y. Fujii, D. Johnson and B. S. Kawasaki, "Photosensitivity in optical fiber waveguides: Application to reflection filter fabrication," *Applied Physics Letters,* vol. 32, p. 647, 1978.
8. G. Meltz, W. Morey and W. Glenn, "Formation of Bragg gratings in optical fibers by a transverse holographic method," *Optics Letters,* vol. 14, no. 15, pp. 823-825, 1989.
9. L. Glavind, I. S. Olesen, B. F. Skipper and M. Kristensen, "Fiber-optic grating sensors for wind turbine blades: a review," *Optical Engineering,* vol. 52, no. 3, Article ID 030901, pp. 1-9, 2013.
10. K. Schroeder, W. Ecke, J. Apitz, E. Lembke and G. Lenschow, "A fibre Bragg grating sensor system monitors operational load in a wind turbine rotor blade," *Measurement Science and Technology,* vol. 17, pp. 1167-1172, 2006.
11. S. Park, T. Park and K. Han, "Real-Time Monitoring of Composite Wind Trubine Blades Using Fiber Bragg Grating Sensors," *Advanced Composite Materials,* vol. 20, pp. 39-51, 2011.
12. P. Schubel and e. al, "Review of structural health and cure monitoring techniques for large wind turbine blades," *Renewable Energy,* vol. 51, pp. 113-123, 2013.
13. S. Doebling, C. Farrar, M. Prime and D. Shevitz, "Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review.," Los Alamos National Laboratory Technical Report LA-13070-MS, 1996.
14. B. Yang and D. Sun, "Testing, inspecting and monitoring technologies for wind turbine blades: A survey," *Renewable and Sustainable Energy Reviews,* vol. 22, pp. 515-526, June 2013.
15. N. Surendra, J. Yang and M. Richardson, "Using Modal analysis for detecting cracks in wind turbine blades," *Sound & Vibration,* pp. 10-13, 2011.
16. Rexroth Bosch Group, "BLADEcontrol Greater output - less risk," 2012. [Online]. Available: http://dc-corp.resource.bosch.com/media/general_use/industries_2/renewable_energies_6/windenergy/products_2/rotor

_blade_condition_monitoring_systems_/BLADEcontrol_AE.pdf. [Accessed 2014].

17. D. E. Bray and R. K. Stanley, Nondestructive Evalutation, Boca Raton: CRC Press, 1997.
18. F. Besnard, J. Nilsson and L. Bertling, "On the economic benefits of using Condition Monitoring System for maintenance management of wind power systems," in *2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems*, Singapore, pp. 14-17, 2010.
19. L. Bond, S. Doctor, D. Jarrell and J. Bond, "Improved economics of nuclear plant life management," in *2nd IAEA International Symposium on Nuclear Power Plant Life management*, Shanghai, China, 15-18 Oct. 2007, IAEA Paper IAEA-CN-155-008KS, 26pp, 2007.
20. L. W. Cleven, "Aircraft Carrier MCA Program Benefit Cost Analysis," American Society Naval Engineers, 2009.
21. World Wind Energy Association, "Wind Energy - Technology and Planning," World Wind Energy Association, 2006. [Online]. Available: http://wwindea.org/technology/ch03/estructura-en.htm. [Accessed 10 August 2014].
22. F. Besnard and L. Bertling, "An Approach for Condition-Based Maintenance Optimization Applied to Wind Turbine Blades," *Sustainable Energy,* vol. 1, no. 2, pp. 77-83, 2010.
23. J. Nilsson and L. Bertling, "Maintenance Management of Wind Power Systems Using Condition Monitoring Systems - Life Cycle Cost analysis for Two Case Studies," *IEEE Transactions on Energy Conversions,* vol. 22, no. 1, pp. 223-229, 2007.
24. B. Sorensen, L. Lading, P. Sendrup, M. McGugan, C. Debel, O. Kristensen, G. Larsen, A. Hansen, J. Rheinlander, J. Rusborg and J. Vestergaard, "Fundamentals for Remote Structural Health Monitoring of Wind Turbine Blades - a Preproject," Riso-R-1336(EN) Report, Riso National Laboratory, Roskilde, 2002.