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Wind Energy's New Role in Supplying the World's Energy: What Role will Structural Health Monitoring Play?

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ABSTRACT

Wind energy installations are leading all other forms of new energy installations in the United States and Europe. In Europe, large wind plants are supplying as much as 25% of Denmark's energy needs and 8% of the electric needs for Germany and Spain, who have more ambitious goals on the horizon. Although wind energy only produces about 2% of the current electricity demand in the United States, the U.S. Department of Energy, in collaboration with wind industry experts, has drafted a plan that would bring the U.S. installed wind capacity up to 20% of the nation's total electrical supply. To meet these expectations, wind energy must be extremely reliable. Structural health monitoring will play a critical role in making this goal successful.

Currently, commercially available condition monitoring systems are used in all multimegawatt turbines. Site maintenance crews are learning how to best process and use the complex information provided by these systems in their operational strategies. Those who can best synthesize the huge volumes of raw data are able to improve their maintenance efficiency, schedule just-in-time repairs, minimize downtime, and maximize their energy production. However, wind turbines operate in very stochastic environments with dynamic loading. This makes damage rate prediction very difficult. Drivetrains are monitored today because of their notorious failure rates and cost to repair. Blades and other major components require unexpected maintenance as well, but they are not monitored. This is due to the lack of a cost-effective and viable monitoring method. There may be other health monitoring opportunities for wind plants. For example, is it possible to use condition monitoring systems to synthesize the huge volumes of data for the full turbine operating behavior and correlate it with turbulent wind conditions that are leading to premature damage? Is it possible for real time control strategies to adapt to these conditions and extend the life of major components? These are the challenges for structural health monitoring in the wind industry.

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INTRODUCTION

Wind energy has expanded dramatically since the early 1980s when small turbines dotted the hillsides of California. Those machines had rudimentary controls, no condition monitoring, were unreliable, and required extensive maintenance. The utilities considered them an insignificant passing fad. Today, wind turbines have multimegawatt ratings, sophisticated controls, and condition monitoring systems on most of the drivetrains. A typical wind plant today may have more than 200 multimegawatt turbines installed and it represents a $600 million asset investment. Each plant is monitored and maintained by a small crew of skilled technicians.

This new generation of turbines is far more reliable than those of the early 80s, but they have to be if we are going to depend on them for a major source of energy. Operations and maintenance costs represent a significant part of the long-range financial risk. An otherwise productive plant in a high wind resource site can be a net loss if not managed responsibly and creatively. Unlike other utility assets that have extensive operations crews to manage one or two generation systems, wind plants have many assets dispersed over a large geographical area. Instead of performing maintenance in an enclosed environment, the crews must work out in the field, sometimes in difficult weather conditions. This can present both challenges and opportunities. The challenges are related to few crews managing many dispersed machines. On the flip side of the coin, the opportunities are related to the large number of machines. If one machine is having problems, it represents a small part of the entire fleet. Also, it can be a leading indicator for the rest of the machines in the fleet. Having many machines in one plant offers rapid accumulation of statistical data and trending. Having many machines also offers the opportunity to compare one with adjacent machines, which could provide clues to cures for the ailing machine.

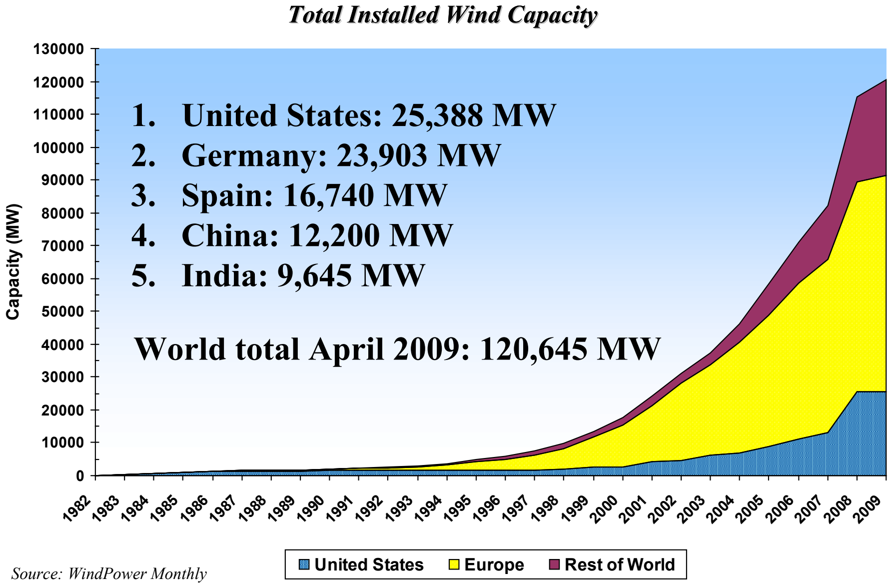
This paper is not intended to be an in-depth study of all the opportunities. Instead it is intended to educate a reader who may be new to the wind industry but is knowledgeable about structural health monitoring or condition monitoring. It is intended to stimulate creative minds to bring their skills to bear on the emerging wind industry and perhaps spawn new health monitoring solutions for the next generation of wind plants.

GROWTH OF WIND ENERGY

In the early 1980s the U.S. market was by far the largest wind energy market. It was stimulated by both a California investment tax credit and a federal investment tax credit. As these tax credits expired in the mid 80s and energy prices dropped, this market disappeared. Some European countries instituted production tax credits and took the farsighted view that this would support a new industry. They were right. Now, with energy prices and global warming front and center, mature Danish and German companies are selling into the new market. Although the United States once again has the largest market, it has many fewer U.S. manufacturers.

Figure 1 shows the growth in world wind energy capacity. Most of this growth has occurred in the last 10 years, from 1999 to 2009. For the first time, the United

States took the lead over other countries in installed capacity with more than 25 GW in 2009, but China is gaining fast. In January 2009, the worldwide installed wind capacity equaled about 10% of the total U.S. installed capacity of all forms of electrical generation. In the early 80s the U.S. industry comprised many U.S. manufactures installing turbines in California. The new U.S. industry is made up of many U.S. developers with very few U.S. manufactures. The emphasis has shifted from manufacturing turbines to installing, operating, and maintaining them, and maintenance is one of the leading roles the United States will play in the new wind industry. Now that it is clear that wind energy will play a significant role in our nation's generation mix, it is imperative that it is reliable and predictable. Because of the dispersed nature of this generation source, new and innovative ways of managing wind plants, which include health monitoring and automated diagnostics, will be required.



Source: WindPower Monthly

Figure 1. Growth of wind energy worldwide [1].

NREL, DOE, and the American Wind Energy Association collaborated on an investigative report, published in 2008, that explores the barriers for further growth in wind energy [1]. The report concludes that there are no real supply-side or technical barriers to providing 20% of the U.S. electricity demand with wind energy by 2030. Based on this information, a realistic growth goal of 20% installed capacity by 2030 was set. Figure 2 shows the cumulative growth and the annual installation rate that would be required to achieve this goal. Last year, the United States installed 9 GW of new wind energy capacity, which far exceeded the expected rate of about 4 GW. This rate of installation indicates that the 20% by 2030 goal is indeed realistic. Figure 3 shows how much of the U.S. capacity is likely to be made up of offshore wind turbines [1]. Some reports put the expected capacity even higher at 80 GW [2].

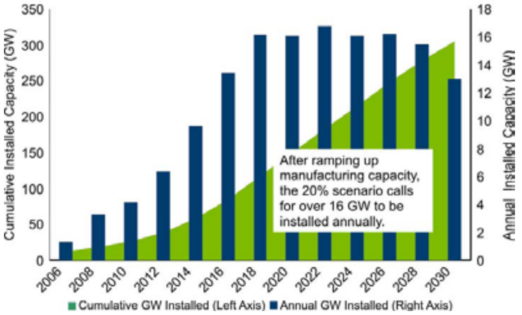


Figure 2. U.S. wind industry growth goals [1].

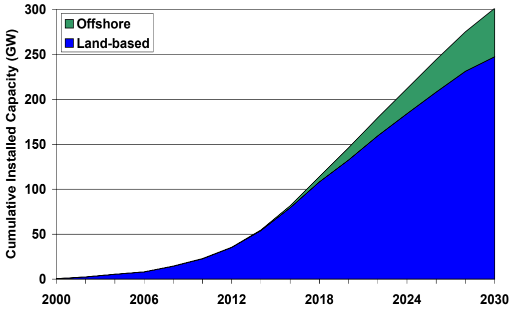
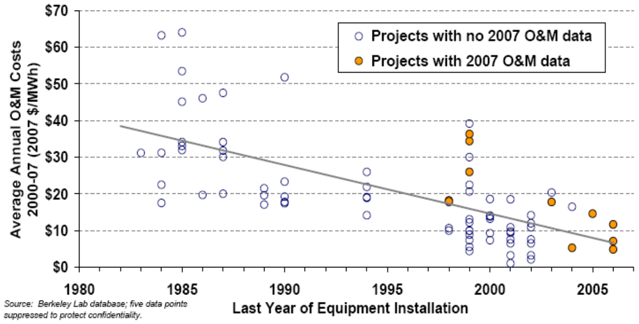


Figure 3. Likely portion from off shore [1].

Figure 4 illustrates how specific operation and maintenance (O&M) costs have decreased during the past three decades. Turbines are much more reliable and maintenance operations have become more efficient. Although this is impressive, costs must be reduced even further. DOE's target for O&M costs is $5/MW-Hr. Figure 5 shows O&M costs for new wind plants in the United States [2]. These data show that costs are twice the DOE goal and they increase with the age of the wind plant. This illustrates the need to manage the ongoing costs of maintenance over the life of the wind plant. Figure 5 also shows that the most recent wind plants almost meet the DOE goals but that long-term O&M costs are expected to rise.



Source: Berkeley Lab database; five data points suppressed to protect confidentiality.

Figure 4. Dramatic reduction in O&M costs over the past three decades [2].

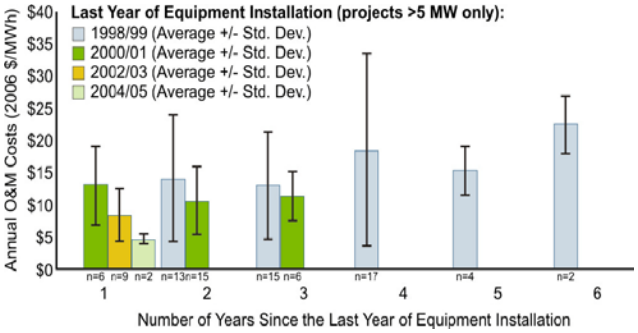


Figure 5. O&M costs for recent wind plants [2].

Figure 6 shows the cause for rising O&M costs as the plant ages [3]. As the plant ages, the risk of component failure increases, and the cumulative risk also tends to rise with the number of components approaching end of life. Finally, it is clear from Hahn, et al [5] that the failure rates are site specific. Figure 7 illustrates how Danish turbines seem to have lower failure rates than German machines. This may be caused by the less energetic winds in many of the Danish sites compared to the sites in Northern Germany. Although there are very few data available for sites in the United States, anecdotal data suggests that the more energetic U.S. sites have higher failure rates than both Northern Germany and Denmark. If this is true, it suggests that the energetic U.S. sites are in greater need of efficient O&M practices than the less energetic European sites.

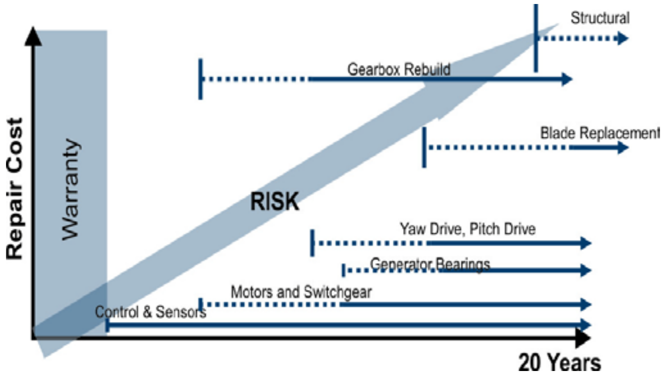


Figure 6. Risk of component failures increase with the age of the wind plant [4].

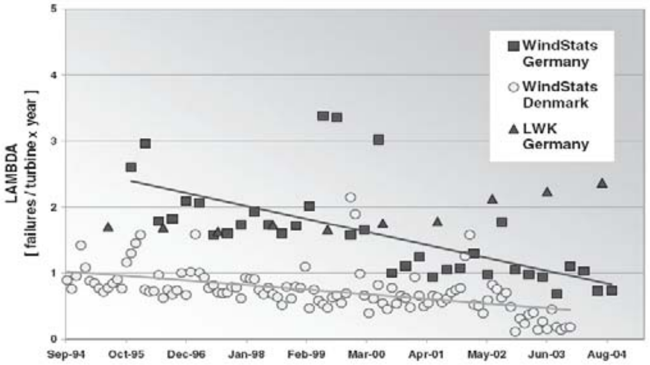


Figure 7. Failures are decreasing but are site specific [5].

MAINTENANCE CHALLENGES

Land-based

Maintenance challenges for land-based turbines result from having turbines widely dispersed geographically. Generally, the turbines need to be placed at distances greater than 7 rotor diameters and preferably more than 10 diameters apart. This spacing reduces losses from turbine wake (one turbine robbing energy from its downwind neighbor). According to this rule, 100 meter rotors need to be placed as much as one kilometer apart. In a typical wind plant of 100 turbines, wind smiths may end up spending a lot of time simply transporting themselves from one turbine to another. Once at the site, crew members must climb a tower that can be as much as 100 meters tall with tools. Finally, any maintenance that requires crane work must be timed to match low-wind periods. Favorable weather windows are less likely at a site that has been selected for high average winds [3].

Offshore

For offshore turbines, each of the issues mentioned for land-based turbines becomes even more critical. Maintenance crews must consider both weather windows and sea state conditions. Transporting crew members to towers must be done with boats or helicopters. If the crew is transported by boat, the crew members must be skilled at jumping from boat to turbine platform and back. If weather conditions and/or sea states deteriorate while they are in a tower, they may be required to wait out the storm. Thus, each tower must have overnight provisions for the crew. Getting equipment to the turbine is likewise challenging. If a major component has to be taken down, a sea-based crane must be mobilized and that requires even more restrictive weather windows. The difficulties of transporting crews has led to research that will enable robust crew transfers from boat to towers [6]. Many European offshore sites transport crew members with helicopters and lower them onto the nacelle. Although this seems like a far riskier and more expensive task then transportation by sea, it provides a greater number of maintenance opportunities because they are not restricted by high sea states. For these reasons, offshore machines must be more reliable than land-based turbines, and remote automated diagnostics will be critically important in offshore applications.

CURRENT STRUCTURAL HEALTH MONITORING PRACTICE

The ISET (Institut für Solare EnergieversorgungsTechnik, Germany) data in Figure 8 shows that electrical components have the highest failure rates, but drivetrains and blades cause the greatest down time and are the most expensive to repair [5]. Thus, drivetrain and blade reliability is more important to monitor than the other components. Early knowledge of their impending failures allows maintenance planning and often can reduce repair costs dramatically.

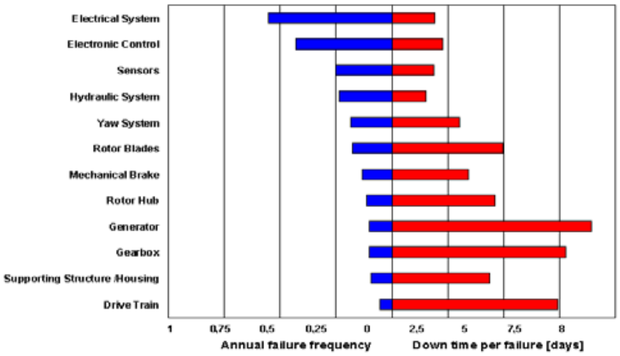


Figure 8. Failure rates and down time for European land-based turbines [5]

Growing concern over failure rates of wind turbine gearboxes has caused many new megawatt-scale turbines to offer condition monitoring systems as standard equipment. In some cases, insurance companies require them. The condition monitoring systems usually include some type of vibration monitoring in multiple locations. Some include lubrication particle counting. They potentially can provide the greatest insight and earliest detection of gear and bearing anomalies [7].

Other structural health monitoring techniques are not as mature. The next most important large component is the blade. Cracks can originate in a variety of locations such as the trailing edge, bonds between the shear web and skin, and near structural transition regions. Detecting such cracks is very difficult and is usually done by visual inspection. Fortunately, they usually grow rather slowly, which allows annual inspections to track and maintain them before they grow to catastrophic dimensions. However, they can occur in locations that are impossible to inspect visually. Furthermore, the blade has a tremendous surface area. So detection techniques that focus on one small region are likely to miss cracks in other areas of the blade, and it is impossible to know in advance where the cracks may originate. Finally, manual inspection is imperfect and can miss critical cracks in their incubation stage. Thus the need for a reliable, inexpensive, automated technique for detecting cracks over large areas of the blade. This is a major challenge that may require strategies that apply comprehensive techniques to one or two lead turbines in each wind plant.

CAPITALIZING ON UNIQUE ASPECTS OF WIND PLANTS

One of the unique aspects of wind plants is the fact that there are many turbines in a single plant. They may be distributed over a large region but they will generally experience similar average wind speeds. An experienced operator can quickly detect when machines are operating in high-turbulence locations. These machines tend to experience high fault rates and can experience low production. They can also be chosen as the lead maintenance machines to watch and perhaps add additional instrumentation.

Sometimes performance, control settings, and faults on adjacent turbines can be compared to detect anomalous faults. This technique can be quite powerful but always requires a skilled technician or engineer to investigate individual turbine behavior. This process is aided by the voluminous detailed data produced from the turbine SCADA system. However, for technicians to determine the best strategies for correcting problems and feel confident that they are fixing the right problem, they need expert systems that can interrogate this database for individual turbines and adjacent turbines and diagnose the problems.

If more information could be gained about the dynamic loads, a more powerful system could be developed. This system would enable operators to compare estimated operating loads with design loads, which would help them understand if turbines were operating in a high-fatigue environment. It would also allow them to correlate high-load operating conditions with weather conditions. This might allow them to choose less aggressive operating strategies to reduce fatigue damage and improve life cycle maintenance costs.

Model assisted load estimators could be used to help determine these operating conditions. If validated structural dynamic models of the turbine were fed with wind speed, control conditions, and performance, the models could estimate the loads and perhaps provide indicators of high loads.

CONCLUSIONS

The wind industry is quickly becoming a significant energy source throughout the world. Maintenance is one of the most costly elements of the life-cycle operating costs. Although condition monitoring can greatly reduce these costs for drivetrains, research is needed to improve the viability of structural health monitoring for blades and other major structural components. Expert systems need to be developed that capitalize on the wind plant's ability to build a statistical database quickly that can be used to diagnose problems with adjacent turbines. Load estimators need to be developed that can help track high fatigue operating conditions and aid in load-reduction strategies. Load-reduction strategies could offer the best failure prevention opportunities.

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