A Cyberinfrastructure for Integrated Monitoring and Life-Cycle Management of Wind Turbines

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Abstract. Integrating structural health monitoring into life-cycle management strategies for wind turbines can help owners and operators to accurately schedule maintenance and repair work at minimum associated life-cycle costs. Continuously updated monitoring data (i.e. structural, environmental, and operational data) can effectively be used to capture the operational and structural behavior of wind turbines and to reduce uncertainty in load and resistance parameters. However, permanently operating monitoring systems generate massive volumes of monitoring data that need to be organized, stored, processed, and analyzed in order to extract meaningful information. In this paper, a cyberinfrastructure framework for integrated structural health monitoring and life-cycle management of wind turbines is proposed. The secure framework is designed for scalable storage of large volumes of monitoring data and for online life-cycle management of wind turbines. This paper describes the overall architecture and the components of the cyberinfrastructure framework, which has been deployed in continuous monitoring of a 500 kW wind turbine for more than three years. Using the cyberinfrastructure framework, case studies are presented investigating the long-term structural performance and the operational efficiency of the wind turbine.

1. Introduction

According to the Global Wind Energy Council, the worldwide wind energy capacity has reached 282 GW in 2012, which is a growth of more than 18% compared to 2011 (GWEC, 2013). As the World Wind Energy Association predicts, the worldwide wind energy capacity is expected to reach more than 1,000 GW by 2020 (WWEA, 2012). As a new record, the global "clean" energy investments, having more than doubled within the past five years, have exceeded $260 billion (GWEC, 2012). However, a total of approximately $380 trillion is needed to meet the projected global energy demand by 2035; a significant budget will also be needed for maintenance and life-cycle management of wind turbines (IEA, 2012).

To facilitate a cost-efficient operation and to ensure high availability of wind turbines, it is essential to continuously monitor and assess structural performance and operational efficiency. In particular, the inherent uncertainties in load and resistance parameters impose the need for continuously updated monitoring data recorded from the wind turbine. Integrated life-cycle management (LCM) systems, coupled with structural health monitoring (SHM) systems that collect and analyze the actual data sets recorded from the wind turbine, are powerful tools for enabling optimal operation and maintenance of wind turbines.

In related engineering disciplines, such as life-cycle management of naval ships or bridges (Frangopol *et al.*, 2011; Okasha and Frangopol, 2012), it has been demonstrated that SHM can be an “enabling technology that will lead to the next significant evolution [for] the ... management of civil infrastructure” (Frangopol and Messervey, 2009). Also in the wind energy sector, as has been shown by Park *et al.* (2013) and Smarsly *et al.* (2011a, 2011b, 2013), coupling life-cycle management with structural health monitoring technologies provide a reliable platform to identify load effects, to ensure structural integrity, and to analyze the actual operational efficiency of wind turbines. However, instead of using continuously updated monitoring data for LCM, general assumptions and periodic inspections – which are time-consuming, costly and do not allow accessing all critical points – serve as a common practice for the life-cycle management of wind turbines (Besnard and Bertling, 2010; LaPuma and Liberman, 2006; D’Souza *et al.*, 2011).

This paper presents a cyberinfrastructure for integrated monitoring and life-cycle management of wind turbines. An integral component of the cyberinfrastructure framework is a SHM system that provides continuously updated structural and environmental data. In addition, operational data such as power output and revolutions, taken from the wind turbine SCADA (supervisory control and data acquisition) system, is integrated into the framework. Serving as an online information platform, the system automatically stores and processes the heterogeneous data sets and the processed data are accessible via secure connections over the Internet by authorized users. This paper first describes the overall architecture and the components of the cyberinfrastructure framework. Two major components, the “SHM system” and the “management module”, are then presented in details. Furthermore, the application of the framework to a 500 kW wind turbine, which has been continuously monitored for more than three years, is demonstrated. Finally, using the cyberinfrastructure framework, two case studies are presented investigating the long-term structural performance and the operational efficiency of the monitored wind turbine.

2. A Cyberinfrastructure Framework for Integrated Monitoring and Life-Cycle Management of Wind Turbines

As shown in Figure 1, the cyberinfrastructure framework consists of six major, interacting components that are installed at spatially distributed locations:

1. A *SHM system*, comprising of sensors, data acquisition units and a local computer, is installed on the wind turbine to continuously collect structural, environmental, and operational data.
2. A *decentralized software system* is installed on different computers at the Institute for Computational Engineering (ICE) in Bochum, Germany. The software system is remotely connected to the SHM system; it continuously processes and stores the monitoring data, supports automated data management, and provides Internet-enabled remote access to the monitoring data.
3. An *agent-based self-diagnostic system* for detecting sensor malfunctions is designed to ensure reliability and availability of the SHM system.
4. A *model updating component* provides computational wind turbine models that are continuously updated by means of system identification to support damage detection analyses based on continuously updated monitoring data.
5. A *management module* enables online life-cycle management through remote analyses of the structural, environmental, and operational wind turbine data.

6. A 32-node *PC cluster*, which is also located at the ICE in Bochum, is integrated into the framework to provide high-performance parallel computing capabilities for solving computationally intensive calculations.

This paper primarily focuses on two of the six components of the cyberinfrastructure framework – component 1 ("SHM System"), and component 5 ("Management Module") – that are described in the following subsections. For details on the other framework components in the system framework, the interested reader is referred to Smarsly *et al.* (2012a-d), Hartmann *et al.* (2011), and Law *et al.* (2012).

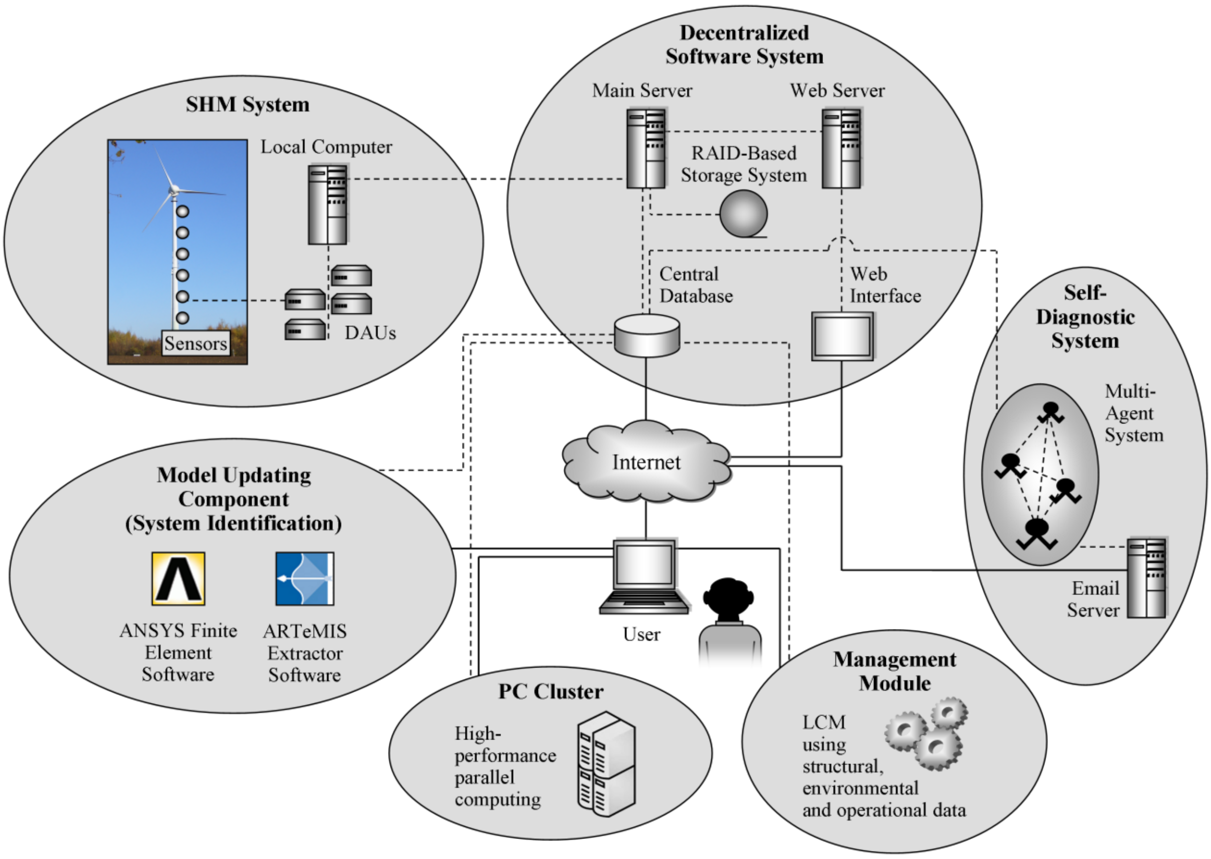

Figure 1: Architecture of the cyberinfrastructure framework

3. Structural Health Monitoring System

The SHM system is installed on a 500 kW wind turbine in Germany (Figure 2). The wind turbine has a hub height of 65.0 m and an upwind rotor of 40.3 m diameter that is equipped with three synchronized blade pitch control systems. As mentioned earlier, the SHM system comprises of a network of sensors, data acquisition units, and a local computer installed in the maintenance room of the wind turbine (Lachmann *et al.*, 2009). The sensors (accelerometers, displacement transducers, and temperature sensors) are placed at different levels inside and outside the steel tower and on the foundation of the wind turbine. In addition, two anemometers are deployed. As shown in Figure 2, one anemometer is installed on top of the nacelle, the other anemometer is mounted on a telescopic mast adjacent to the wind turbine for recording wind speed, wind direction, and air temperature. Operational data, such as revolutions and power production of the wind turbine, is recorded by the wind turbine SCADA system.

All recorded data sets, termed "primary monitoring data", are continuously forwarded from the data acquisition units, which are also installed in the maintenance room of the wind turbine, to the local computer for temporary storage and periodic backups. Using a permanently installed DSL connection, the local computer transfers the primary monitoring data to a central database installed at the ICE. When transferring the primary monitoring data from the local computer to the database, the data sets are synchronized and aggregated, and metadata is added to provide definitions of installed sensors, IDs of data acquisition units, output specification details, date and time formats, etc. ("secondary monitoring data"). In addition to the primary and secondary monitoring data, "tertiary monitoring data" is periodically computed and persistently stored in the database, summarizing the basic statistics of the data sets such as quartiles, medians, and means. Once being stored, all monitoring data is available to authorized users and to the other components of the cyberinfrastructure framework.

Figure 2: Monitored wind turbine and anemometers used

4. Management Module

For online life-cycle management and remote analyses of the monitoring data, the management module – written in Java – offers basic statistical analyses, such as simple linear regression and analysis of covariance (ANCOVA), as well as advanced functionalities supporting, e.g., fast Fourier transforms or calculations of tip speed ratios, wind shear coefficients, and wind turbine power coefficients. Figure 3 shows an abbreviated UML class diagram of the management module illustrating its architecture and core classes. The architecture combines several software design patterns and software architectures commonly adopted in software engineering – primarily the "three-tier model" and the "adapter pattern" (Gamma *et al.,* 1995). The three-tier model, being both a software design pattern and a software architecture, ensures a concise separation of the management module's user interface ("presentation"), the functional process logic ("controller"), and the monitoring data ("data access"). The architecture allows any of the three tiers to be upgraded, changed, or replaced independently from each other, and improves scalability, integrity and performance of the management module.

The first tier, the presentation, provides access to the management module and can be installed on any PC, laptop, and on Java-enabled mobile devices such as cell phones and smart phones. The data access tier is designed to enable remote database access for requesting monitoring data recorded from the wind turbine. The connection to the database is realized through a programming interface based on the Java Database Connectivity (JDBC), a Java-based data access technology providing methods for querying and updating data sets in relational databases. The security of database requests and data transmissions are provided by the database, which requires password and username as well as secure drivers to be specified when accessing the database. The third tier, the controller, contains specific algorithms to be used for structural as well as operational analyses and for life-cycle management of the wind turbine. As shown in Figure 3, the algorithms as well as external software modules are modularly integrated into the management module in terms of adapters.

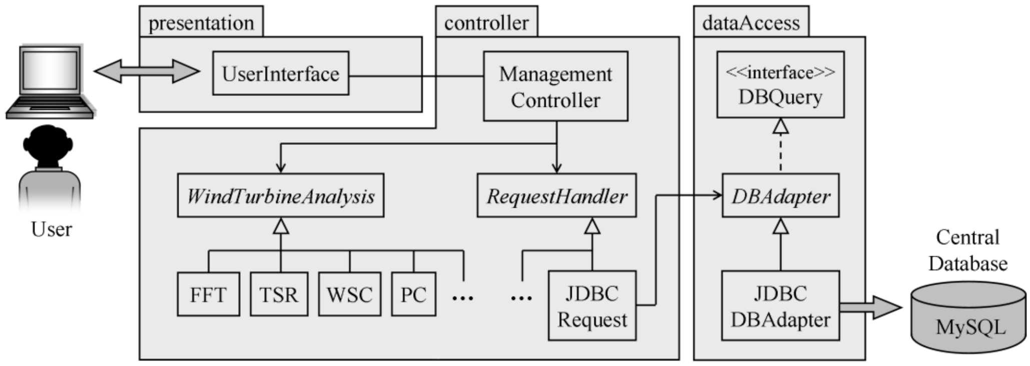

Figure 3: Architecture of the management module

5. Wind Turbine Analysis

Two case studies, investigating the structural performance and the operational efficiency of the wind turbine, are presented in the following subsections. Using the management module, long-term monitoring data collected by the SHM system is exemplarily analyzed to demonstrate the functionality and the practicability of the cyberinfrastructure framework.

5.1 Structural Performance of the Wind Turbine

To briefly illustrate the rapid online assessment of the wind turbine's modal properties, two data sets – recorded in October 2011 and in March 2012 – are compared with respect to potential long-term changes in the structural performance. Specifically, the horizontal accelerations of the wind turbine tower, recorded from the tower at 63 m height, are analyzed. The acceleration data represents the vibration response of the wind turbine structure due to an unknown wind loading, which is assumed to be approximately a broadband "white" excitation (white-noise or impulse input). Both acceleration time histories used in this study are taken at similar environmental conditions, i.e. at a wind speed of about 2 m/s and a temperature of about 12 °C. Figure 4 shows the recorded acceleration responses of the wind turbine tower in October 2011 and in March 2012.

For determining the modal properties of the wind turbine tower, the acceleration data is automatically transformed into the frequency domain using the Cooley-Tukey FFT algorithm (Cooley and Tukey, 1965). Then, a peak-picking (PP) algorithm, representing a relatively simple but computationally efficient method for identifying modal properties, is used to determine high-valued spectrum peaks from the frequency spectra and for determining the natural frequencies of the wind turbine. The Fourier spectra calculated from the acceleration data obtained in October 2011 are exemplarily shown in Figure 5. As for comparison, the first natural frequencies derived from the acceleration data in October 2011 and in March 2012 are in close agreement. Table 1 summarizes the results obtained in this study and the results from previous studies in related projects (Liu *et al.*, 2012; Höffer *et al.*, 2012; Leimbach *et al.* 2012). The comparisons are based (i) on the Stochastic Subspace Identification (SSI) method, (ii) on the Enhanced Frequency Domain Decomposition (EFDD) method, and (iii) on finite element analyses of a wind turbine model that is part of framework component 4 ("Model Updating Component"). As shown in Table 1, the natural frequencies calculated in the current study are found to be similar to those of the previous studies with only minor differences.

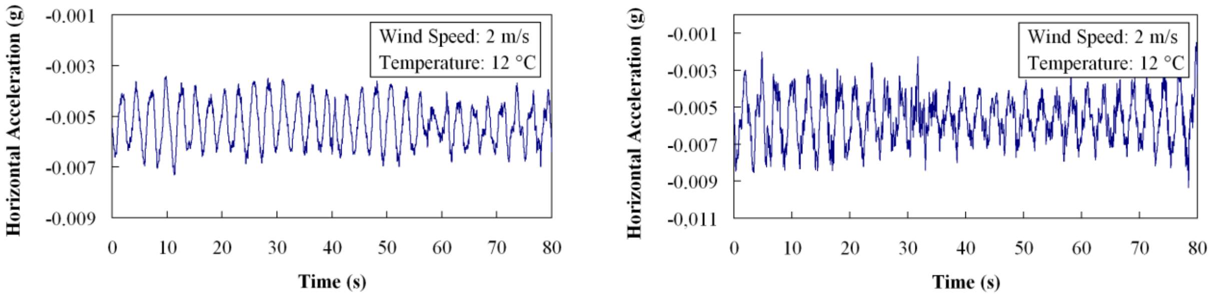

Figure 4: Example time histories of horizontal acceleration response of the wind turbine tower at 65 m height recorded in October 2011 (left) and in March 2012 (right)

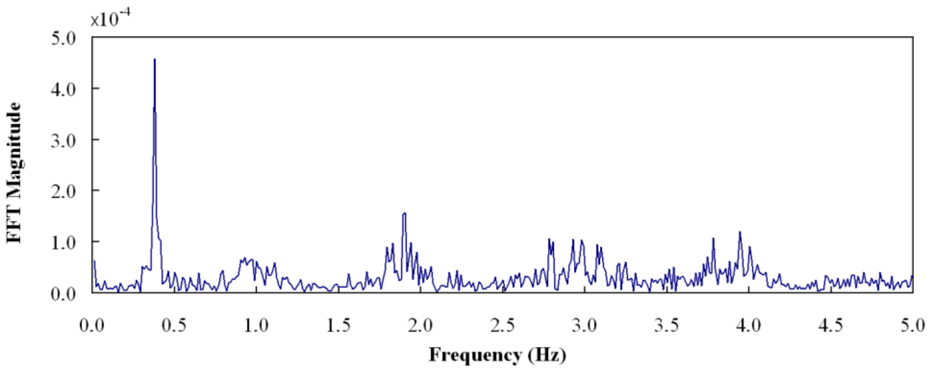

Figure 5: Frequency response function calculated by the management module (October 2011)

Table 1: Calculated first modal frequencies of the wind turbine tower

	Frequency (Hz)	**Deviation (%)**
Cyberinfrastructure Framework (March, 2012)	0.37	-
Cyberinfrastructure Framework (October, 2011)	0.39	6.8
SSI (Liu *et al.*, 2012)	0.37	0.3
SSI (Höffer *et al.*, 2012)	0.38	2.5
EFDD (Liu *et al.*, 2012)	0.37	0.3
EFDD (Höffer *et al.*, 2012)	0.39	5.5
Finite Element Model (Leimbach *et al.*, 2012)	0.36	1.3

5.2 Operational Efficiency of the Wind Turbine

To verify the wind turbine efficiency and to evaluate long-term trends in the operational behavior, environmental and operational data – the latter provided by the wind turbine SCADA system – is analyzed through the management module of the cyberinfrastructure framework. The online data analyses performed can help not only to understand the operational behavior of the wind turbine, but also to validate particular measures undertaken to optimize the operational performance, to quantify energy losses that usually remain undetected (e.g. due to structural deterioration), and to minimize the costs for operation and maintenance.

Figure 6 exemplarily shows the wind turbine performance over a 2-year period. For the comparison, power curves are constructed based on 1-month monitoring data recorded in March 2010, March 2011, and March 2012. In addition, the power curve provided by the manufacturer is shown in the figure. The power curves are calculated by the management module from the measured power output and from the wind speed measurements, and are plotted in terms of polynomial functions which fit the measured data very well (R^2_{2010} = 0.989, R^2_{2011} = 0.996, and R^2_{2012} = 0.994). As can be seen from Figure 6, the results demonstrate that no decrease in power output can be found when comparing the power curves of 2010, 2011, and 2012. (The results have also been confirmed in another study, as reported in Smarsly *et al*., 2012d, using ANCOVA and statistical hypothesis testing). The actual power curves constructed from the monitoring data are found to be similar to the power curve provided by the manufacturer.

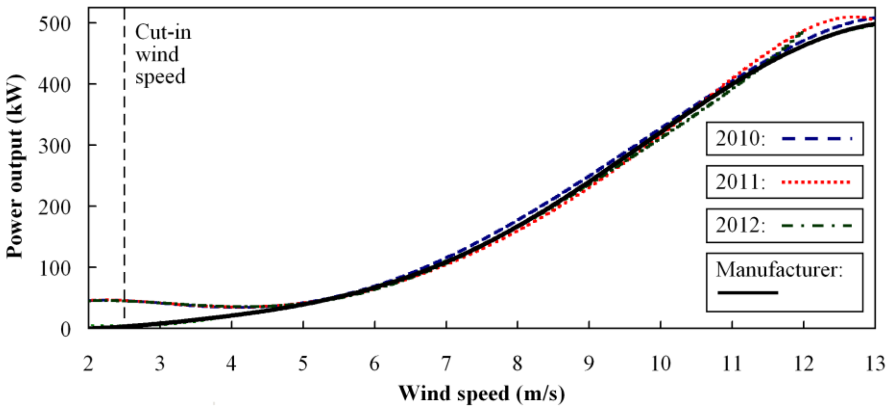

Figure 6: Power curves of the wind turbine in March 2010, 2011, and 2012

The actual wind turbine efficiency is illustrated in Figure 7. The figure shows the wind turbine power coefficient C_P which is defined as the power extracted by the wind turbine relative to the power available in the wind stream. Representing the theoretical maximum of power efficiency, the Betz limit is also shown in Figure 7; the Betz limit implies that no wind turbine can convert more that 59.3% of the kinetic energy of the wind into mechanical energy. The efficiency of the monitored wind turbine – as a result of this example calculation – is largest at the optimum wind speed that is found between V = 7.5 m/s and V = 8.5 m/s in each of the regarded time spans.

It is worth mentioning that the cyberinfrastructure framework can also be used for the verification of assumptions that are made when planning and implementing wind energy projects. For example, when choosing optimal wind turbines for specific sites, several parameters are of critical importance, such as cut-in wind speed (i.e. the minimum wind speed at which the wind turbine will generate usable power) and cut-out wind speed (i.e. the wind speed at which the turbine's rated speed is exceeded so that further increases in wind speed would not lead to increased power output). Depending on the site, Weibull distributions are typically used to characterize the wind speed and to estimate the power output, because actual wind speed distributions are usually not available. As shown in Figure 8, the framework provides actual wind speed distributions in 50 kW intervals based on 30-minute mean values. As a result, it is corroborated that, even when just considering the length of time explored in this case study, the 500 kW wind turbine, with a cut-in wind speed of 2.5 m/s and a cut-out wind speed between 28-34 m/s, is an excellent choice for the given site conditions. Figure 9 shows the distribution of the power output over the time period of this study. Comparing Figures 8 and 9, it can be seen that the quantities of power outputs correspond very well to the mean values of the wind speed distributions.

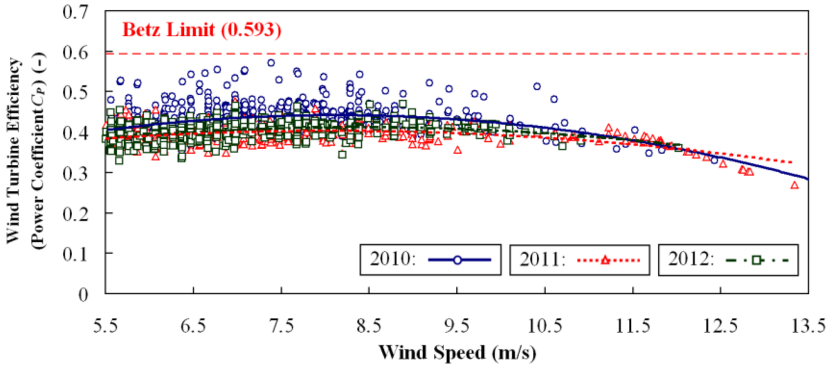

Figure 7: Wind turbine efficiency in March 2010, 2011, and 2012

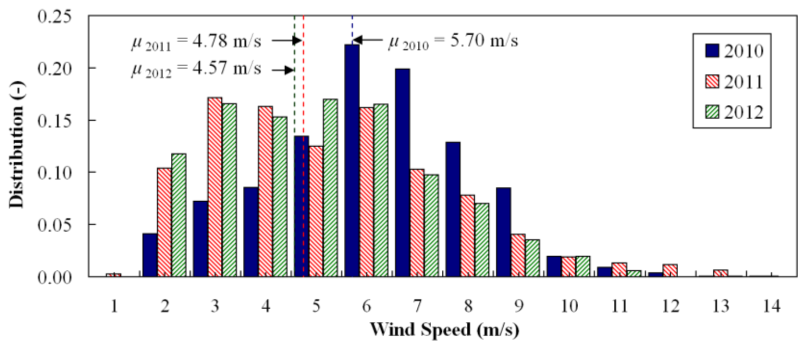

Figure 8: Mean wind speed in March 2010, 2011, and 2012

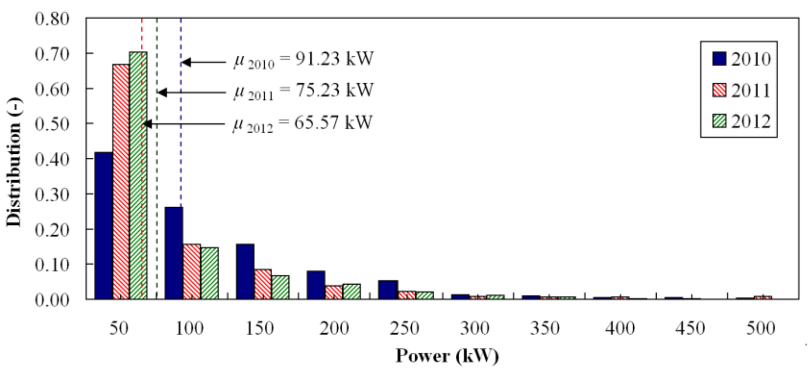

Figure 9: Generated power in March 2010, 2011, and 2012

6. Summary and Conclusions

With the cyberinfrastructure framework presented in this paper, an approach has been proposed for integrated online monitoring and life-cycle management as well as reliability assessment, optimum maintenance and inspection planning of wind turbines. The framework consists of several decentralized and interactively connected components. For example, a robust and modular SHM system is integrated into the cyberinfrastructure framework to continuously collect structural, environmental, and operational data from a 500 kW wind turbine. The massive data sets generated by the SHM system are stored and managed by a secure database that is remotely accessible by authorized users and, also, by the components of the framework. A management module, another major component of the framework, is devised to support the wind turbine life-cycle management through remote analyses of the monitoring data.

The functionality and the practicability of the cyberinfrastructure framework have been demonstrated in two case studies investigating the structural performance and the operational efficiency of the monitored wind turbine. The life-cycle analyses conducted in the case studies have revealed that (i) the monitored wind turbine is in an excellent condition and that (ii) the selected wind turbine model is an appropriate choice with respect to the given site characteristics (wind speed distribution, etc.). Although the current cyberinfrastructure framework, as described herein, can serve as a practical tool for owners, operators, and decision makers, a number of opportunities exists to further improve the framework and its components. For example, further research is needed to increase the reliability and the availability of SHM systems that constitute the basis for a robust and accurate life-cycle management. In addition, an important next step will be to explore the transfer of the proposed concepts from a single wind turbine to a wind farm, which would provide new insights into the overall (structural and operational) wind farm performance.

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