Maintenance Cost Of Wind Turbines – A Review On Major Component Failures And Maintenance Strategies

David Philipp[1], Samuel Lima[2], Adão Muniz[3]
Technische Hochschule Köln[1]; Energo Engenharia[2], Chesf – Companhia Hidrelétrica de São Francisco[3]
david.philipp@smail.th-koeln.de, adaolm@chesf.gov.br, samuel.lima@energo.eng.br

Introduction

Relevant insights about global climate developments and the collectively developed consciousness about the importance of the preservation and protection of the environment for future generations, triggered international interest in renewable energy systems (RES). In research and development, the investments relating RES have increased more than tenfold between 2004 and 2011 [1]. Especially the wind energy branch has developed dynamically in the past decade and today represents the strongest renewable energy sector all over the globe. In 2000 the total installed wind capacity was 17.400 MW, grew to 432.883 MW in 2015 (Fig. 1) and is expected to maintain its trend in the future.

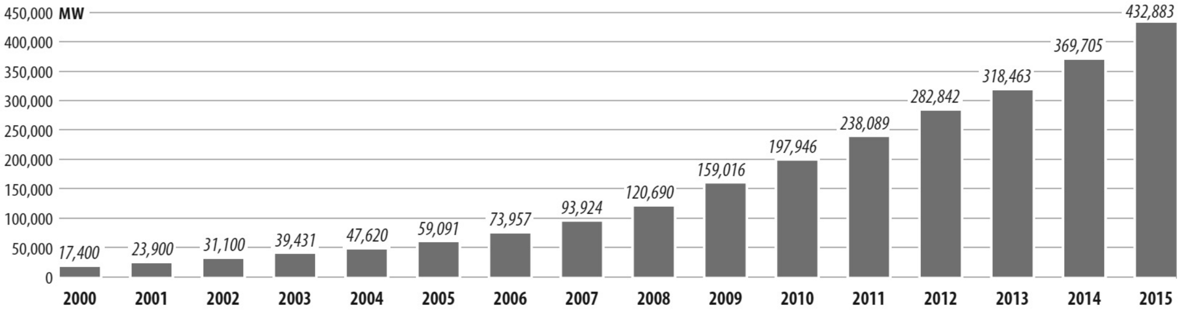

Figure 1: Global Installed Wind Capacity from 2000 – 2015 (Source: Global Wind Energy Council, 2016)

With the rising quantity of installed turbines, the demand of service providers continues to gain importance. Being designed to operate over a period of more than 20 years under the direct influence of fluctuating environmental conditions, wind turbines deteriorate faster than similar electricity generation installations and have a higher demand on maintenance and servicing [2]. The expiration of initial operations and maintenance (O&M) warranty contracts poses big future business opportunities for independent service contractors, as the majority of O&M services are contracted for 5 years. Maintenance expenditures tend to increase with the assets age due to accumulation of component failures. Cost prediction and plant availability guarantees are important for plant operators. Especially in smaller niche markets, where original equipment manufacturers (OEMs) have not consolidated their services, possibilities for service providers arise to offer cost efficient O&M contracts [3].

Brazil is one of the top 10 leading wind power markets globally and is expected to keep developing its market structures. In the future, further focus on research and development and operations and maintenance is expected [2]. Its favorable wind characteristics - especially in the northeastern region – promote the increase of wind power in the national energy matrix. Throughout 2015, various factories covering various elements of the supply chain have been opened in Brazil.

This paper gives an overview of empirical data published by wind energy update (WEU) on major components failure rates and downtimes, analyzes major O&M cost drivers and introduces the most applied maintenance strategies. The intention is to present facts, that facilitate the evaluation of proper maintenance strategies and financial reserves in the maintenance package in the northeastern region of Brazil.

Methodological approaches

The methodological approaches are mainly based on literature reviews. The information on major component operational behavior characteristics and some replacement cost information are derived from the publications of WEU Onshore Asset Optimization & Reliability Benchmarking Report 2015, which consist of empirical studies and industry interviews. O&M market size data is derived from GWEC publications. Studies carried out by National Renewable Energy Laboratories (NREL) form the base of evaluations on cost drivers and expected major component failure rates. Various other scientific papers have been reviewed in order to gain insight of state of the art research state. Expert knowledge of Energo O&M engineers evaluate the gathered data to its applicability on the local market.

Wind Turbine Component Categories and Sub-components

Modern wind turbines are installations, that convert kinetic energy from the air-flow into electric power. Technological developments of the past decades have shown, that HAWT (horizontal axis wind turbines) reach the highest efficiencies amongst possible configurations due to their enhanced controllability through pitch- and yaw-adjustment [4].

This paper structures the wind turbine in systems/categories and sub-components, listed in Table 1 derived from WEU. Each component category is in charge of a specific task, that contributes to the system function in its entirety. The operational modes of the turbine subsystems components depend on their reliabilities. Only if the components operate with their initial design function, the wind turbine achieves its intended operational mode. It is the objective of O&M to ensure this operational mode over the greatest time span possible in order to keep the plant available. The component reliabilities are of essential importance in this context, which is why critical subcomponents have to be identified, their failure modes characterized and their root cause determined. Therefore, a profound understanding of the components and their operating environment is necessary.

Table 1: Component categories and sub-components (Source: WEU, 2015)

Category/System	**Sub-Components**
Gearbox	Gearboxes
Generator	Generators
Blades	Blades
Mechanical	Yaw systems, mechanical brakes, hydraulic systems, rotor hubs, drivetrains
Electrical	Sensors, electrics, control systems
Others	Structural components (towers, nacelle housings, foundations and bolts and others)

The turbine systems work under different environmental and operational influences that determine their components deterioration characteristics. Such information will have to be gathered throughout the asset life cycle, approximated values however may be used from plants under similar conditions. Inappropriate design assumptions, misjudgment of environmental conditions or insufficient product quality control often lead to premature component failures. It is therefore important to familiarize with the components deterioration modes and failure characteristics to predict failures and plan maintenance actions.

In accordance with Sandia Laboratories [5], that quote the Institute of Electrical and Electronics Engineers, the failure characteristics of individual pieces of electrical equipment may be partially described by failure rate and downtime. It furthermore states the inherent availability and reliability data, that includes: Component, unit-years, failures, failure rate (failures/year), MTBF (Mean Time Between Failures), MTTR (Mean Time to Repair). These data are important to collect and already have been documented in other installations such as conventional power plants that use similar components installed in wind turbines (e.g. gearbox, shafts, couplings, seals, bearings etc.). However, the environment in which wind turbines operate is much more severe due to the uncertainty of the wind recourse, which is why engineering evaluation is necessary when selecting availability and reliability data.

In WEU Onshore Asset Optimization & Reliability Benchmarking Report 2015, turbine sub-components failure rates and downtimes have been published, based on data collected by data analytics specialist Sciemus between 1993 and 2009, covering a combined turbine capacity of 5.9 GW. The used data contains about 180,000 years of operational project data collected from Academic, Financial Services and Engineering sources. In figure 1 the distribution of failure rates by sub-components is illustrated.

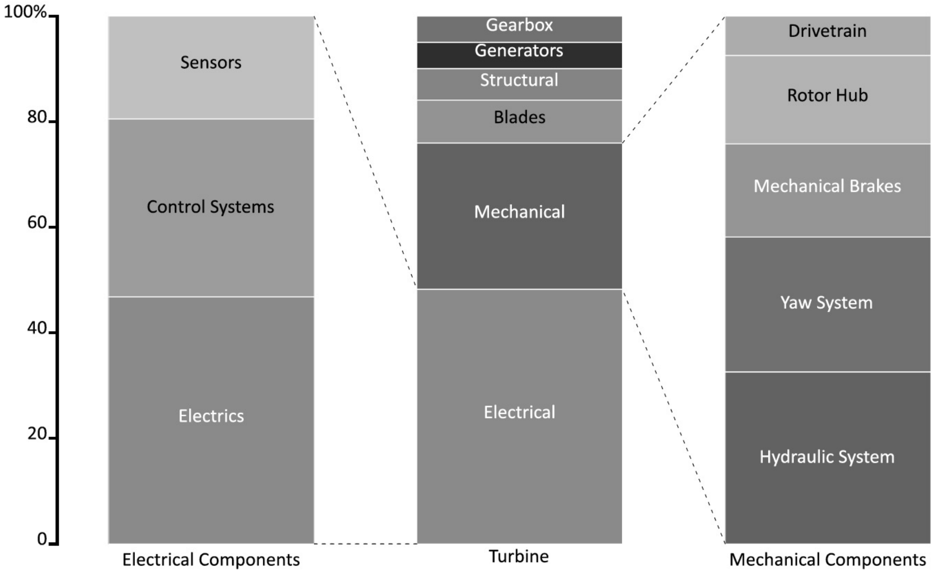

Figure 2: Failure rates of sub-components (Source: WEU, 2015)

It can be identified, that the most frequent failing component category is the electrical. Its main contributors are electrics, followed by the control system. The second most failing category are mechanical breakdowns, mainly driven by hydraulic or yaw system system failures. It is noticeable, that the drivetrain shows the merest failure rates of all sub-components.

As mentioned, the downtime per category, hence the lost production, is another important data that has to be taken into account when evaluating the turbine failure characteristics. Figure 3 illustrates the lost days per year on turbine sub-components.

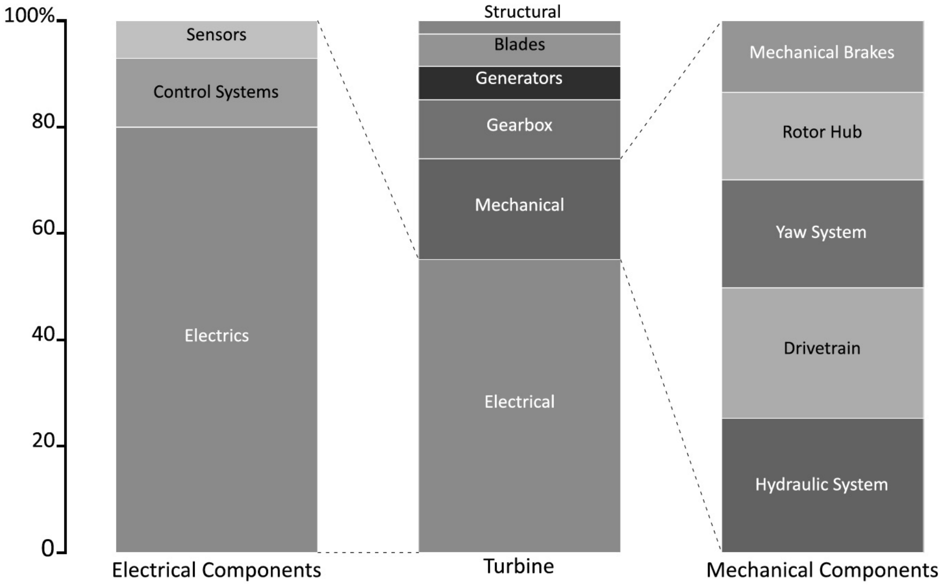

Figure 3: Lost days per year by sub-component (Source: WEU, 2015)

It becomes clear that the electrical components contribute to more than 50% of the lost production days per year. It is stated that this contribution can be explained mainly by the variety of electric failures in wind turbines which result in simple maintenance actions such as replacements of fuses or turbine reset, but yet require maintenance crew deployment. The greatest financial impact, however, is posed by catastrophic major component failures and necessary corrective actions. Figure 4 shows the average downtime per failure by turbine sub-components.

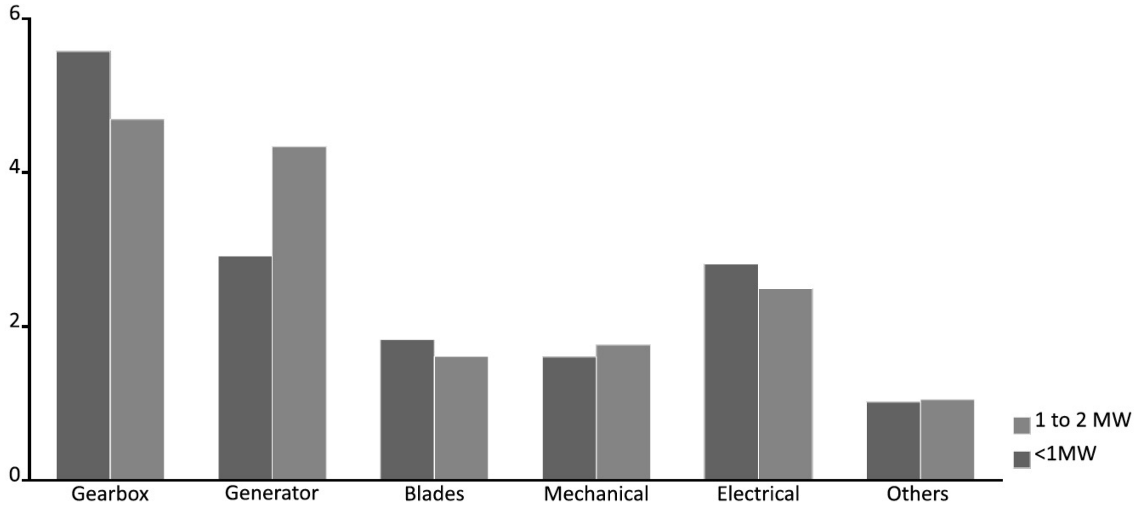

Figure 4: Average downtime for failures >1 hour by sub-components (Source: WEU, 2015)

It becomes clear, that the breakdown of gearbox and the generator, followed by the blades, cause the greatest average downtimes. Such failure events result in massive lost revenue, costly crane deployment and ordering/installation of spare parts or whole assemblies. Major components replacements depend the site weather conditions, because under improper conditions, such actions won't be possible, as a safe operation of the crane has to be provided The earlier a catastrophic failure is detectable, the better the corrective action planning possibilities.

LeBlanc and Graves give an overview on major component replacement cost in [6]:

• Gearbox replacement:	$250.000	–	$350.000
o Refurbishment:	$150.000	–	$200.000
o Single Stage replacement:	$50.000	–	$90.000
• Generator replacement:	$90.000	–	$120.000
o Refurbishment:	$70.000	–	$90.000
• Blade replacement:	$120.000	–	$200.000
o Repair:	$10.000	–	$50.000

Cost of Energy

The failure characteristics of a wind turbine directly influence its availability, because the turbine won't be functional during failure event caused downtime. The financial impact is lost revenue at its best, additional replacement cost, crane cost and labor cost at its worst. Yet, as a main criteria of a reliable energy supply, the availability of the power generating plants is essential. Wind turbines operate reactive to the wind velocity, which is why their availability is naturally limited by the local wind quality. It is objective of O&M actions to keep the turbines availability as high as possible.

According to the technical directive of the Association of German grid operators VDE "2006-11-10 Technische Richtlinie Instandhaltung", maintenance is the combination of all technical and administrative actions during the lifecycle of a unit, in order to determine and judge its current state, as well as to maintain or restore its initial designs functionality [7]. These actions have high value to the system reliability, as their objective is to ensure the functionality of a system in a given point in time.

Sandia National Laboratories have published a report on wind turbine reliability and O&M cost in 2006 [8]. It states inter alia that maintenance actions are done to preserve the components integrity and to extend their useful life, including planning, monitoring, inspecting, measuring, replacing, adjusting and repairing of a wind turbine. The economic execution of maintenance is an important issue to the asset holder, because it drives the cost of energy (COE). The COE (equation 1) is a technology evaluating metric, putting the annually resulting costs from unreliability in relation to the actually produced energy. It includes all cost-driving factors: the initial capital cost (ICC) as the total project investment, the leveled replacement cost (LRC) related to major component overhauls or replacements over the turbine lifecycle, the fixed charge rate (FCR) and the annual energy production (AEP). Scheduled maintenance as well as unplanned cost, related to component failures and resulting replacements, are expressed by the cost of O&M.

$$COE = \frac{ICC * FCR + LRC}{AEP} + O\&M \qquad (1)$$

ICC:	Initial Capital Cost	[$]
FCR:	Fixed Charge Rate	[%/year]
LRC:	Leveled Replacement Cost	[$/year]
AEP:	Annual Energy Production	[kWh/year]
O&M:	O&M Cost	[$/kWh]

To calculate the COE, project specific information is required. As pointed out, O&M cost make up a significant part and strongly vary depending unpredictable factors. However, scenarios are commonly used to state possible developments and calculate the expected costs. The priory mentioned availability and reliability data has to be discovered in order to determine the cost of energy. Sandia Laboratories evaluates the COE to be around $0.005 – $0.006/kWh for new wind turbine projects and escalates up to $0.018 – $0.022 over the 20 years of turbine life. It is further stated, that O&M cost accounts for approximately 10 – 20% of annual COE and, over the life cycle, accumulates to 75% - 90% of a turbine's initial investment cost.

O&M Cost contributors

To perform cost efficient maintenance, the cost elements have to be identified and understood. Sandia National Laboratories state, that cost can be separated in the following broad categories: operations, scheduled maintenance, unscheduled maintenance. It is further stated, that O&M cost caused by unscheduled maintenance make up to 30 – 60% of total O&M expenditure, generally increasing with asset age. National Renewable Energies Laboratory (NREL) [9] separates the O&M cost in two broad categories: facility cost and turbine cost (see table 2).

Table 2: O&M Cost categories (Source: NREL, 2006)

Facility cost	**Turbine cost**
Operations and administration	Labor
Site maintenance	Parts
Equipment and supplies	Consumables

Facility cost is assumed to be a constant cost contributor, as its expenditure depends on project size and turbine quantity. It is driven by the cost of operations and administration, site maintenance and equipment and supplies.
Turbine cost is asset age and size dependent and tends to increase with the project age. It is mainly driven by labor cost of deployed technicians, replacement cost or components incl. additional cost and consumables.

Maintenance strategies

To approach the lifecycle cost of wind turbine assets, effective maintenance strategies have to be deployed. In accordance with the association of grid operators (VDN) [10], the most common and distinguishable maintenance.

• Corrective maintenance	(reactive maintenance)
• Preventive maintenance	(scheduled maintenance)
• Predictive maintenance	(CBM/performance monitoring)

Corrective maintenance

Corrective maintenance, or reactive maintenance, takes place after a failure has occurred. "Run to Failure" – The machine won't be maintained until a damage occurs. This type of maintenance is used in installations, that allow spontaneous and quick corrective actions and require labor force with a high level of technical competence to keep the downtime low.

Corrective maintenance ensures the full absorption of the components useful life, however is inadequate for logistical planning and thus improper for installations in continuous operation, especially the ones suffering from fluctuating loads and spontaneous breakdown. This strategy wouldn't be applicable for wind turbines, because their operational characteristics contradict these requirements.

Preventive maintenance

The preventive, or scheduled maintenance, tries to avoid component breakdowns by defining periodic activities to ensure the systems integrity. The discoveries of inspection help adjust the defined maintenance intervals. The scheduled nature of this maintenance type enables good planning conditions with respect to anticipation of labor cost and related logistic decisions. Fischer et Al. state in [11], that preventive maintenance favors reduction of downtimes due to spare part lead time, avoiding unavailability of auxiliary equipment such as cranes. However, a big disadvantage is that the components lifespan is not used to its full potential, while not eliminating the possibility of spontaneous component breakdown. According to WEU, 42% of the questioned participant industry players apply this strategy.

Predictive maintenance

This maintenance category splits in two subcategories: condition based and performance based. The predictive maintenance combines the advantages of both reactive and preventive maintenance. It is assumed to be an initially costlier maintenance strategy, that however pays off over the lifecycle of the asset. According to VDN, the predictive maintenance utilizes the operational data resulting from component working condition monitoring. The analysis and determination of operation parameters are coupled with the degradation process of the turbines components which then result in maintenance instructions. The turbine condition can be predicted by performance monitoring or condition based monitoring (CBM).

Performance Monitoring

WEU states, that performance monitoring is done by supervision of the turbines capacity factor, power curve, wind velocity and direction, rotor speed and blade pitch angle. The resulting values are compared with the manufacturer performance specifications in order to identify the turbines efficiency. Known correlations between the parameters help notice unusual operating points and identify their root-cause. The evaluated parameters are usually acquired by the turbine integrated SCADA-system. In figure 6, the SCADA-data based failure mechanism is illustrated, whereas figure 7 illustrates detectable major problems by SCADA-data analysis application, both stated by WEU.

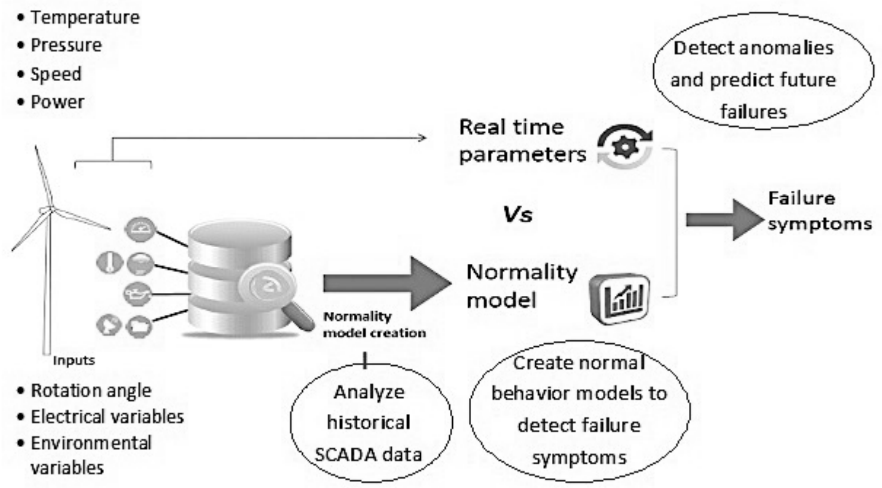

Figure 6: Failure identification by SCADA-Data Analysis (Source: WEU, 2015)

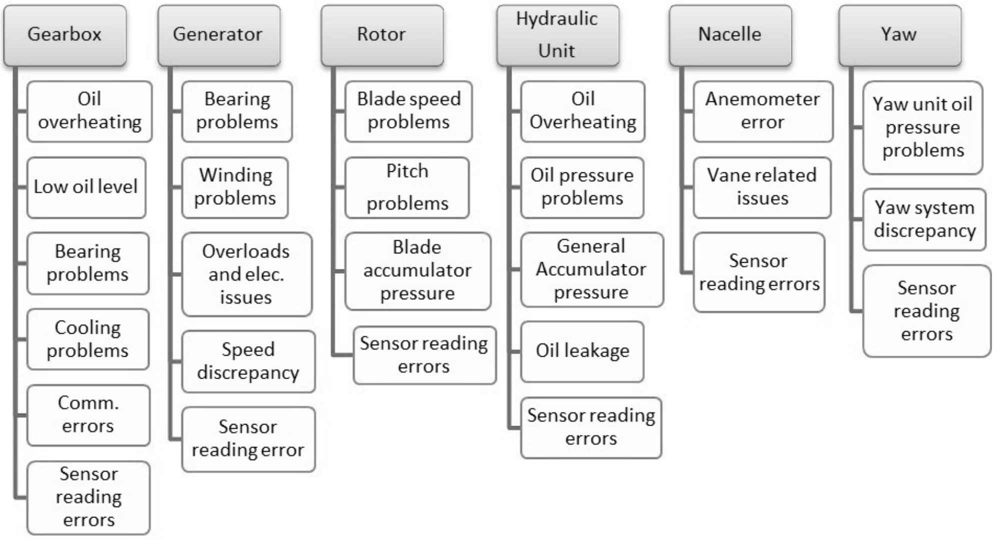

Figure 7: Detectable turbine problems by SCADA-Data Analysis Application (Source: WEU, 2015)

Condition Bases Monitoring (CBM)

The condition based maintenance strategy tries to absorb the full lifecycle potential of each wind turbine component while avoiding a system breakdown. To achieve this, it is necessary to provide a full monitoring of the wind turbine operation conditions, which requires a CBM supervision approach. In order to organize O&M actions as economic as possible, the plant state has to be evaluable to the greatest extent possible in each point of time. The limited quantity of SCADA data due to its sample rate of 5-10 minutes often doesn't satisfy this requirement, which is why additional CBM sensors are being installed. According to a WEU survey, 77% of the participants use CBM systems on their assets.

CBM applications are mostly restricted to vibration analysis on the gearbox, generator and drivetrain. The complementary results for further component damage identification is the oil debris monitoring. Damage caused debris is being transported through the hydraulic circuit and leads to elevated debris levels in the lubricant, which can be detected. Initial suspicions on damages due to vibration monitoring can thereby by confirmed, and the extent of damage determined.

Structural health monitoring (SHM) is conducted by strain measurement using copper strain gauges in order to predict remaining life of heavily stressed components like the tower or blades. Optic fiber measurements (OFM) are, currently by wind operated incorporated, sensors consisting of temperature and strain sensors and allow measuring of various SHM relevant parameters. Tchakoua et Al. state in [12], that OFM allow strain measurement for monitoring the blade loading and vibration level, temperature measurement for likely over-heating, acceleration measurement for monitoring the pitch angle and rotor position and crack detection measurements and lightning detection for measuring the front steepness, maximum current and specific energy.

WEU however states, that the implementation of such sensors is costly in comparison with other condition monitoring technologies. Shock pulse methods (SPM) is used to identify bearing damages that are difficult to identify by vibration analysis. Thermography is often applied on electric components to identify wear or other system failures in hot spots. Temperature monitoring is a classic and cheap method to identify ongoing deterioration on faulty bearings and gears, indicated by SCADA data. Acoustic monitoring, visual inspection, ultrasonic testing and radiographic inspection are all methodologies of condition based maintenance actions.

By the application of CBM, corrective actions, spare parts logistics and eventually required heavy machinery can be planned and optimized in advance, to conduct the administrative and corrective actions the most economic way possible.

Conclusion

The objective of O&M actions, which are defined to include planning, monitoring, inspecting, measuring, replacing, adjusting and repairing [3], is to preserve the components integrity and to extend their useful life. As the site conditions determine the failure characteristics of the wind turbine sub-components, the business decisions of service contractors relating component failures and resulting corrective actions depend on the site conditions.

The northeastern region of Brazil is characterized by its favorable wind recourses. However, the fragile regional supply chain makes corrective actions inflexible and costly. Service contractors, that guarantee plant availabilities, have the need of failure event prediction in order to plan maintenance actions. The annual maintenance reserve investments have to be evaluated properly in order to economically operate the wind turbine. Component lifecycle breakdowns may be approached by literature values and modified with gained experience, when the asset is growing older. Maintenance strategies from conventional power plants are only partially applicable, because wind turbines are less accessible and their component failures occur in less constant patterns due to the fluctuating character of the wind recourse. As consequential cost of major component breakdown like lost revenue, crane cost, additional labor or spare part stocking cost may easily escalate, careful planning of maintenance actions is necessary. The proper maintenance strategy is of paramount importance to this objective.

Corrective maintenance is not applicable for wind turbines due to its unpredictable and spontaneous character, to which the operational mode of wind turbines does not apply.

Preventive approaches do only apply to constantly deteriorating components, as the useful life of other components won't be used to their full extent and may cause elevated life cycle cost.

Condition based maintenance approaches are mainly applied on the turbines drive-trains. The cost saving potential by implementation of CM sensors is indisputable, as drive-train failures may be detected early, corrective actions planned and thus excessive cost is avoided. The additional cost of CM sensors however will confront the turbine operator with the decision of investing in additional sensors. As they can always be installed at some later point, CM sensors may not be evaluated necessary as the investor might want to "try out" the failure behavior of his asset and afterwards, if necessary, install additional CM sensors. The investor sees the wind turbine as cash-flow investment, to which the CM sensors initially won't contribute, even though they might pay off during the life cycle as catastrophic failures may be easier detectable with CM sensors.

The most economic and applicable maintenance strategy for regions with a developing market is performance monitoring. The gathered SCADA data from the wind turbine is benchmarked used to train a machine learning algorithm that compares the real time wind turbine parameters with the "normal" behavior of the turbine, based on the available historic datasets. The low frame rate of the SCADA data currently poses a risk to the model reliability. Especially very dynamic variables like e.g. drive-train vibration need a greater resolution to make accurate interpretation possible. The algorithm identifies correlations and processes possible failure root-causes. The more data is available, the more accurate the prediction will become.
The dynamically developing wind marked in the northeastern region of Brazil promises vast available operational data in the future. The implementation of a regional performance monitoring based data analysis network has the benefit, that its effectiveness rises with the number of installed wind turbines, as they contribute to the data volume available for benchmarking.

References

[1] Gonzalo Escribano Francés, José María Marín-Quemada, Enrique San Martín González, *RES and risk: Renewable energy's contribution to energy security. A portfolio-based approach*, Renewable and Sustainable Energy Reviews, Volume 26, October 2013, Pages 549–559

[2] Global Wind Energy Council GWEC, *Annual Market Update 2015*, 2016

[3] Wind Energy Update, *WEU, Onshore Asset Optimization & Reliability Benchmarking Report 2015,* 2015

[4] Peter J. Schubel, Richard J. Crossley, *Wind Turbine Blade Design,* Energies 2012, 5, 3425-3449

[5] Sandia National Laboratories, *Wind Turbine Reliability: A Database and Analysis Approach*, 2008

[6] Marc LeBlanc, AnneMarie Graves, *Condition Monitoring Systems: Trends and Cost Benefits*, GL Garrad Hassan, n.d.

[7] Verband der Netzbetreiber VDN, *Technische Richtline für die Instandhaltung von Betriebsmitteln und Anlagen in Elektrizitätsversorgungsnetzen*, 2006

[8] Sandia National Laboratories, *Wind Turbine Reliability: Understanding and Minimizing Wind Turbine Operation and Maintenance Costs*, 2006

[9] National Renewable Energy Laboratory, *Development of an Operations and Maintenance Cost Model to Identify Cost of Energy Savings for Low Wind Speed Turbines*, 2006

[10] Verband der Netzbetreiber, *Technische Richtlinie für die Instandsetzung von Betriebsmitteln und Anlagen in Elektrizitätsversorgungsnetzen*, 2006

[11] Bertrand Kerres, Katharina Fischer, Reinhart Madlener, *Economic evaluation of maintenance strategies*, IET Renew. Power Gener., 2015, Vol. 9, Iss. 7, pp. 766–774

[12] Tchakoua et al., *Wind Turbine Condition Monitoring: State-of-the-Art Review, New Trends, and Future Challenges*, Energies 2014, 7, 2595-2630