PROJECT DELIVERABLE REPORT

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Demonstration of Methods and Tools for the Optimisation of Operational Reliability of Large-Scale Industrial Wind Turbines

Collaborative project

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1 Summary

This document focuses on the energy costing model needed to calculate the whole lifecycle costs of wind turbines.

The outcomes obtained by the model will be essential to evaluate the validity of the technology developed by the consortium.

The energy costing model will be linked with the overall wind turbine reliability model previously developed in task 1.3 ***(Analysis of collected data and definition of key reliability issues for wind turbines***), and its theoretical cost saving benefit will be demonstrated during the field trials in WP3 ***(Condition monitoring of wind turbine electrical and power control systems)*** and WP5 ***(Cost-effective condition monitoring technology for wind turbines)***.

2 Introduction

Climate change has motivated the study and development of renewable energy, where the new, cleaner and efficient energy technologies have an important role in sustainable development in the future energy scenario [2.1][1], [2.2] [2]and [2.3][3].

Growth in the wind energy industry has resulted in companies focusing more on competitive costs. For example, for a 20-year life, the operations and maintenance (O&M) costs for 750kW turbines might account for about 25%-30% of the overall energy generation cost [2.4][4] or 75%-90% of the investment costs [2.5][5]

Reference [2.6][6] suggests that larger wind turbines fail more frequently and thus require more maintenance. Reducing inspection and maintenance costs has become increasingly important as wind turbine size and number have continued to rise. On the one hand, Condition Monitoring Systems (CMS) are probably the most effective approaches to minimize O&M costs and to improve the availability of wind turbines by early detection of the faults. On the other hand, CMS are usually a complex task for any company because they require a set of sensors and data acquisition systems to monitor different parameters of wind turbines. They also require knowledge and expertise to interpret the large volume of data collected from the wind turbines. In this research work the economic feasibility of a CMS in a wind turbine is studied. The main objective of this work is the development of a life cycle cost (LCC) model for a CMS on wind turbines, being applied to a real case study.

[1] [2.1] C. Ghenai, "Life Cycle Analysis of Wind Turbine", Sustainable Development – Energy Engineering and Technologies – Manufacturing and Environment, pp. 19-32.
[2] [2.2] K.T. Fung, R.L. Scheffler and J. Stolpe, "Wind Energy – A Utility Perspective", IEEE Transactions of Power Apparatus and Systems, pp. 1176-1182, 1981.
[3] [2.3] S. Ezio, C. Claudio, "Exploitation of Wind as an Energy Source to Meet the World's Electricity Demand", Journal of Wind Engineering and Industrial Aerodynamics, vol. 74-76, pp. 375-387, 1998.
[4] [2.4] D. Milborrow, Operation and maintenance costs compared and revealed. Wrind Stats, 19(3):3, 2006.
[5] [2.5] W. Vachon, Long-term O&M cost of wind turbines based on failure rates and repair costs, Proceedings WINDPOWER, American wind energy association annual conference. Portland: Oregon, pp. 2-5, June, 2002.
[6] [2.6] P.J. Tavner, F. Spinato, G.J.W. van Bussel, E. Koutoulakos. Reliability of different wind turbine concepts with relevance of offshore application. Brussels, European Wind Energy Conference. April, 2008.

3 Life Cycle Costs

Life cycle costs (LCC) can be defined as the sum of all recurring and non-recurring (one-time) costs over the full life span, or a specified period, of a particular solution. LCC includes direct and initial costs plus any periodic or continuing costs for operation and maintenance [3.1][7]. The International Electromechanical Commission (IEC) divides the LCC into two different subcategories (IEC 300-3-3, 1996):

- Investment or acquisition cost, i.e. the initial costs that will be produced before operation.

- Cost of ownership, or life support cost once operational, i.e. operating, maintenance and repair costs. These terms must be discounted to their present value since they arise in subsequent years.

The purpose of this research work is the application of a LCC model on CMS for wind turbines. The model has been applied to a real case study, the wind farms located at Schleswig Holstein, Germany considered in the LKW study.

[7] [3.1] Life Cycle Costing Guideline, 2004. Total Asset Management, New South Wales Treasury.

4 Wind Turbines and Wind Turbine Condition Monitoring

4.1 Wind turbines

Generally, wind turbines are rotary systems designed to harvest the energy from the wind. The main parts of a wind turbine are depicted in Figure 4.1 [4.1][8].

1- Base/Foundations
2- Tower
3- Blades
4- Meteorological unit (vane & anemometry)
5- Nacelle
6- Pitch system
7- Hub
8- Bearing

9- Low speed (main) shaft
10- Gearbox
11- High speed shaft
12- Brake system
13- Generator
14- Yaw system
15- Converter
16- Bedplate

N.B. Drive train = 9+11

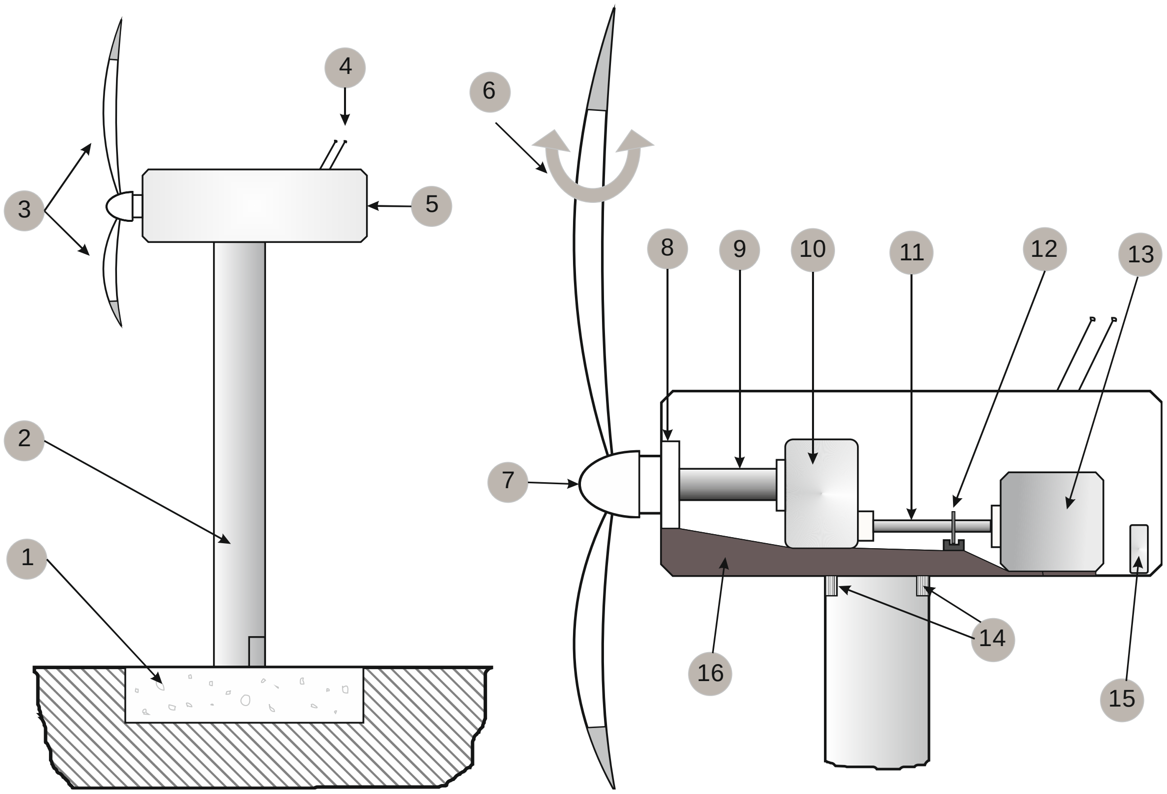

Figure 4.1: Components of the WT

The operation of wind turbines is summarised as follows: The blades, connected to the rotor via the hub are moved by the wind. Their aerodynamic design enables them to capture as much energy as possible from the wind but at the same produce as little noise as possible while they rotate. The rotor is also designed to capture the maximum surface of the wind and transmits the mechanical energy via the low speed (main) shaft through the gearbox to the high speed shaft,

[8] [4.1] G. de Novaes Pires, E. Alencar, A. Kraj, "Remote Conditioning Monitoring System for a Hybrid Wind Diesel System-Application at Fernando de Naronha Island, Brasil". http://www.ontario-sea.org (19-07-10).

ending in the generator which produces electricity from the rotation of the rotor. The low speed shaft is supported by the main bearing. The alignment to the direction of the wind is controlled by a yaw system that turns the housing (or "nacelle") for that purpose. The nacelle seals and protects the generator, the gearbox, the converter, etc. and is mounted at the top of the tower, which supports the nacelle and the blades and is assembled on a base or foundation. The pitch system (mounted in each blade) is a mechanism that turns the blade to control the wind power captured, and it can be employed as an aerodynamic brake. The wind turbine also has a hydraulic brake to stop the rotation. The meteorological unit, or weather station, provides the weather data (e.g. wind speed and direction) to the control system allowing control of the mentioned systems (pitch, brake, yaw, etc.).

A description of the different wind turbine configurations can be found in [4.2][9]

4.2 Condition monitoring for Wind turbines

Under the assumption that "*a significant change is indicative of a developing failure*" [4.3][10], CMS have recently emerged as a new technique employed by the wind energy industry that consist of monitoring the state of the components of the wind turbine via combinations of sensors and signal processing equipment. CMS together with a detection of any deterioration of these components (based on the parameters/features obtained by measurements) is called Fault Detection and Diagnosis (FDD) [4.4][11]. CMS can be divided into two subcategories [4.5][12]:

- On-line CMS: provides instantaneous feedback of condition;
- Off-line CMS: the data is collected at regular time intervals using measurement systems that are not integrated with the equipment [4.6][13].

CMS helps to significantly reduce the maintenance tasks resulting in increased reliability, availability, maintainability and safety (RAMS), while downtimes and O&M costs are substantially reduced; [4.7][14]and [4.8][15]. The benefits of these modern techniques have been especially effective in offshore wind farms owing to the high cost of O&M at sea and the large dimensions of the turbines [4.9][16].

[9] [4.2] J.M. Pinar Pérez, F.P. García Márquez, A.M. Tobias and M. Papaelias, "Wind Turbine Reliability Analysis", Renewable and Sustainable Energy Reviews, vol. 23, pp. 463-472.
[10] [4.3] E. Wiggelinkhuizen, T. Verbruggen, J. Xian, Watson SJ, G. Giebel, E. Norton et al. CONMOW: condition monitoring for offshore wind farms. In: Proceedings of the 2007 EWEA European Wind Energy Conference (EWEC2007), Milan, Italy; 7-10 May 2007.
[11] [4.4] J. Tongdan and M. Mechehoul, Minimize Production Loss in Device Testing via Condition-Based Equipment Maintenance. IEEE Transactions on Automation and Science Engineering, Vol. 7(4), October 2010.
[12] [4.5] M.A. Rumsey and J.A. Paquette, Structural Health Monitoring of Wind Turbine Blades, Proc. SPIE, Vol. 6933, 2008.
[13] [4.6] P.A. Scarf, A Framework for Condition Monitoring and Condition Based Maintenance. Quality Technology and Quantitative Management, vol. 4(2), pp. 301-312, 2007.
[14] [4.7] W.X. Yang, P.J. Tavner, C.J. Crabtree, M. Wilkinson, Cost effective condition monitoring for wind turbines. IEEE Transactions on Industrial Electronics, Vol. 57(1), 2010.
[15] [4.8] A.K. S. Jardine, D. Lin and D. Banjevic, A review on machinery diagnostics and prognostics implementing condition-based maintenance, Mechanical Systems and Signal Processing, vol 20(7), pp. 1483-1510, 2006.
[16] [4.9] J. Nilsson, L. Bertling, Maintenance Management of Wind Power Systems Using Condition Monitoring Systems – Life Cycle Costs analysis for Two Case Studies. IEEE Transactions on Energy Conversion, vol 22(1), pp. 223-229, 2007.

The implementation of CMS requires:

- the use of sensors and data acquisition systems to collect and store the information of the system;
- a processing unit to interpret the data;
- a fault detection step to implement effective maintenance policies.

This implies that CMS are more complex than other maintenance strategies such as run-to-failure maintenance (RFM) or scheduled maintenance (SM) [4.10][17].

The effectiveness of CMS depends on three main different elements:

- the technique applied;
- the number and type of sensors;
- the associated signal processing to extract the useful information from the different signals.

Different studies can be found in the scientific literature regarding the technology applied:

- Vibration analysis is the most popular and known for CMS, being usually applied for rotating equipment; [4.11][18], [4.12][19] and [4.13][20].
- Acoustic emission is another popular non-destructive CMS that has been applied for the diagnostics of bearings and bears [4.14][21] and for the structural health of the blades [4.15][22].
- Ultrasonic testing are also non-destructive techniques extensively used in the detection of internal defects in towers and blades; [4.16][23] and [4.17][24].
- Oil analysis is usually used to monitor the status of the components oil lubricated in wind turbines. These techniques can be applied off-line [4.18][25] or on-line [4.19][26].

[17] [4.10] R.F. Orsagh, H. Lee, M. Watson, C.S. Byington and J. Powers, Advanced Vibration Monitoring for Wind Turbine Health Management, Impact Technologies, http://www.impact-tek.com.
[18] [4.11] Y. Amirat, M.E.H. Benbouzid, B. Bensaker and R. Wamkeue, Condition Monitoring and Fault Diagnosis in Wind Energy Conversion Systems: A Review, Electric Machines and Drives Conference 2007 (IEMDC07), Antalya, Turkey, pp. 1434-1439, 2007.
[19] [4.12] T. Wakui and R. Yokoyama, Wind Speed Sensorless performance monitoring based on operating behaviour for stand-alone vertical axis wind turbine, Renewable Energy, vol. 53(1), pp. 49-59, 2013.
[20] [4.13] A. Kusiak, Z. Zhang and A. Verma, Prediction, Operations, and Condition Monitoring in Wind Energy, Energy, vol. 60(1), pp. 1-2, 2013.
[21] [4.14] L. Li, L. Wenxiu and C. Fulei, Application of AE techniques for the detection of wind turbine using Hilbert-Huang transform, PHM'10 Prognostics and Health Management Conference, Macao, China, pp. 1-7, 2010.
[22] [4.15] N. Tsopelas, D. Kourousis, I. Ladis, A. Anastasopulos, D.J. Lekou, and F. Mouzakis, Health monitoring of operating wind turbine blades with acoustic emission, in Emerging Technologies in Non-Destructive Testing V, editors Paipetis et al. Taylor and Francis Group, London, pp. 347-352, 2012.
[23] [4.16] J. Knezevic, Reliability, Maintainability and supportability engineering: a probabilistic approach. McGraw Hill, 1993.
[24] [4.17] J. Endrenyi, McCauley and C. Shing. The present status of maintenance strategies and the impact of maintenance and reliability. IEEE Transactions on Power Systems, 2001, vol. 16(4): pp. 638-646, 2001.
[25] [4.18] Z. Hameed, Y.S. Hong, Y.M. Choa, S.H. Ahn and C.K. Song. Condition Monitoring and fault detection for wind turbines and related algorithms: A review. Renewable and Sustainable Energy Reviews, vol 13, pp. 1-39, 2009.
[26] [4.19] B.R. Wiesent, M. Schardt, A.W. Koch. Gear oil condition monitoring for Offshore Wind turbines, available online at http://www.machinerylubrication.com/Read/28782/gear-oil-condition-monitoring.

Strain measurements are used for lifetime forecasting and to avoid critical structure stress levels; [4.20][27]and [4.21][28].

- Thermography is often used for monitoring electric and electronic components [4.22][29], but applications have been reported for the detection of damage in wind turbines [4.23][30].
- Other important techniques applied to wind turbines are shock pulse method (SPM), performance monitoring or radiographic inspection, among others; [4.24][31], [4.25][32] and [4.26][33].

Different options can be found in the scientific community regardless of the technique:

- Trend analysis has been applied in the monitoring of pitch mechanisms. It collects data from different sensors and searches for trends [4.27][34].
- Time-domain analysis studies variations in signals and trends to detect possible faults in wind turbines [4.28][35].
- Amplitude modulation analysis extracts very low-amplitude and low-frequency periodic signals that might be masked by other higher energy vibration as in wind turbine gearboxes [4.29][36].
- Wavelet transformations has been successfully applied to monitor the vibration level caused by misalignment or bearing and can be used as a general indication of a fault produced in a wind turbine; [4.30][37] and [4.31][38]. It provides a time-frequency 3D map of the signal being studied and its decomposition into a set of sub-signals with different frequencies.

[27] [4.20] E. Morfiadakis, K. Papadopoulos, T.P. Philippidis, Assessment of the stain gauge technique for measurement of wind energy turbine blade loads. Wind Energy, vol 3(1), pp. 35-65, 2000.

[28] [4.21] 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(5), pp. 1167-1172, 2006.

[29] [4.22] B.M. Smith, Condition Monitoring by thermography. NDT International, vol 11(3), pp. 121-122, 1978.

[30] [4.23] M.A. Rumsey, W. Musial, Application of infrared thermography non destructive testing during wind turbine blade tests. Journal of Solar Energy Engineering, vol. 123(4), 2001.

[31] [4.24] L. Zhen, H. Zhengjia, Z. Yanyang and C. Xuefeng. Bearing condition monitoring based on shock pulse method and improved redundant lifting scheme. Mathematics and Computers in Simulation, vol 79(3), 318-338, 2008.

[32] [4.25] B.F. Sorensen, L. Lading, P. Sendrup, M. McGugan, C.P. Debel, O.J.D. Kristensen et al., Fundamentals for remote structural health monitoring of wind turbines blades – A Preproject. Riso-R-1336(EN), 2002.

[33] [4.26] R. Raisutis, E. Jasiuniene, R. Sliteris and A. Vladisauskas. The review of non-destructive testing techniques suitable for inspection of the wind turbines blades. Ultragarsas (Ultrasound), vol. 63(1), pp. 26-30, 2008.

[34] [4.27] P. Caselitz, J. Giebhardt, Fault prediction techniques for offshore wind farm maintenance and repair strategies, In Proceedings of the EWEC2003, 2003.

[35] [4.28] J. Cheng, Y. Yang, D. Yu. The envelope order spectrum based on generalized demodulation time-frequency analysis and its application to gear fault diagnosis. Mechanical Systems and Signal Processing, vol. 24, 508-521, 2010.

[36] [4.29] N. Tandon. B.C. Nakra, Comparison of vibration and acoustic measurement techniques for the condition monitoring of rolling element bearings. Tribology International, vol. 25(3), pp. 205-212, 1992.

[37] [4.30] W.J. Staszewski, G.R. Tomlinson, Application of the wavelet transform to fault detection in a Spur gear. Mechanical Systems and Signal Processing, vol 8, 289-307, 1994.

[38] [4.31] G. Y. Luo, D. Osypiw, M. Irle. Online vibration análisis with Fast continuous wavelet algorithm for condition monitoring of bearing. Journal of vibration and control, vol 9, pp. 931-947, 2003.

- Hidden Markov Models (HMV) have been successfully applied in bearing fault detection [4.32][39] and vibration signals analysis in the machine [4.33][40].
- Other promising techniques such as artificial intelligence have been applied in the fault detection of mechanical equipment [4.34][41].

Finally, an extended explanation of the condition monitoring of wind turbines can be found in [4.35][42].

[39] [4.32] H. Ocak, K.A. Loparo. A new bearing fault detection and diagnosis scheme base on Hidden Markov modeling of vibrations signals, IEEE ICASSP vol. 5, pp. 3141-3144, 2001.
[40] [4.33] Q. Miaoa, V. Makis, Condition monitoring and classification of rotating machinery using wavelets and Hidden Markov Models. Mechanical Systems and Signal Processing, vol.21, pp. 840-855, 2007.
[41] [4.34] R.C.M. Yam, P.W. Tse, L. Li, P. Tu. Intelligent predictive decision support system for condition-based maintenance. The International Journal of Advanced Manufacturing Technology, vol. 17(5), pp. 383-391, 2001.
[42] [4.35] F.P. García Márquez, A.M. Tobias, J.M. Pinar Pérez and M. Papaelias. Condition monitoring of wind turbines: Techniques and methods. Renewable Energy, vol. 46, 169-178, 2012.

5 State of the Art

There are different studies about the LCC in wind turbines or wind farms. In [5.1][43] an analysis is presented based on the cost breakdown structure (CBS). Reference [5.2][44] shows a novel theoretical methodology process to study the LCC of floating offshore wind farms. It is based on CBS and adapted to offshore wind energy. The methodology used considers technical and economic issues and their relationships.

A general economic analysis about repowering wind farms in Spain is reported in [5.3][45]. The study describes different economic aspects, such as net present value and internal profitability rate of the repowering process for the wind farms.

[5.4][46] develops a LCC model for offshore wind farms that takes into account the different types of costs and revenues expected in the construction of a wind farm. Different simulations are presented in order to study the impact in the result of failure rates, inflation rate, interest rate and discount rate.

A stochastic optimization model for opportunistic service maintenance of offshore wind farms is developed in [5.5][47]. This model is based on a rolling horizon, and a demonstration based on real world data is presented showing that more than 30 % of the cost for production losses and transportation could be saved.

Reference [5.6][48] reveals a calculation scheme to quantify wind farm production losses in terms of scheduled and unscheduled downtimes and speed losses.

A cost model is presented in reference [5.7][49] to analyse the influence of different designs and economic parameters on the cost of an onshore wind farm. The cost model is developed using extended radial basis functions (E-RBF). The model is tested with real data. The main conclusion obtained is that the cost of a wind farm is appreciably sensitive to the rotor diameter and the number of wind turbines for a given desirable total power output.

[43] [5.1] W.J. Fabrycky, B.S. Blanchard, Life-cycle cost and economic analysis, Prentice Hall 1991.
[44] [5.2] L. Castro-Santos, G. Prado García, V. Diaz-Casas, Methodology to study the life cycle cost of floating offshore wind farms, 10th Deep sea wind R&D conference, 2013.
[45] [5.3] L. Castro-Santos, A. Filgueira Vizoso, E. Muñoz Camacho and L. Piegiari, General Economic Analysis about the Wind Farms Repowering in Spain, Journal of Energy and Power Engineering vol. 6, pp. 1158-1162, 2012.
[46] [5.4] M. Nordahl, The development of a Life Cycle Cost model for an offshore wind farm, Göteborg : Chalmers tekniska högskola, 2011. Diploma work - Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden, ISSN 1652-8557; 2011:08, 2011.
[47] [5.5] F. Besnard, M. Patriksson, A-B. Strömberg, A. Wojciechowski, K. Fischer and L. Bertling, A Stochastic Model for Opportunistic Maintenance Planning of Offshore Wind Farms, Proceedings IEEE Powertech Conference, Trondheim, Norway, June 2011.
[48] [5.6] H.-J. Krokoszinski, Efficiency and effectiveness of wind farms – keys to cost optimized operation and maintenance, Renewable Energy, vol. 28, pp. 2165-2178, 2003.
[49] [5.7] J. Zhang, S. Chowdhury, A. Messac, L. Castillo and J. Lebron. Response Surface Based Cost Model for Onshore Wind Farms Using Extended Radial Basis Functions. ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Vol. 1, 36th Design Automation Conference, Parts A and B, 2010.

In reference [5.8][50], the costs of the elements associated with wind farm O&M costs and availability are identified. Additionally, the different causes of uncertainty in estimating wind turbine component reliability are discussed and different actions to reduce O&M costs in wind energy are presented.

In [5.9][51] is described a risk-based life cycle approach for an optimal scheduling of O&M in offshore wind turbines. The approach is based on Bayesian decision theory.

Reference [5.10][52] shows the application of LCC with probabilistic methods and sensitivity analysis to identify the benefit of using CMS. Two approaches are used to analyse how the random behaviour of the failures can affect the LCC and what are the critical parameters (subject to uncertainty). The results of the study depict a high economic benefit of using CMS and substantial benefits on the risk.

In [5.11][53] a reliability-centred asset maintenance (RCAM) strategy for maintenance optimization of wind farms is presented. The corrective and condition based maintenance strategies were compared by carrying out a LCC analysis showing the cost-benefit of CMS with respect to the reliability and availability of wind turbines today.

Reference [5.12][54] shows an optimal condition based maintenance (CBM) to address the economic dependencies between wind turbines and their components. A simulation method is developed to evaluate the cost of the CBM and numerical simulations are provided to illustrate the effectiveness of the proposed approach in the reduction of the maintenance costs.

A method to optimize the maintenance of components based on the severity of their damage is proposed in [5.13][55]. Simulations were performed to evaluate the expected life cycle maintenance costs for inspection-based maintenance strategies and condition based maintenance. The results reported that the optimal inspection interval was 6 months for inspection with a CMS and 3 months for visual inspections.

[50] [5.8] Walford CA. Wind turbine reliability: understanding and minimizing wind turbine operation and maintenance costs. Sandia Report, SAND2006-1100. Sandia National Laboratories, Albuquerque, New Mexico 87185 and Livermore, California 94550; 2006.

[51] [5.9] J. Dalsgaard Sorensen, Framework for Risk-based Planning of Operation and Maintenance for Offshore Wind Turbines, Wind Energy, vol. 12, pp. 493-506, 2009.

[52] [5.10] F. Besnard, J. Nilsson and L. Bertling, On the economic benefits of using Condition Monitoring Systems for maintenance management of wind power systems. 2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems, pp. 160-165, 2010.

[53] [5.11] F. Besnard, K. Fischer and L. Bertling, Reliability-Centred Asset Maintenance – A step towards enhanced reliability, availability, and profitability of wind power plants. 2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe), pp. 1-8, 2010.

[54] [5.12] Z. Tian, T. Jin, B. Wu and F. Ding, Condition based maintenance optimization for wind power generation systems under continuous monitoring, Renewable Energy, vol. 36, pp. 1502-1509, 2011.

[55] [5.13] F. Besnard and L. Bertling, An Approach for Condition-Based Maintenance Optimization applied to Wind Turbine Blades, IEEE Transactions on Sustainable Energy, vol. 1(2), 2010.

An LCC analysis with different strategies using CMS is developed in reference [4.9][56]. The analysis of different real case studies found that CMS improves maintenance planning in offshore and onshore farms.

In reference [5.14][57] different features of CMS are studied in order to show that the cost of CMS design and installation is greater compared to other maintenance approaches in short-term. But in long-term CMS provide benefits surpassing the costs. The reported results depicts that CMS are an excellent and viable option to increasing the production rate and reducing the downtimes in wind turbines.

The literature does not collect any information about the LCC of CMS using different annual rates of return and providing a numerical solution for a type of wind turbine.

[56] [4.9] J. Nilsson, L. Bertling, Maintenance Management of Wind Power Systems Using Condition Monitoring Systems – Life Cycle Costs analysis for Two Case Studies. IEEE Transactions on Energy Conversion, vol 22(1), pp. 223-229, 2007.
[57] [5.14] Z. Hameed, S.H. Ahn and Y.M. Cho, Practical aspects of a condition monitoring system for a wind turbine with emphasis on its design, system architecture, testing and installation, Renewable Energy, vol. 35, pp. 879-894, 2010.

6 Case of Study

This work is based on the data from wind turbines installed in Schleswig Holstein in Germany (LWK). LWK statistical data, used in this research work, comprises data from 729 wind turbines of 20 different types in a period of 5 years.

The number of failures of these 729 wind turbines collected from 2005 to 2009 reveals that only four components accounted for 45,5% of the accumulated failures. These components were: electrical system, blades, gearbox and generator.

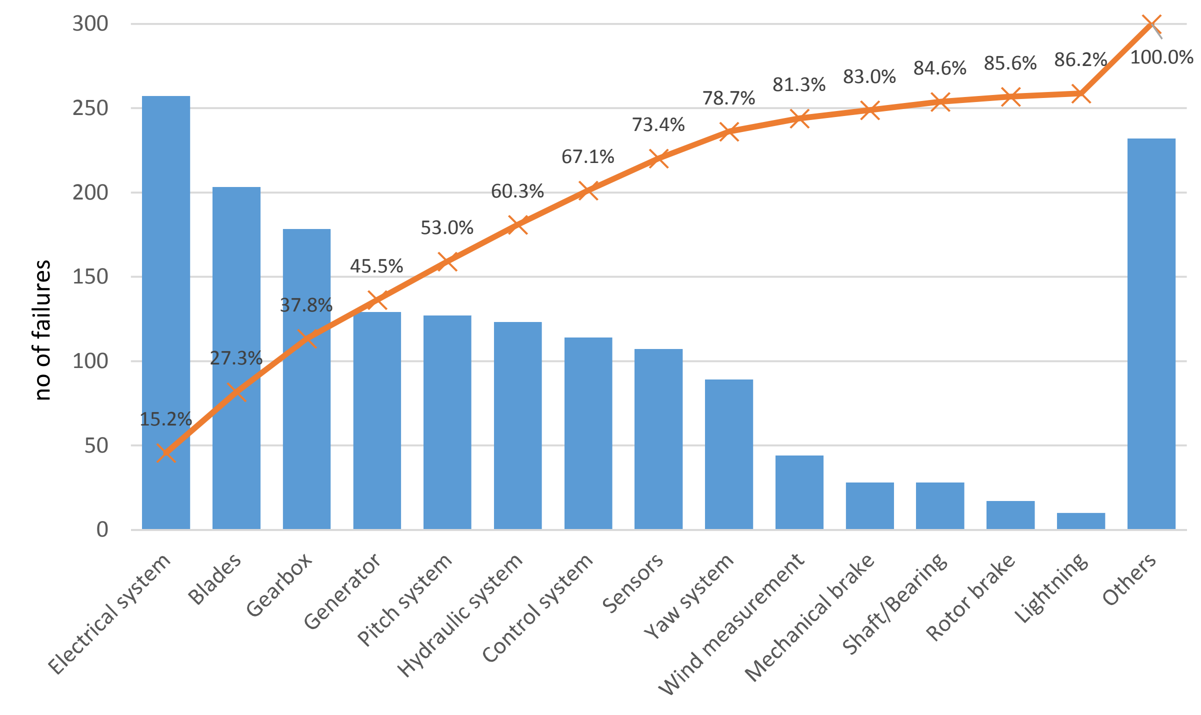

Figure 6.1: Pareto chart for the case of study

This research work considers a more complex analysis of the failure rate data. The average failure rate is given by the number of failures per turbine per year, i.e.:

$$f = \frac{\sum_{i=1}^{I} N_i}{\sum_{i=1}^{I} X_i \cdot T_i}$$

f : Failure rate (failures per turbine per year)

N_i: Number of failures that occurred during the time interval

T_i : Time interval (I in total of 1 year each one)

X_i: Number of WTs reported for the time interval

i: 1,2,…,I. (years)

The downtime is the time during which a wind turbine is not operating mainly for any maintenance task. The downtime is composed typically by:

- diagnosing the failure (in the case of non-condition monitoring systems),
- gathering repair equipment and spare parts,
- accessing the mechanism, and
- repairing and restarting the WT (usually the longest);

It is calculated as:

$$d = \frac{\sum_{i=1}^{I} d_i}{\sum_{i=1}^{I} X_i \cdot T_i}$$

d : Downtime due to failures per WT per year [hours per turbine per year]

d_i : Productive hours lost during the time interval due to failures.

LWK data collect information about different types of wind turbines. This work is focused on Vestas V66 of 1.65 MW. The failure rate and downtime of Vestas V66 wind turbine have been calculated. Table 6.1 shows these calculations.

Component	Failure rate	Downtime
Blades	0.478261	25.17391
Tower		
Pitch system	0.326087	9.717391
Mechanical brake	0.108696	0.543478
Shaft/Bearing	0.021739	0.434783
Gearbox	0.543478	119.0652
Generator	0.347826	88.36957
Hydraulic system	0.434783	16.58696
Yaw system	0.130435	4.782609
Wind measurement	0.173913	7.065217
Control system	0.521739	13.45652
Sensors	0.326087	8.565217
Electrical system	0.717391	35.95652
Others	0.282609	4.695652

Table 6.1: Failure rate and downtime for the components of Vestas V66

7 Application of the LCC Model

7.1 Model definition

The LCC model presented in this document is based on the model described in reference [7.1][58]
Following assumptions have been taken into account:

- Property tax, value added tax, etc., and general inflation are constant and included within the annual discount rate.
- Cash required for investment is provided by the enterprise (rather than being borrowed) so the equity rate is 1; the standard LCC model can be written as:

$$Y = \sum_{i=1}^{n} y_i = \lambda \sum_{i=1}^{n} a_i \, c_i^T$$

where:

- **Y** is the total cost and denotes the cumulative cost in year ***t***
- The subscript ***T*** is the total number of years
- y_i indicates the cost of breakdown in category ***i***

  In the case of study considered in this work, it has been appropriated to select $n = 5$:
    - CMS investment: $i = 1$
    - CMS operation: $i = 2$
    - CMS maintenance: $i = 3$
    - maintenance reductions by CMS: $i = 4$
    - energy production and energy losses by CMS: $i = 5$
- λ is the net present value (NPV) factor vector
- the matrix **A** and **C** can be described as:

$$\boldsymbol{A} = \begin{pmatrix} \boldsymbol{a_1} \\ \boldsymbol{a_2} \\ \boldsymbol{a_3} \\ \boldsymbol{a_4} \\ \boldsymbol{a_5} \end{pmatrix} \quad and \quad \boldsymbol{C} = \begin{pmatrix} \boldsymbol{c_1} \\ \boldsymbol{c_2} \\ \boldsymbol{c_3} \\ \boldsymbol{c_4} \\ \boldsymbol{c_5} \end{pmatrix}$$

  where $\mathbf{a}_i$ and $\mathbf{c}_i$ are one dimensional arrays of length *j*. In this case study j **= 4** and indicates one of the four elements of the wind turbine considered:
    - General, $j = 1$
    - Tower, $j = 2$
    - Nacelle, $j = 3$
    - Blades, $j = 4$

$$\boldsymbol{a_i} = (\boldsymbol{a_{11}} \quad \boldsymbol{a_{12}} \quad \boldsymbol{a_{13}} \quad \boldsymbol{a_{14}}) \qquad and \qquad \boldsymbol{c_i} = (\boldsymbol{c_{11}} \quad \boldsymbol{c_{12}} \quad \boldsymbol{c_{13}} \quad \boldsymbol{c_{14}})$$

[58] [7.1] F.P. García Márquez, R. W. Lewis, A.M. Tobias and C. Roberts, "Life cycle costs for railway condition monitoring", Transportation Research, Part E, vol. 44, pp. 1175-1187.

- Thus, matrix **A** and **C** results as:

$$\boldsymbol{A} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \\ a_{51} & a_{52} & a_{53} & a_{54} \end{pmatrix} \quad and \quad \boldsymbol{C} = \begin{pmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \\ c_{51} & c_{52} & c_{53} & c_{54} \end{pmatrix}$$

	General	Tower	Nacelle	Blades
CMS investment	11	12	13	14
CMS operation	21	22	23	24
CMS maintenance	31	32	33	34
maintenance reductions by CMS	41	42	43	44
energy production and energy losses by CMS	51	52	53	54

where each element of matrix **C** expresses the costs (per category and wind turbine component) and each element of **A** matrix indicates the number of times that the unit cost is incurred.

7.2 CMS Investment costs

The condition monitoring system investment cost $\boldsymbol{c_1}$ is related to the costs of capital. These costs include the general investment costs of CMS (capital, installation, regulatory approval, initial testing, software, power and communications), and the costs of the different parts of the CMS installed in the wind turbine (tower, nacelle and blades). The elements of $\boldsymbol{c_1}$ are therefore described as follows:

- General investment costs: $\boldsymbol{c_{11}}$ = -66600.00 €; $\boldsymbol{a_{11}}$ = 1
- Tower CMS investment costs: $\boldsymbol{c_{12}}$ = - 7051.96 €; $\boldsymbol{a_{12}}$ = 1
- Nacelle CMS investment costs: $\boldsymbol{c_{13}}$ = -8900.91 €; $\boldsymbol{a_{13}}$ = 1
- Blades CMS investment costs: $\boldsymbol{c_{14}}$ = -35151.94 €; $\boldsymbol{a_{14}}$ = 1

The elements of $\boldsymbol{a_1}$ are equal to 1, because the initial investment is made just once.

7.3 CMS Operation costs

The CMS operation cost $\boldsymbol{c_2}$ is the cost incurred by the technical operation process in a period of time.
These costs are collected in the CMS general operation costs $\boldsymbol{c_{21}}$ (taking into account the costs of: data acquisition and transmission, software, testing, power consume and human resources); thus $\boldsymbol{c_{22}}$, $\boldsymbol{c_{23}}$ and $\boldsymbol{c_{24}}$ are equal to zero.

The costs above described are calculated by month, therefore $\boldsymbol{a_2}$ = 12

- $\boldsymbol{a_{21}} = \boldsymbol{a_{22}} = \boldsymbol{a_{23}} = \boldsymbol{a_{24}} = 12$

7.4 CMS Maintenance costs

The CMS maintenance costs $\boldsymbol{c_3}$ are the cost for condition monitoring system maintenance management processes.

The general CMS maintenance cost C_{31} collects the costs of corrective and preventive CMS maintenance costs being

- $\boldsymbol{c_{31}}$ = 2500 € per year, and $\boldsymbol{c_{32}} = \boldsymbol{c_{33}} = \boldsymbol{c_{34}} = 0$.

7.5 Maintenance reduction costs by CMS

An analysis of the cost of overall WT maintenance tasks, with and without CMS, is presented in this sub-section. It includes preventive and corrective maintenance costs.

- Preventive and inspection costs are reduced in 75% with CMS.
- Corrective maintenance costs are reduced in 40% with CMS.

$\boldsymbol{c_{41}}$ is related to the general costs and includes preventive costs (ground inspections, cleaning, road network maintenance, general inspections…) and corrective costs (other failures, see failures rates in Table 6.1).

The tower maintenance reduction cost is represented by $\boldsymbol{c_{42}}$.

The nacelle maintenance reduction cost $\boldsymbol{c_{43}}$ includes the preventive and corrective maintenance cost of different elements such as generator, gearbox, shaft/bearings, brake system, electrical system.

Finally, $\boldsymbol{c_{44}}$ is related to the maintenance reduction cost in blades.

The values obtained are:

- $\boldsymbol{c_{41}}$ = 2026.09 € per year
- $\boldsymbol{c_{42}}$ = 900.00 € per year
- $\boldsymbol{c_{43}}$ = 29367.93 € per year
- $\boldsymbol{c_{44}}$ = 7178.26 € per year

7.6 Energy production and energy losses by CMS

The cost due to production losses is given by the costs difference of production losses with and without CMS. Some assumptions are taken into account for this study and showed in Table 7.1.

Assumptions	
Hours by year	8760
Power (kW)	1600
Efficiency (%)	60
Electricity price (€/kWh)	0.083
% Failures reduction by CM	40

Table 7.1: Assumptions for calculations

The elements of $\boldsymbol{c_5}$ are defined as the electricity price (0.083 €/kWh).
The elements of $\boldsymbol{a_5}$ are the difference of power loss (kWh) between the different elements with and without CMS. The downtime of each component (see Table 7.1) of the wind turbine is used to calculate the following items.

- $\boldsymbol{a_{51}}$ = 1803.13 kWh (general production losses)
- $\boldsymbol{a_{52}}$ = 0.00 kWh (production losses by the tower)
- $\boldsymbol{a_{53}}$ = 113213.20 kWh (production losses by the nacelle)
- $\boldsymbol{a_{54}}$ = 9666.78 kWh (production losses by the blades)

7.7 Net present value

The net present value (NPV) is defined as the sum of the present values (PVs) of the individual cash flows. The NPV is defined by the following expression:

$$NPV_t = \frac{CF_t}{(1+k)^{t-1}}$$

where *CFt* is the cash flow in year *t* assuming that all costs are defined using base-year prices, and *k* is the annual rate of return on investment, referred to as the cost of capital by some researchers. The total discounted cost over *t* years of life is therefore achieved by the following expression:

$$NPV = -I_0 + \sum_{t=1}^{T} \frac{CF_t}{(1+k)^{t-1}}$$

being I_0 the initial investment. Additionally, assuming that the previous costs remains constant throughout the lifetime of the project, *CF1 = CF2 = … = CFT = CF*, the NPV factor is given as follows:

$$\lambda = \sum_{t=1}^{T} \frac{1}{(1+k)^{t-1}} = \frac{1}{k}\left[1-(1+k)^{-T}\right]$$

Considering the above expressions, the NPV value can be calculated as

$$NPV = -I_0 + CF\,\lambda = -I_0 + \frac{CF}{k}\left[1-(1+k)^{-T}\right]$$

7.8 Calculation of LCC

In this study the base year has been set 0. The values that compose the matrixes A and C are the following:

$$\boldsymbol{A} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \\ a_{51} & a_{52} & a_{53} & a_{54} \end{pmatrix} \quad and \quad \boldsymbol{C} = \begin{pmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \\ c_{51} & c_{52} & c_{53} & c_{54} \end{pmatrix}$$

$$\boldsymbol{A} = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 12 & 12 & 12 & 12 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1803.13 & 0 & 113213.2 & 9666.78 \end{pmatrix}$$

$$\boldsymbol{C} = \begin{pmatrix} -66600 & -7051.962 & -8900.906 & -35151.940 \\ -1750 & 0 & 0 & 0 \\ -2500 & 0 & 0 & 0 \\ 2026.087 & 900 & 29367.93 & 7178.261 \\ 0.083 & 0.083 & 0.083 & 0.083 \end{pmatrix}$$

The values obtained from LCC and NPV are illustrated in Figure 3. This graph shows different curves depending on the annual rate of return (k). The initial investment will be recovered for all values of *k* between the 4th and the 6th years.

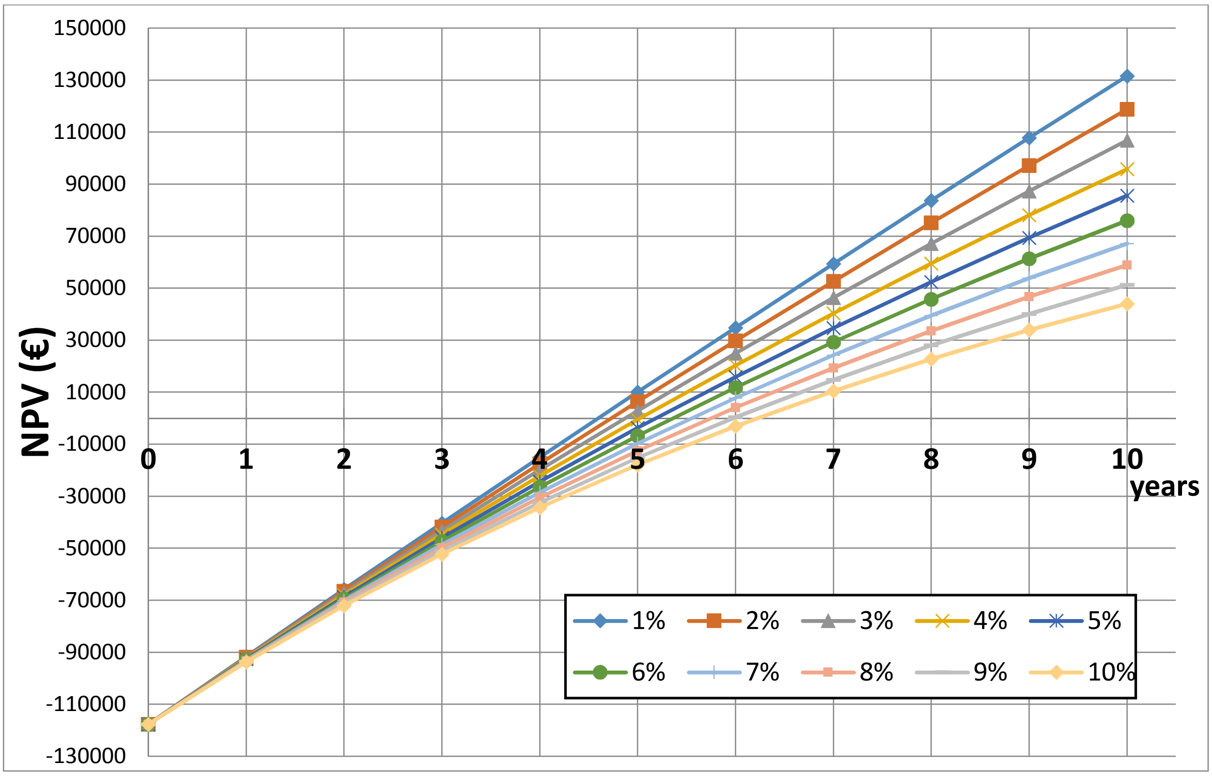

Figure 7.1: NPV with different annual rate of return

Nowadays the operator companies assume the initial investments with a bank credit. The following figure shows the inclusion in the LCC of an amortization of the initial investment with a rate of 6% and 10 years.

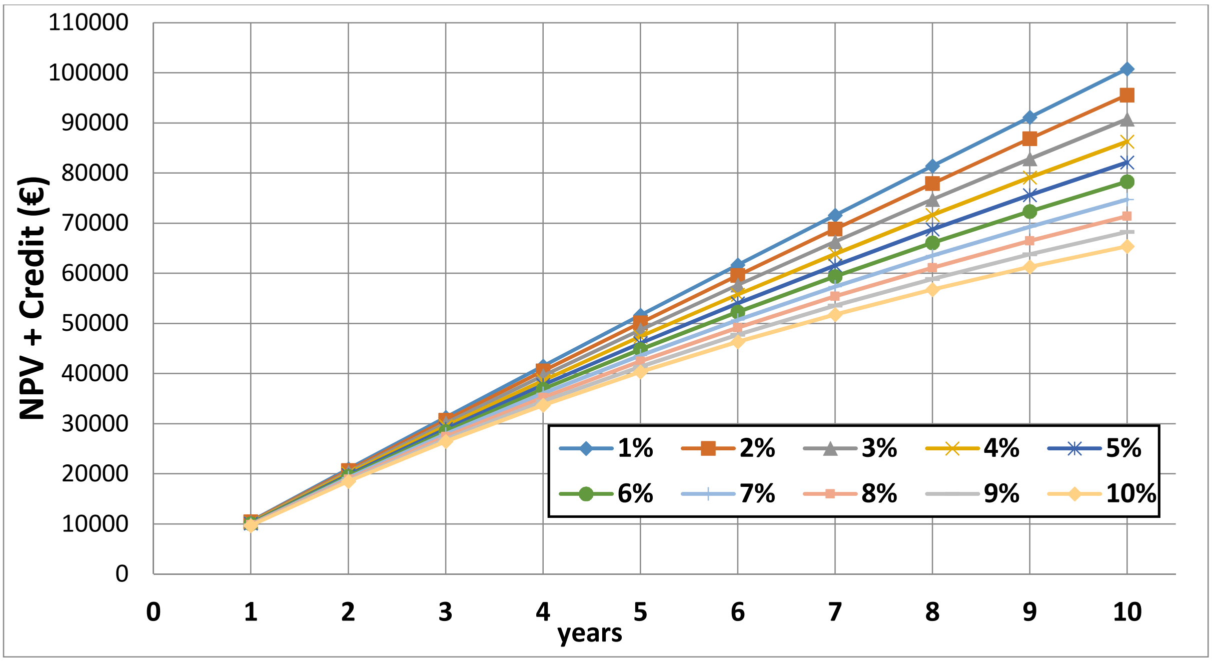

Figure 7.2: NPV with the amortization of a credit for initial investment

8 Offshore Wind Farms Maintenance

Current offshore wind turbines have not been designed specifically to cope effectively with the harsh environmental conditions that prevail in the open sea, because onshore wind turbine designs have been employed in offshore wind farms [8.1][59], [8.2][60], [8.3][61], [8.4][62]. This has resulted in reduced reliability levels for offshore wind farms. In addition, maintenance practices used for onshore wind farms and employed in offshore wind farms are inadequate for future such projects [8.5][63]. A widely practiced maintenance strategy adopted by offshore wind farm operators is Reactive Response [8.1][59], [8.6][64], [8.7][65]. However, it has been reported that this O&M strategy has led to over-maintenance [8.5][63] and hence unnecessary costs, leading to high expenditure per unit of energy. This particular O&M strategy has also been found to be inadequate when considering future large offshore wind farms in remote locations or under wave and weather conditions that are adverse for maintenance crews [8.5][63].

Prognostic and preventive based maintenance policy is required but maintenance optimisations for offshore wind farms are subjected to a variety of constraints such as reliability, adverse weather conditions, accessibility and availability of parts, equipment and technical personnel that must be accounted for in the O&M optimisation [8.8][66].When considering the reliability of the gearbox and power converter units in wind turbines, it has been reported as being two of the critical components that suffer from the highest failure rates within the wind turbine assembly 8.1][67], [8.2][68], [8.3][69], [8.4][70].

Therefore, not only an optimisation of the O&M policy is required but also the need for increasing the gearbox and power converter availability is of high importance for the economic viability of existing and future offshore wind farms. A Planned Intervention (PI) maintenance policy to meet the O&M needs of remote large offshore wind farms as suggested by Karyotakis and Bucknall is far more desirable than current strategies employed by offshore wind farm operators [8.8][71].

[59] [8.1] Van Bussel, G., Operation and Maintenance Aspects of Large Offshore wind farms', Proceedings of the 1997 European Wind Energy Conference, Dublin, Ireland. pp 272-279, 1997.
[60] [8.2] Nijssen et al., The application of scaling rules in up-scaling and marinisation of a wind turbine, Offshore Wind Energy Special Topic Conference, Brussels, Belgium, December 2001.
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[67] [8.1] Van Bussel, G., Operation and Maintenance Aspects of Large Offshore wind farms', Proceedings of the 1997 European Wind Energy Conference, Dublin, Ireland. pp 272-279, 1997.
[68] [8.2] Nijssen et al., The application of scaling rules in up-scaling and marinisation of a wind turbine, Offshore Wind Energy Special Topic Conference, Brussels, Belgium, December 2001.
[69] [8.3] EWEA 2013, 'Deep Water, The next step for offshore wind energy', a report prepared by the European Wind Energy Association, July 2013.
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[71] [8.8] Karyotakis A. and Bucknall, R. W. G., A redundancy model applied to the wind turbine power converter by engaging the planned invervention maintenance policy for offshore wind farms, In the Proceedings of the International Conference for Condition Monitoring and Machinery Prevention Failure Technologies, Manchester, UK, 2014 (Keynote Paper).

O&M costs of onshore wind farms normally do not exceed 20-25% of the overall project cost. However, in the case of the offshore projects current experience has shown that these costs can reach and even exceed 40% of the total project cost leading to very high OPEX and much higher energy production costs per MWh produced.

9 Conclusions

The rising wind energy in addition to the increasing number of failures of the larger wind turbines makes necessary the reduction of costs in this industry to make it more competitive in the sector. For this proposal the wind energy industry is focused on the reduction of operation and maintenance (O&M) costs. Condition Monitoring Systems (CMS) are probably the most effective approach to minimize O&M cost and substantially improve the availability, reliability and safety of wind turbines by early detection of the faults. CMS requires knowledge and expertise to analyse the large volume of data collected from the sensors located in the wind turbines. The main objective of this work is the development of a life cycle cost (LCC) model of the CMS for a wind turbine and the analysis of its economic feasibility. The LCC model has been applied to a real case study in Germany finding that the return of the investment will be after the 4th year of operation for an annual rate of return of 1%.

10 References

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