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Influence of Maintenance on the Performance of a Wind farm

Abstract. *This article focuses on the modeling and simulation of the performance of a wind farm with the objective of defining an optimal maintenance. Considered as an alternative source of clean energy, it is still subject to hourly or seasonal variations in speed and wind direction. Therefore, turbines undergo random charge unlike most industrial machines operating under more or less static. The task of forecasting failures becomes complex due to the random load. The process of decision making regarding the choice of schedule and the type of maintenance applied, these in turn are challenges that must be overcome with adequate modeling of the wind turbines operation. The simulation in Matlab environment based on a deterministic optimization model will contribute to the definition of a maintenance strategy to even enable greater availability and therefore an increased power output.*

Streszczenie. *W artykule skupiono się na zagadnieniu modelowania i symulacji farmy wiatrowej na potrzeby optymalnego serwisowania. Ze względu na specyfikę pracy turbin wiatrowych, niejednostajności wytwarzania energii, zmiany obciążenia, konieczne jest przewidywanie potencjalnych uszkodzeń. W tym celu opracowano model symulacyjny w programie Matlab, który umożliwia zarówno analizę utrzymania i serwisowania, jak i dzięki temu, zwiększenie otrzymywanej mocy. (**Wpływ serwisowania na wydajność farm wiatrowych**).*

Keywords: Wind Farm; Maintenance; Performance; Optimization.
Słowa kluczowe: Farma wiatrowa; Utrzymanie;. Wydajność; Optymalizacja.

Introduction

A wind farm is a group of wind turbines producing clean energy. It is usually a reliable site with strong winds to maximize energy production. Sometimes, the turbines are stopped during periods of strong winds to avoid unlikely catastrophic failure. Wind turbines onshore/offshore are widely affected stochastically by climate. Stochastic load or stress on wind turbines can cause failures [1]. The occurrence of these failures and faults in the wind turbine equipments causes an increase in transaction costs and a loss in revenues. The design and implementation of an appropriate maintenance plan to determine the best relationship between preventive maintenance and corrective maintenance to minimize operational costs maintain acceptable levels of power generation and optimize the performance of the wind farm [2].

In this article, we seek to determine an optimal maintenance strategy capable of performing well-planned interventions responding to unexpected failures by minimizing operational costs.

Maintenance activities

In general maintenance activities can be divided into two: corrective maintenance and preventive maintenance, corrective maintenance is performed when the component is faulty, and preventive maintenance is performed to prevent the occurrence of the failure. Preventive maintenance can be divided into scheduled maintenance (SM) and condition-based maintenance (CBM). Planned maintenance can be performed in programmed time intervals, and can be, for example, lubrication, tightening bolts, changing filters and checking the equipment safety [3]. Condition-based maintenance is a policy in which the maintenance action is decided on the basis of measurement of one or several variables correlated with degradation or loss of system performance. So it requires a system state monitoring with on-line monitoring and/or inspections [4]. The corrective maintenance strategy is the simplest, but it has several drawbacks. The failure of a minor component can cause the damage to a major component, which requires very high costs for repair/replacement. Other failures often occur during periods with high wind loads, and the site will be inaccessible during this period, resulting in a loss of production, so the costs for corrective maintenance are associated with much greater uncertainty than that of preventive maintenance. [5]

Operations and maintenance of a wind farm

The reliability of wind turbine equipment is the direct guide of O&M costs, e.g. for offshore wind turbines, O&M costs are in the order of 30-35% of electricity costs. Approximately 25 to 35% is related to preventive maintenance and 65 to 75% is related to corrective maintenance. The loss of revenues for offshore wind turbines are estimated in the same order as the direct costs for repair while for Onshore projects, loss of revenues are negligible [6].

Maintenance optimization

Maintenance function strongly influences the performance of a system. Its optimization is complex because it must take into account various criteria sometimes antagonists such as availability and cost [7], [8]. In addition, there is a multitude of ways to maintain a facility. We can play on the type of maintenance, types of tasks, their frequency, the level of intervention, etc..

There have been several simulation studies concerning the operations of wind farms. We present simulation studies directly linked to operations and maintenance of a wind farm.

Rademakers et al [9] describe a Monte Carlo simulation model for operations and maintenance of offshore wind farms developed by the Delft University of Technology (TU-Delft). The illustration of the model by the case of a wind farm of 100 MW. The model simulates aspects of operations and maintenance during a period by considering several critical factors of successful repair actions, such as failure of wind farms. Failures of turbine components are stochastically generated based on statistics such as shifts MTTF (Mean Time to faillure) distributions and reliability. In addition, weather conditions are realized with the percentages given summer and winter storms of a specific site. The model considers only corrective maintenance, and simulation results indicate that the loss of revenue accounted for 55% of all maintenance costs. Mainly due to the long period of preparation of parts and long waiting time until encountering favorable weather conditions for repairs. The models described above do not consider the state of degradation of each component of the wind turbine.

However, Macmillan and Ault [10], used a Monte Carlo simulation to quantify the cost-performance of monitoring equipment condition, and compare the performance of two strategies for maintenance policies, which are the SM (scheduled maintenance) and CBM (condition based maintenance). They used several probabilistic models for presenting uncertainties.For example, Markov models are used to represent the degradation behavior of a component. In their simulation model, we assume that the monitoring equipment condition shows exactly the state of degradation of each component. They also consider the time constraints in performing repair actions. Various scenarios with different profiles of wind, time periods of failures and replacement costs show the economic benefits of CBM against SM for onshore turbines. The simulation is also used for the evaluation of various approaches of operations and maintenance O & M.

Andrawus et al [11] suggest the optimal replacement time for each component of a wind turbine using statistical approaches and evaluate the strategy suggested by the Monte Carlo simulation. In their study, the Weibull distribution is used to model the failure of each component before deciding on the optimal replacement cycle for each component. In their study case of horizontal axis turbines of 600 kilowatts, to minimize the total cost of maintenance, the gearbox of the wind turbine should be replaced every six years and the generator every three years. They assess the reliability, availability and maintenance costs by simulating a wind farm of 26 turbines for four years using a commercial software called ReliaSoft BlockSim-7.

Similarly, Hall and Strutt [12] also developped probabilistic models of failure for the component reliability using Monte Carlo simulation combined with statistical analysis.

Mathematical models

We consider the wind turbines with identical blades, very low friction coefficient and wind speed with uniform distribution on all blades, the mechanical model of the wind turbine may be presented by the organs of the figure (1) [13].

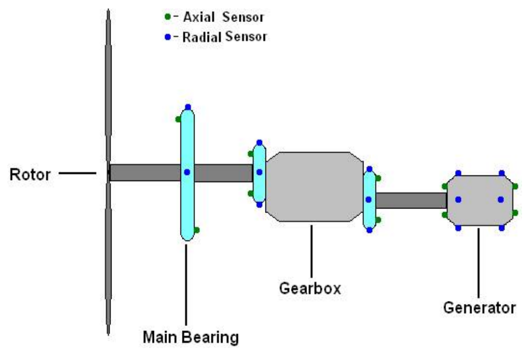

Fig.1: A simplified mechanical model of the turbine [13].

Model of wind speed

The dynamic properties of the wind are crucial for the study of the entire energy conversion system because, under optimal conditions, the wind power is function of the cube of the wind speed. Wind speed is a three-dimensional vector. However, the direction of the wind speed vector considered in this model is limited to the horizontal dimension. The behavioral model of wind can then be simplified considerably. The wind speed is usually represented by scalar functions that evolve over time.

(1) $v = f(t)$

This function can be modeled under deterministic form in the absence of wind data and can be decomposed into a slowly varying mean component with fluctuations [14]:

(2) $$v(t) = v_0 + \sum_{i=1}^{n} A_i \sin(\omega_i t + \varphi_i)$$

Such as: v_0 - Is the mean component; $A_i, \omega_i et \varphi_i$ - Are respectively the amplitude, angular frequency and initial phase of each fluctuation spectral component.

Figure (2) represents the mean speed profile adapted with our own wind system.

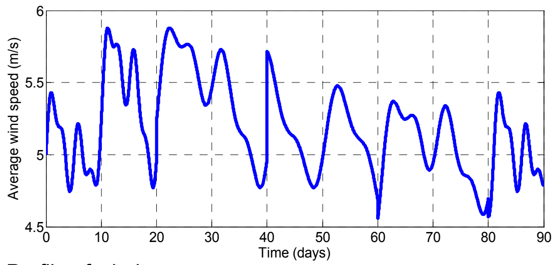

Fig.2: Profile of wind.

Power model

According to Betz theorem and the second law of Newton, the extracted power from wind by a turbine is expressed by the following relation [15]:

(3) $$P_t = \frac{1}{4}\rho S(v + v_2)(v^2 - v_2^2)$$

Where: ρ - is the density of the air; S - is the surface scanned by the turbine rotor; v - is the speed of the wind turbine lover,

v_2 - is the wind speed downstream of the turbine.

In addition, the total power of a non disturbed air flux through the same surface of this turbine without presence of rotor which disturbs the wind is given by:

(4) $$P_v = \frac{1}{2}\rho S v^3$$

The relationship between these two powers is expressed by:

(5) $$\frac{P_t}{P_v} = (\frac{1}{2}(1 - \frac{v_2^2}{v^2})(1 + \frac{v_2}{v})$$

We can note that the relation P_t / P_v reaches its maximum for ($v_2 / v = 1/3$) and the maximum value of the extracted power from wind is 0.59 of the total power contained in wind.

However, we can constate that practically the conversion system extracts a power less than the power P_v. We define then the power coefficient of the aero generator by the following relation:

(6) $$C_p = \frac{P_t}{P_v}$$

we can write:

(7) $$P_t = C_p P_v$$

We replace P_v by its expression in (4), we obtain:

(8) $$P_t = \frac{1}{2} C_p \rho S v^3$$

The value of the power coefficient C_p depends on turbine specific speed λ and the pitch angle blade β and can be expressed as follows:

(9) $$C_p = C_p(\lambda, \beta)$$

With:

(10) $$\lambda = \frac{R\,\Omega_t}{v}$$

where: $R\Omega_t$ - is the peripheric linear speed in the blade end.

The power coefficient C_p represents the turbine aerodynamic yield. Relation (11) represents the expression of this coefficient for a wind farm of 1.5 MW taken as an application example in this study:

(11) $$C_p(\lambda, \beta) = (0.5 - 0.00167(\beta - 2)). \\ .\sin[\frac{\pi(\lambda + 0.1)}{18.5 - 0.3(\beta - 2)}] - 0.00184(\lambda - 3)(\beta - 2)$$

Power coefficient

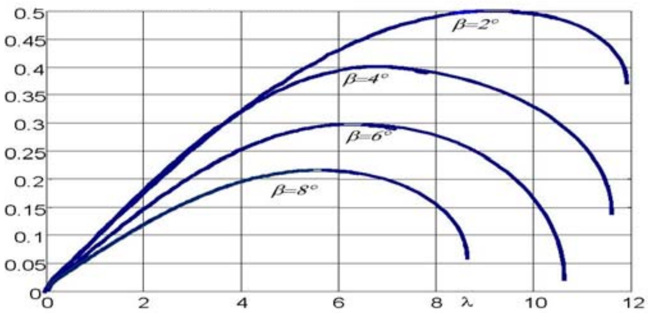

Fig.:3: $C_p(\lambda, \beta)$ in our study of the wind turbine.

Cost model

Objective function of optimization model

(12) $$\min \sum_{i\in WT,\, j\in CM} ny_{ij}.C_{CM_{ij}} + \sum_{i\in WT,\, j\in PM} nx_{ij}.C_{PM_{ij}} + ne.C_{pen} + \\ + \left[\sum_{i\in WT,\, j\in CM} ny_{ij}.E_{ij}^{CM} + \sum_{i\in WT,\, j\in PM} nx_{ij}.E_{ij}^{PM}\right].C_{élec}$$

With: nx_{ij} and ny_{ij} : Are Boolean variables respectively indicate the status of execution of the task j of preventive or corrective maintenance in the turbine i. They can take the value 0 or 1.

C_{CMij} - is task j cost for corrective maintenance in wind turbine i [DA]; C_{PMij} - is task j cost for preventive maintenance in wind turbine i [DA]; C_{pen} - is penality cost of maintenance supplementary works [DA / h]; $C_{élec}$ - is electricity cost [DA / kWh]; E_{ij}^{CM} - is energy loss if task j for corrective maintenance is effected in time t [kWh]; E_{ij}^{PM} - is energy loss if task j for preventive maintenance is effected in time t [kWh]; $i = \{1,2,3\}$ - is number of wind farm turbines in our case.

Application example

In this example we consider an onshore farm with three 4.5 MW wind turbines, with five preventive maintenance tasks to be performed on each turbine in a period of 90 days, this corresponds to five working days of the maintenance service team. The tasks of the manufacturer scheduled maintenance (SM) are assumed to be distributed as shown in figure 4.

Failure in the three turbines is generated randomly, assuming respectively default rates of 8, 4 and 12 failures per turbine per year.

The distribution of corrective maintenance tasks in each wind turbine is shown in figure 4, and the average repair time was supposed to be one day for each failure.

Wind forecasts are shown in figure 2 and the energy forecasts are based on wind scenarios forecasts, using the reference curves of power.

Scenarios of electric power production and accumulated energy in time are shown in figures 5 and 6.

Power losses for corrective maintenance CM and preventive maintenance PM are calculated based on deterministic model of wind speed and maintenance and repair times according to equations 13 and 14:

(13) $$P_f = p_t. \sum_{i\in WT,\, j\in CM,PM} (1 - ny_{ij})\,(1 - nx_{ij})$$

With: P_f - is the electrical power produced by the wind farm.

(14) $$E_f = P_f \sum_{i\in WT,\, j\in CM,PM} t_f - t_{CM_{ij}} - t_{PM_{ij}} + ti_{CPM_{ij}}$$

With: E_f - is the accumulated energy along time; t_f - is the final simulation time; $t_{CM_{ij}}$ - is the execution time of task j for the corrective maintenance CM; $t_{PM_{ij}}$ - is the execution time of task j for the preventive maintenance (PM); $ti_{CPM_{ij}}$ - is the intersection execution time for CM and PM.

The price of electricity is assumed 3 DA / kWh (electricity prices in Algeria), and the penalty cost for overtime maintenance is 500 DA/h for a team of three technicians.

In our application example we neglect the transport costs and the costs of access to the wind farm assuming weather conditions are favorable.

Results

The distribution of tasks in the maintenance plan initially applied to the wind farm generates several stops due to scheduled maintenance work and failures repair where considerable energy is lost in addition to high repair costs.

The distribution of tasks in the original plan of maintenance is shown in Figure 4.

The produced power and accumulated energy are depicted in figures 5 and 6.

The simulation in Matlab environment allow the optimization of the total cost of O & M in Eq.12 and define a best maintenance strategy based on the random distribution of failures simulated previously.

The result is a set of predictions of preventive maintenance tasks that are recommended to be carried out to minimize the number of wind system stops. This optimization plan of the maintenance schedule is shown in figure 7.

The produced electric power and the accumulated energy due to this new maintenance policy are represented in figures 8 and 9.

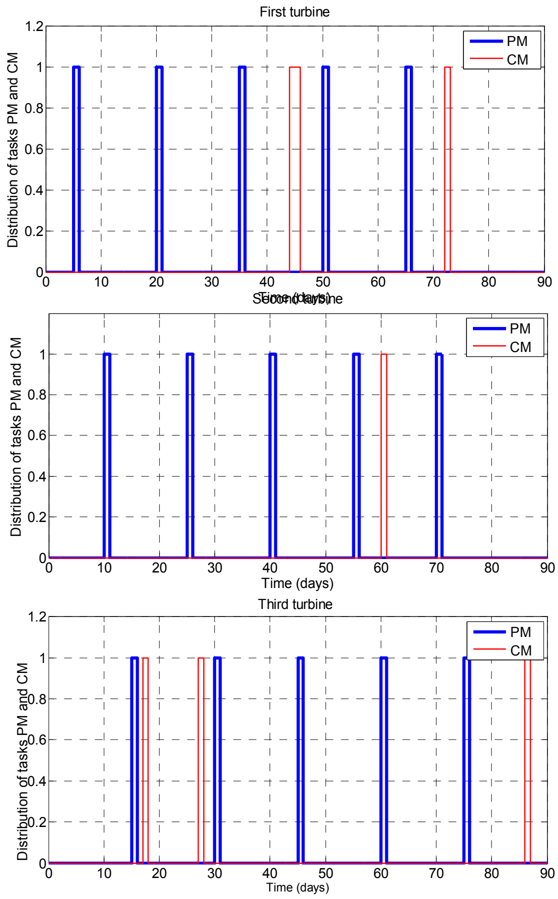

Fig.4. Distribution of tasks CM and PM

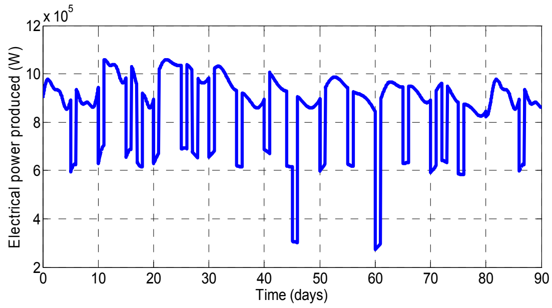

Fig.5. Electrical power produced in time.

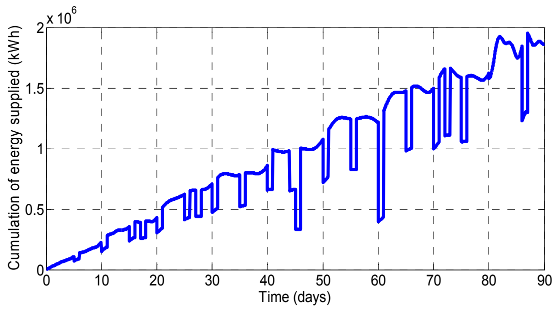

Fig.6. cumulates of the energy supplied.

By comparing the electric power curves and the accumulated energy in the two cases: case of normal planning before optimization and planning after optimization, we can clearly see a significant gain in electrical power or a gain in accumulated energy.

Comparisons of the produced electric power and the accumulated energy in three months in the normal case and the optimized case are respectively shown in figures 10 and 11.

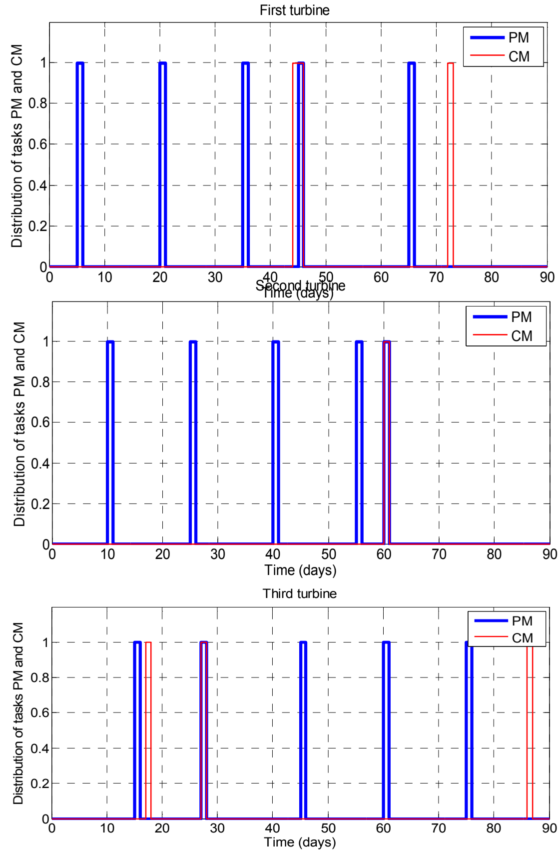

Fig.7: Distribution of CM and PM tasks according to plan Optimized maintenance

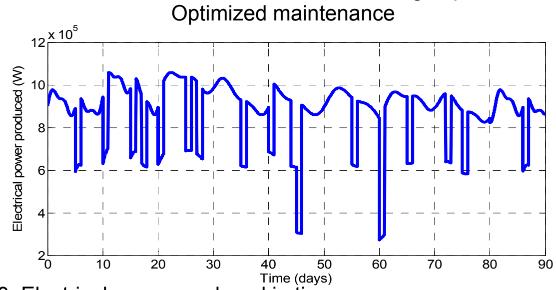

Fig.8. Electrical power produced in time.

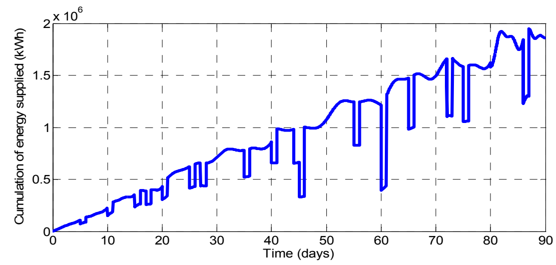

Fig.9. Energy accumulated in time.

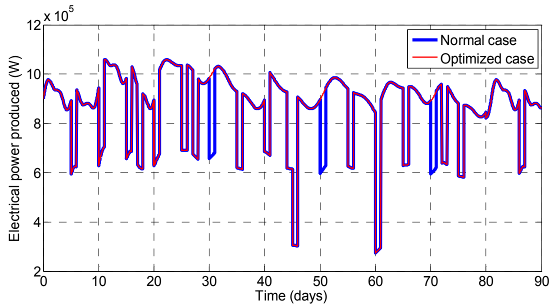

Fig.10. Comparison of the electric power produced in both cases (before and after optimization).

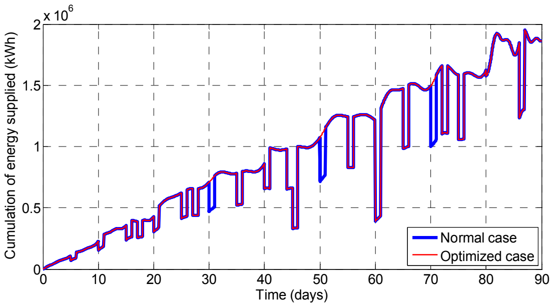

Fig.11. Comparison of the electrical energy accumulated in the normal case and the case optimization.

The gain in electrical energy is given by the following relation:

(15) $$BE = EF_{opt} - EF_{nor}$$

With: BE is the gain in electrical energy [kWh];

EF_{opt} - is the electrical energy of the wind farm after optimization [kWh]; EF_{nor} - is the wind farm electrical energy in normal case before optimization [kWh];

A.N: BE= 1.4698e+006 - 1.4077e+006 = **0.0621e6 kWh.**

The gain in cost is given by the following expression:

(16) $$BC = BE.C_{élec}$$

With: BC - is the gain in cost [DA].

A.N: BC= 0.0621e6*3=62100*3=**186300 DA.**

Conclusion

In this paper, we presented a deterministic optimization model to perform the tasks of plan maintenance service with lower cost. This new maintenance plan meets the unexpected failures of wind turbines and allows for a significant gain in power generation. The model was illustrated by an application example of onshore wind farm using a deterministic model of Wind speed. Simulation results show a wind farm availability of **75.53%** with a gain in energy production of **4.22%** in 90 days or **186 300 DA** in terms of cost.

REFERENCES

[1] Eunshin Byon, Eduardo Pérez, Yu Ding and Lewis Ntaimo. Simulation of wind farm operations and maintenance using discrete event system specification. SIMULATION, Volume 87 (12): 1093 SAGE Journal– Dec 1, 2011.

[2] S. Carlos, A. Sanchez, S. Martorell, I. Marton. Onshore wind farms maintenance optimization using a stochastic model. Mathematical and computer modeling, ELSEVIER. 2012.

[3] Julia Nilsson, Lina Bertling. Maintenance Management of Wind Power Systems Using Condition Monitoring Systems – Life Cycle Cost Analysis for Tow Case Studies. IEEE Transactions on Energy Conversion, Vol.22, N°. 1, 2007.

[4] B. Niang, K. H. Adjallah, P. A. Ndiaye. Evaluation of maintenance parameters of a wind system of energy production per Monte Carlo simulation. Journal des sciences pour l'ingénieur. N° 8, pages 14 à 19, 2007.

[5] T. W. Verbruggen. Wind Turbine Operation & Maintenance based on Condition Monitoring. WT- Ω Final. ECN internal report, ECN-C-03-047, 2003.

[6] Vaughn Nelson. Wind Energy: Renewable Energy and the Environment. International standard book, Number-13: 978-1-4200-7568-7 (Hardcover).

[7] Lyonnet, P. Optimisation d'une politique de maintenance. Edité par TEC ET DOC, 1999.

[8] M. Glade. Modélisation des coûts de cycle de vie : prévision des coûts de maintenance et de la fiabilité. Application à l'aéronautique. Thèse de doctorat, Ecole centrale de Layon, 2007.

[9] Rademakers L.W.M.M, Braam H, Zaaijer M.B and van Bussel G.J.W. Assessment and optimization of operation and maintenance of offshore wind turbines. Technical Report, 5 pages,2003. Available at http://www.ecn.nl/library/reports/main.html

[10] McMillan D and Ault GW. Condition monitoring benefit for onshore wind turbines: sensitivity to operational parameters. IET Renew Power Gener; 2(1): 60–72, 2008.

[11] Andrawus J.A, Watson J and Kishk M. Modeling system failures to optimize wind turbine maintenance. Wind Eng; 1(6): 503–522, 2007.

[12] Hall P. L and Strutt J. E. Probabilistic physics-of-failure models for component reliabilities using Monte Carlo simulation and Weibull analysis: a parametric study. Reliab Eng Syst Safety; 80: 233–242, 2007.

[13] National instruments products for wind turbines condition monitoring. 2010. Available at the link : http://zone.ni.com/devzone/cda/tut/p/id/7676

[14] A. Abdelli. Optimisation Multicritère d'une Chaîne Eolienne Passive. PhD in Electrical Engineering, National Polytechnic Institute of Toulouse, France, 2007.

[15] L. Khettache. Etude et Commande d'un Système Eolien à Base d'une Machine Electrique Double Alimentée. Magister thesis, University of Batna, Algeria, 2007.

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